Analysis of a Graphite Foam-NaCl Latent Heat Storage System for Supercritical CO₂ Power Cycles for Concentrated Solar Power

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Abstract

A latent heat thermal energy storage (LHTES) system that operates at high temperature was analyzed for applications to supercritical CO₂ (s-CO₂) power cycles for a concentrated solar power (CSP) plant. Because the operation temperature of the s-CO₂ power cycles is high (650–700 °C), sodium chloride (NaCl), with a melting point of 800 °C, was selected as the phase-change material (PCM) for energy storage. Due to the low thermal conductivity of salt materials (usually < 1 W/m K), use of graphite foam was chosen to improve the overall thermal conductivity of the graphite foam-PCM combination. Three-dimensional (3-D) heat transfer simulations were conducted for the envisioned full-scale LHTES system. The anisotropic thermal conductivities of graphite foam were considered in the simulations. The thermal performance and the exergy efficiency were investigated for the full-scale LHTES system to study the improvements due to the graphite foam. The results show that this material improves the heat transfer performance in the LHTES system and, therefore, significantly reduces the total number of the heat transfer fluid (HTF) pipes needed in the storage system by a factor of 12 compared to a PCM-only system. Furthermore, the graphite foam helps to increase the exergy efficiency of the LHTES system considerably. The system parameter (i.e., HTF inlet temperature, flow velocity) effects on the thermal performance and exergy efficiency of the graphite foam-PCM LHTES system were analyzed in the paper. Moreover, the graphite foam-NaCl system matches the temperature requirements of the s-CO₂ power cycles for the CSP plant.

Keywords: Concentrated solar power; Graphite foam-NaCl combination; Latent heat thermal energy storage; Supercritical CO₂ power cycle

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Nomenclature

$B(T)$	liquid fraction
c_p	heat capacity (J/kg K)
$D(T)$	Gaussian function
Ex_{HTF_char}	exergy supplied by heat transfer fluid during charging (J)
Ex_{HTF_dis}	exergy recovered from heat transfer fluid during discharging (J)
k	thermal conductivity (W/m K)
k_{xy}	thermal conductivity in the low thermal conductivity direction (W/m K)
k_z	thermal conductivity in the high thermal conductivity direction (W/m K)
L	latent heat of fusion (J/kg)
T	temperature (K)
t	time (s)
V	heat transfer fluid velocity (m/s)
x	x -direction
y	y -direction
z	z -direction

Greek symbols

γ	open porosity of foam (%)
ρ	density (kg/m ³)
ψ_{round}	round-trip exergy efficiency (%)
ω	weight percentage (%)

Subscripts

<i>graphite</i>	graphite component
<i>HTF_char</i>	heat transfer fluid during charging
<i>HTF_dis</i>	heat transfer fluid during discharging
<i>inlet_char</i>	inlet of heat transfer fluid during charging
<i>inlet_dis</i>	inlet of heat transfer fluid during discharging
<i>outlet_char</i>	average outlet of heat transfer fluid during charging
<i>outlet_dis</i>	average outlet of heat transfer fluid during discharging
<i>PCM</i>	phase change material component
<i>l</i>	liquid state
<i>s</i>	solid state

Acronyms

3-D	three-dimensional
CSP	concentrated solar power
HTF	heat transfer fluid
LCOE	levelized cost of electricity
LHTES	latent heat thermal energy storage
PCM	phase change material
s-CO ₂	supercritical CO ₂
TES	thermal energy storage

1. Introduction

Current CSP plants use the two-tank molten salt or one-tank thermocline sensible heat storage system for storing thermal energy (Kuravi et al., 2013; Medrano et al., 2010). The operation temperature range for the sensible heat storage is typically between 292 °C and 565 °C (Burgaleta et al., 2011; Kuravi et al., 2013; Medrano et al., 2010). The types of HTFs are usually molten salt, oil, or steam in the CSP plants (Medrano et al., 2010). Because of the low conversion efficiency of the current steam Rankine-cycle power block (37.5%) (Herrmann et al., 2004; Kelly and Kearney, 2006), the plant capacity is usually small (≤ 50 MW_e) (Burgaleta et al., 2011; Kuravi et al., 2013; Medrano et al., 2010). Therefore, for large-scale power generation with a plant capacity of >50 MW_e, higher efficiency power cycles are desired to reduce the levelized cost of electricity (LCOE) from CSP.

Supercritical-CO₂ power cycles operating in a closed-loop recompression Brayton cycle (Ma and Turchi, 2011) with temperatures up to 650-700 °C (Gary, 2011) have been considered for the CSP plants for large-scale power generation. The conversion efficiency of the s-CO₂ power cycles can reach 50% (Gary, 2011). The supercritical CO₂ is used as both the HTF for the solar collector and the thermal energy storage (TES) system and the working fluid for the power cycle in the CSP plant. This arrangement eliminates heat exchangers in the CSP plants and, therefore, simplifies the power plant configuration (Ma and Turchi, 2011; Turchi, 2009). Furthermore, the size of the s-CO₂ power turbine is much smaller than that of the steam power turbine for the same plant capacity (Chapman and Arias, 2009; Persichilli et al., 2012; Turchi, 2009). Thus, it can increase the power plant efficiency (Turchi, 2009). One disadvantage of the s-CO₂ power cycles is the high pressure in the pipe system (Chapman and Arias, 2009). Nevertheless, the pumping power for the power plant does not increase much compared to the current synthetic-oil HTF system due to the lower density and viscosity of CO₂ (Chapman and Arias, 2009). Therefore, the s-CO₂ power cycle has the potential to be applied in the CSP plants for large-scale power generation at low cost.

To achieve the high operation temperature required for the s-CO₂ turbine, a high-temperature TES system must be used. The latent heat storage system has a much higher energy density than a sensible heat storage system. Also compared with sensible heat storage, latent heat storage provides a smaller temperature difference between charging and discharging processes and a smaller volume requirement of materials for storing the same amount of energy. Therefore, the LHTES system is attracting significant attention. High-melting-point PCMs (melting point > 750 °C) are considered as a potential storage medium for the LHTES system to meet the temperature requirements for the s-CO₂ power cycle. In the present study, NaCl, with a melting point of 800 °C (Janz et al., 1979), was selected as the PCM for the s-CO₂ power cycle application.

Due to the low thermal conductivity of salt materials (usually less than 1 W/m K), a high-conductivity porous material, i.e., graphite foam, was applied as an additive to enhance the overall thermal conductivity of the PCM and, therefore, to significantly improve the thermal performance of the LHTES system. The open porosity of graphite foam is around 80-90%, based on commercial graphite foam suppliers. The thermal performance of the graphite foam-NaCl LHTES system was evaluated and the improvements that resulted from applying the graphite foam were analyzed through 3-D numerical heat transfer simulations using the commercial

software COMSOL. According to our previous study, the graphite foam can improve the heat transfer performance as well as the exergy efficiency in the storage system (Zhao et al., 2014).

The objectives of the current study are to evaluate the heat transfer performance and the exergy efficiency of a full-scale LHTES system for s-CO₂ power cycles in a CSP plant. The heat transfer simulations for the full-scale system are intended to show the thermal performance improvements by incorporating the graphite foam in the TES system and to verify the storage system temperatures meeting the s-CO₂ power cycle requirements. The system parameters, i.e., HTF flow rates and inlet temperatures, were analyzed to investigate their effects on the thermal performance and exergy efficiency of the LHTES system. The detailed knowledge of the thermal performance obtained from the simulations is expected to optimize the design and the operation of the LHTES system.

2. Mathematical modeling

2.1. Graphite foam-NaCl LHTES system for the CSP plant

The CSP plant capacity was assumed to be 100 MW_e with a 12-hour storage capacity. Thus, the LHTES system requires 200 MW_t (2400 MWh) thermal storage capacity, based on the efficiency of the s-CO₂ power cycle of approximately 50% (Gary, 2011), which is equivalent to about 15,342 tons of the graphite foam-NaCl combination as the storage medium. The HTF pipes are inserted in the graphite foam-NaCl for heat exchange. The HTF outlet temperature from the storage system should be ≥ 720 °C to achieve the temperature requirement (650-700 °C) of the s-CO₂ power cycle.

A modular design for the storage system has been developed instead of a single large tank system to simplify the fabrication, site installation, and maintenance of the storage system and reduce the overall LHTES system cost. The relative small size modules can be manufactured off-site in a controlled environment with current technology. Field installation is minimized and simplified, and maintenance is facilitated by the removal of an individual module for repair or replacement without causing a plant outage.

The entire storage system consists of several LHTES modules, as sketched in Fig. 1(a). Each module contains seven HTF pipes. Standard 2-in. pipes (outer diameter, 60.32 mm; inner diameter, 54.79 mm) were used as the HTF pipes in the storage system. The size of the HTF pipes is based on the capital and the operating costs of the TES system studied by the present authors (Kim et al., 2014).

To ensure most of the PCM undergoes a phase change during the 8-hour charge/12-hour discharge, the size of each module was around 1.25 m in diameter and 10 m in height, as shown in Figs. 1(b) and (c). The distance between each pipe in the module was 0.45 m. To achieve the 2400 MWh storage capacity, around 801 modules are required in the whole storage system. Thus, the diameter of the entire storage system is approximately 35 m, and the height of the whole LHTES system is 10 m based on the height of the storage tank of Gemasolar, a CSP plant in Spain (Burgaleta et al., 2011). A single module was used for the current simulations to

represent the entire LHTES system because of the adiabatic boundary condition around each module.

Fig. 1. Schematic of the LHTES system.

Supercritical CO₂ was used as the HTF, and its properties are given in Table 1. According to the literature (Chapman and Arias, 2009), the solar field inlet pressure is around 200 bar for the s-CO₂ power cycle. Thus, the density of the s-CO₂ was estimated on the basis of this pressure (Colina et al., 2003).

Table 1
Thermophysical properties of supercritical CO₂ (Amooey, 2014; Colina et al., 2003; Heidaryan et al., 2011).

	Density (kg/m ³)	Specific heat (J/kg K)	Thermal conductivity (W/m K)	Dynamic viscosity (Ns/m ²)
Supercritical CO ₂	110	1136	0.085 (at 800 °C)	4.2×10 ⁻⁵ (under 200 bar at 800 °C)

2.2. Heat transfer simulations and exergy efficiency analyses

Incoloy 800H was used as the material for the HTF pipes and the prototype container because of its superior oxidation resistance. It should be noted that the actual piping material will also depend on the mechanical properties at the operating conditions. The thermal properties of the graphite foam-NaCl combination and Incoloy are displayed in Table 2. The properties of the graphite foam-NaCl combination were calculated based on the percentage of the graphite and NaCl components in the combination, as expressed in Eqs. (1)-(3).

The density of the combination was defined as

$$\rho = \rho_{\text{graphite}}(1 - \gamma) + \rho_{\text{PCM}}\gamma \quad (1)$$

where ρ is the density of the graphite foam-PCM combination; ρ_{graphite} is the density of graphite; ρ_{PCM} is the density of PCM; γ is the open porosity of graphite foam (it is 90% (volume percentage) in the present study).

The specific heat of the graphite foam-PCM combination was calculated based on Eq. (2).

$$c_p = c_{p_{graphite}}(1 - \omega) + c_{p_{PCM}}\omega \quad (2)$$

where c_p is the specific heat of the graphite foam-PCM combination; $c_{p_{graphite}}$ is specific heat of graphite; $c_{p_{PCM}}$ is specific heat of PCM; ω is the weight percentage of PCM in the graphite foam-PCM combination ($\omega = \frac{\rho_{PCM}\gamma}{\rho_{PCM}\gamma + \rho_{graphite}(1-\gamma)}$).

The overall latent heat of fusion of the combination was defined as

$$L = L_{PCM}\omega \quad (3)$$

where L is the overall latent heat of fusion of the graphite foam-PCM combination; L is the latent heat of fusion of PCM.

The anisotropic thermal conductivities of graphite foam were considered in the simulations. The thermal conductivity of graphite foam is higher in one direction and relatively lower in the other two directions (KFOAM, Koppers graphite foam; Klett et al., 2004). The thermal conductivity values of graphite foam in the high thermal conductivity direction, k_z , are approximately two times as those in the other two low thermal conductivity directions, k_{xy} (Gyekenyesi and Singh, 2013; KFOAM, Koppers graphite foam). The high thermal conductivity direction were placed in the radial direction in the module cylinder, perpendicular to the HTF pipe direction. This arrangement allows more PCM to undergo the phase change during the charging/discharging processes.

Table 2
Thermophysical properties of graphite foam-NaCl and Incoloy 800H (Janz et al., 1979; Poling et al., 2008).

	Density (kg/m ³)	Specific heat (J/kg K)	Thermal conductivity, k (at 800 °C) (W/m K)		Latent heat of fusion (J/kg)
Graphite foam-NaCl	1624	1240 (at melting point of NaCl)	k_z ~25 ^a	k_{xy} ~12.5 ^a	414342
Incoloy 800H ^b	7940	460	24.7		---

^a Estimated based on the properties of graphite foam (Gyekenyesi and Singh, 2013) and NaCl (Janz et al., 1979).

^b Incoloy alloy 800H & 800HT, Special Metals Corporation, 2004.

Several assumptions were made in the simulations. First, the LHTES system was assumed to be well insulated. The heat loss from the LHTES system was neglected. Second, the HTF inlet temperature was maintained at a constant set value. Third, the flow velocity was maintained at a constant value in the HTF pipes during the charging/discharging processes. Fourth, the buoyancy-driven convection in the molten PCM was neglected because it is not significant in the porous material (Sedeh and Khodadadi, 2013). Fifth, the volume change of the PCM during the phase change process was not considered in the current simulations. Sixth, the thermal resistance of the gap between the HTF pipes and the graphite foam-PCM combination was neglected in the present simulations because it would be filled with the brazing material or the PCM (Zhao et al., 2014).

The equivalent heat capacity method was applied for the phase-change simulations in COMSOL (Faghri et al., 2010; Samara et al., 2012). The simulation method was explained in detail by the present authors in a previous publication (Zhao et al. 2014). The energy equation for the phase-change process is given by the following equation (Incropera and DeWitt, 2002):

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) \quad (4)$$

where T is the temperature; t is the time.

Here, c_p is determined by (Samara et al., 2012)

$$c_p = c_{p,s} + (c_{p,l} - c_{p,s})B(T) + LD(T) \quad (5)$$

where $c_{p,s}$ and $c_{p,l}$ are the heat capacities of the solid- and liquid-state graphite foam-PCM combinations, respectively; L is the latent heat of fusion of the graphite foam-PCM combination; $D(T)$ is the Gaussian function used to account for the latent heat of fusion (Samara et al., 2012); and the function $B(T)$ is the liquid fraction used to determine the change in the thermophysical properties (c_p , etc.) between the solid and liquid phases of the graphite foam-PCM combination (Samara et al., 2012; Zhao et al., 2014).

The round-trip exergy efficiency of the real LHTES system in the CSP plant was analyzed as well. The round-trip exergy efficiency (ψ_{round}) was determined by the exergy recovered from the HTF during the discharging process (Ex_{HTF_dis}) as a fraction of the total exergy supplied by the HTF during the charging process (Ex_{HTF_char}), which is expressed as (Jegadheeswaran et al., 2010)

$$\psi_{round} = \frac{Ex_{HTF_dis}}{Ex_{HTF_char}} \quad (6)$$

2.3. Model parameters

In the CSP plant, the charging time (energy storage time) for the LHTES system is 8 hours, while the discharging time (energy retrieval time) is expected to be 12 hours. The s-CO₂ flow velocity in the HTF pipes was assumed to be 18 m/s during the charging process, based on the literature data (Ma and Turchi, 2011). The CO₂ flow velocity during the discharging process was estimated as 12 m/s (2/3 of the charging velocity because of the longer discharging time). The s-CO₂ HTF flow direction was from the bottom of the storage system to the top. The inlet CO₂ temperature for the LHTES system during the charging process was set at 880 °C. The average outlet CO₂ temperature during the discharging process was above 720 °C (to match the s-CO₂ power cycle temperature requirements). The melting point of the PCM (NaCl) is 800 °C. The initial temperature of the storage medium was assumed to be 720 °C before the charging process started.

The simulation model consisted of 3,527,990 domain elements, 319,688 boundary elements, and 38,260 edge elements. Based on a mesh independence study, these mesh elements were sufficient in the simulations for the LHTES system.

2.4. Model verification

The simulation model was verified by comparison between the current 3-D COMSOL heat transfer simulation and a 1-D numerical simulation using the front-tracking method (a different method for phase-change simulations) (Zhao et al., 2014). A single HTF pipe system was used for the verification simulations. The melting front movements and the temperature profiles at the axial midpoint of the storage system obtained by the 3-D COMSOL simulations were compared to those from the 1-D numerical simulations using the front-tracking method. The simulation results of the two methods were very close to each other, with the differences <5% (Zhao et al., 2014).

3. Results and discussion

3.1. NaCl LHTES system without graphite foam

Fig. 2 shows the simulation results for the locations of the melting fronts in a NaCl LHTES system without graphite foam after the 8-hour charging process. In the phase transition graphs, the red region (1 on index) indicates complete liquid-state PCM, while the blue region (0) indicates complete solid-state PCM. Because of the low thermal conductivity of NaCl (around 1 W/m K) (Janz et al., 1979), the heat transfer performance in the storage system was very poor. Only a very small portion of the PCM around the HTF pipes was melted after the 8-hour charging process, as indicated in Fig. 2, due to the large thermal resistance related to heat conduction in NaCl. To ensure that most of the PCM is melted during the charging process (to achieve the 2400 MWh storage capacity), the total number of the HTF pipes in the storage system is about 66,557 for the pure NaCl LHTES system without the graphite foam, which translates to high capital and operating costs of the TES system. Note that the buoyancy-driven convection in the molten NaCl was neglected in the current simulations. This action slightly reduces the accuracy of the simulation results. However, it does not change the order of magnitude of the HTF pipes in the system when no graphite foam is applied (Zhao et al., 2014).

Fig. 2. Locations of the melting front in NaCl without graphite foam after the 8-hour charging process.

3.2. Graphite foam-NaCl LHTES system

Improvement of the heat transfer performance were obtained through the addition of graphite foam in the LHTES system. Because of the high thermal conductivity of graphite foam, the thermal performance in the TES system was improved significantly, as displayed in the following figures. Figs. 3 and 4 show the melting/solidification front movements and temperature profiles during the charging/discharging processes. After the 8-hour charging process, almost all of the PCM in the module system was melted (energy storage process), as shown in Figs. 3(e) and (f). The melting front in the y -direction moved faster than that in the x -direction, as displayed in Figs. 3(a) and (b), due to the anisotropic thermal conductivity of graphite foam. However, because the heat transfer occurred in the circumferential direction through the graphite foam, the front movement and temperature differences between the x - and y -directions were not very significant. Similar front movements occurred in the discharging process, as shown in Fig. 4. After the 12-hour discharging process, all PCM in the module system was solidified (energy retrieval process), as displayed in Figs. 4(e) and (f). The high thermal conductivities of graphite foam remarkably increased the heat transfer performance in the LHTES system. This improved heat transfer decreases the total number of HTF pipes needed in the storage system to around 5,607, a reduction factor of 12 compared to the non-graphite foam storage system, and this decrease considerably reduces the costs of the TES system.

Because of the liquid-like densities of supercritical CO_2 , the heat transfer characteristics of the HTF is excellent, and the heat transfer coefficient of the HTF is very high, with a large Biot number of around 5.4. Thus, the temperature gradient in the radial direction (x - and y -directions) was significant. The PCM close to the HTF pipes melted or solidified first during the charging or discharging process, respectively. Then, the heat conducted radially (in x - and y -directions) to melt/solidify the PCM away from the HTF pipes, as displayed in Figs. 3 and 4.

Phase transition between
solid state and liquid state PCM

(a) Location of melting front at 4 hours (overall view)

Time=14400 s Phase transition between solid state and liquid state PCM

(b) Location of melting front at 4 hours
(at middle cross section)

Time=14400 s
Surface: Temperature (degC)

(c) Temperature profile at 4 hours (overall view)

Time=14400 s Surface: Temperature (degC)

(d) Temperature profile at 4 hours
(at middle cross section)

Fig. 3. Melting front movement and temperature profiles in the LHTES system during charging process.

(c) Temperature profile at 4 hours (overall view)

(d) Temperature profile at 4 hours (at middle cross section)

Phase transition between
solid state and liquid state PCM

(e) Solidification front after the 12-hour discharging process (overall view)

Time=43200 s
Surface: Temperature (degC)

(f) Temperature profile after the 12-hour discharging process (overall view)

Fig. 4. Solidification front movement and temperature profiles in the LHTES system during discharging process.

Fig. 5 shows the temperature profiles in the y - (radial) and z - (axial) directions in the storage module system. The center line of the middle HTF pipe is located at the origin ($x = 0, y = 0$), as shown in Fig. 1(b). Figs. 5(a) and (c) are the temperature profiles in the y -direction at the axial midpoint ($z = 5$ m) of the storage module system during charging and discharging processes, respectively. In the legends of Figs. 5(a) and (c), small y value indicates that the location is close

to the HTF pipe, while large y value indicates that the location is far from the HTF pipe. Because of the large Biot number, the temperature gradient in the y -direction (high thermal conductivity direction) was high during the phase change processes. Figs. 5(b) and (d) show the temperature profiles in the z -direction at $y = 0.225$ m (half of the distance between two pipes). Here, z equal to zero indicates a location at the bottom of the storage system, while z equal to 10 m is a location at the top of the storage system. A temperature difference between inlet and outlet s-CO₂ (around 10 °C difference) resulted in a slight temperature difference in the axial direction, as displayed in Figs. 5(b) and (d). The local temperature at the bottom increased or decreased slightly faster than that at the top during charging or discharging processes, respectively, due to the HTF flow direction from the bottom of the storage system to the top.

Fig. 5. Temperature profiles in the graphite foam-NaCl LHTES system during the charging/discharging processes.

3.3. Exergy efficiency analyses

The round-trip exergy efficiency of the LHTES system was calculated from Eq. (5) for two cases, as illustrated in Table 3. Case 1 is the pure NaCl system without graphite foam. The low thermal conductivity of NaCl causes the poor heat transfer performance in the storage system. Only a very small portion of PCM is melted after the charging process, which results in the low latent heat storage in the system. Therefore, the exergy efficiency of the NaCl LHTES system is quite low, just 48.4%. Case 2 is the graphite foam-NaCl LHTES system. The high thermal conductivities of graphite foam significantly improve the heat transfer performance in the LHTES system. Thus, the exergy efficiency of the graphite foam-NaCl LHTES system is increased to 96.3%. Furthermore, the average HTF outlet temperature from the LHTES system during the discharging process is above 720 °C, which meets the temperature requirements (650-700 °C) of the s-CO₂ power cycle. Therefore, the graphite foam-PCM LHTES system is capable of large-scale energy storage in the CSP plant.

Table 3
Exergy efficiency for LHTES with and without graphite foam

Round-trip exergy efficiency, ψ_{round}	
<i>Case 1</i>	
Storage medium: NaCl (No graphite foam)	
8-h charging, inlet temp. 880 °C	
average outlet temp. 878.3 °C	
$V_{HTF_char} = 18$ m/s	48.4%
12-h discharging, inlet temp. 720 °C	
average outlet temp. 720.8 °C	
$V_{HTF_dis} = 12$ m/s	
<i>Case 2</i>	
Storage medium: Graphite foam-NaCl	
8-h charging, inlet temp. 880 °C	
average outlet temp. 870.1 °C	
$V_{HTF_char} = 18$ m/s	96.3%
12-h discharging, inlet temp. 715 °C	
average outlet temp. 725.1 °C	
$V_{HTF_dis} = 12$ m/s	

Table 4 illustrates the exergy efficiency and the thermal performance of the graphite foam-NaCl LHTES systems under different conditions. The first condition is the base line for the graphite foam-NaCl storage system with the HTF inlet temperature during charging process 880 °C and flow velocities in the HTF pipes around 18m/s and 12 m/s for charging and discharging process, respectively.

The second and third conditions consider the different s-CO₂ flow velocities in the HTF pipes under the same HTF inlet temperature. The effect of the flow velocity on the system exergy efficiency is basically very small. The lower flow velocity can slightly improve the exergy efficiency of the graphite foam-NaCl LHTES system because lower flow velocity reduces the entropy generation in the system. Furthermore, the higher s-CO₂ flow velocity can improve the heat transfer performance in the storage medium to reduce the number of HTF pipes in the storage system as illustrated in Table 4. However, the improvement levels off when the HTF flow velocity increases above a certain value. Therefore, the s-CO₂ flow velocity is not necessary

to be higher than 18 m/s based on the analysis of the current system. Thus, with reduced pumping power, the operating cost for the storage system could be lowered.

The fourth and fifth conditions in the table are for different HTF inlet temperatures during charging process under the same flow velocity. The higher HTF temperature will cause decrease of the round trip efficiency because larger temperature difference between HTF and PCM will result in the higher entropy generation due to the heat transfer between the HTF and storage medium (Jegadheeswaran et al., 2010). Therefore, the HTF temperature cannot be too far from the PCM melt temperature in order to keep high exergy efficiency of the system. However, the HTF temperature cannot be too close to the PCM temperature, either, because too small temperature difference would not have enough energy to melt or solidify the PCM in the system, which would increase the total number of HTF pipes in the system for heat exchange (Conditions 4 and 5). Therefore, the optimum HTF temperature should be chosen to have high exergy efficiency and keep the number of HTF pipes in a reasonable range in the storage system.

According to the analyses, the optimum HTF inlet temperature during the charging process is around 880 °C, leading to the melting point of PCM in the middle of the HTF temperature and the initial temperature of the storage medium, because lower HTF inlet temperature causes the dramatic increase of the number of HTF pipes in the system while the higher HTF inlet temperature results in a decrease of the exergy efficiency as illustrated in Table 4.

Because of the good heat transfer performance of the graphite foam-PCM storage systems, the round trip exergy efficiencies of the systems are basically very high. Therefore, the effects of both the HTF inlet temperature and the flow velocity are not significant for the current graphite foam-PCM LHTES system.

Table 4
Round trip exergy efficiency of graphite foam-NaCl LHTES systems

Conditions	T_{inlet_char} (°C)	T_{outlet_char} (°C)	V_{HTF_char} (m/s)	T_{inlet_dis} (°C)	T_{outlet_dis} (°C)	V_{HTF_dis} (m/s)	ψ_{round} (%)	Total # of HTF pipes
1	880	870.1	18	715	725.1	12	96.3	5,607
2	880	866.3	12	715	729.2	8	97.5	5,996
3	880	872.5	24	715	722.7	16	96.1	5,532
4	900	889.2	18	715	726.0	12	95.2	5,162
5	850	843.4	18	715	721.8	12	98.6	8,271

4. Conclusions

The LHTES system in the CSP plant was modeled and simulated to demonstrate the feasibility of the graphite foam-NaCl LHTES system for the s-CO₂ power cycle. The full-scale LHTES system was analyzed to show the thermal performance improvement of the storage system when using graphite foam. The graphite foam can enhance the overall thermal conductivity of the storage medium and, therefore, significantly improve the heat transfer performance of the storage system. With the graphite foam, the total number of the HTF pipes in the TES system can be reduced by a factor of 12 compared to that in the non-graphite foam system, resulting in lower capital and operating costs. The graphite foam can also increase the exergy efficiency of the storage system. The round-trip exergy efficiency of the graphite foam-NaCl system is around 96.3%, much higher than that of the non-graphite foam LHTES system. Furthermore, the system

parameters (i.e., HTF inlet temperature, flow velocity) were analyzed to investigate their effects on the system thermal performance and exergy efficiency. Larger HTF inlet temperature during the charging process causes the decrease of the exergy efficiency. The optimum HTF inlet temperature during charging process is expected to be around 880 °C for the current LHTES system (make the melting point of PCM be in the middle of the HTF temperature and the initial temperature of storage medium) in order to have high round trip exergy efficiency and meantime to have a reasonable number of HTF pipes in the storage system. The lower s-CO₂ flow velocity in the HTF pipes slightly improves the exergy efficiency of the LHTES system. Therefore, the flow velocity is not necessary to be high in the system. Finally, the average HTF outlet temperature above 720 °C during the discharging process meets the s-CO₂ power cycle requirements in the CSP plant. Therefore, the proposed graphite foam-NaCl system can be a potential LHTES system for the s-CO₂ power cycles in large-scale CSP plants.

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