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System-level performance optimization of molten-salt packed-bed thermal energy storage for concentrating solar power

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HIGHLIGHTS

- Investigates the variation in packed-bed storage performance with cut-off temperatures.
- Evaluates the impact of deep charge on the operation of a 100 MW_e concentrating solar power plant.
- Identifies the cost-optimized charging cut-off temperatures for different packed-bed configurations.
- Demonstrates the cost-effectiveness of deep charge operations of the packed-bed storage system.

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ABSTRACT

Molten-salt packed-bed thermal energy storage using thermocline technology is more cost-competitive than the conventional two-tank thermal energy storage, due to its integrated design and the employment of a low-cost packed-bed. However, such a storage configuration suffers the main drawback of a low capacity factor when applied to concentrating solar power because of the adoption of conservative cut-off temperatures. The present work evaluates the feasibility of taking less conservative cut-off temperatures to improve the utilization of the packed-bed thermal energy storage from the perspectives of a system-level operation and storage economy. The investigations are carried out on two levels. The first-level investigation reveals the effects of both the charging and discharging cut-off temperature on the thermal performance of the packed-bed thermal energy storage under ideal operating conditions. Three typical packed-bed configurations are involved. The results show that the capacity factor of the packed-bed thermal energy storage increases as the charging cut-off temperature increases and the discharging cut-off temperature decreases, especially for the configurations using latent-heat when the adopted cut-off temperatures jump over the phase change points of the encapsulated phase change materials. The second-level investigation discusses the impacts of different levels of deep charges (using high charging cut-off temperatures) on the scale design of the packed-bed thermal energy storage, the daily operation of the low temperature molten-salt pump (LT-pump) and the central receiver of a 100 MW_e conventional concentrating solar power tower plant. The results indicate that a deeper charge operation is always accompanied with a smaller required packed-bed size as well as a higher required delivery capacity and higher pressure head of the LT-pump and that it always results in a larger daily pumping consumption, a higher peak inlet temperature ramping rate and a higher receiver pressure drop. The maximum allowable charging cut-off temperature is identified to be 500 °C for each packed-bed configuration, according to the operating limitations on the pump and receiver. Moreover, a cost analysis is carried out to obtain the optimum charging cut-off temperature for each packed-bed configuration. The obtained results show that performing deep charges with the cost-optimized charging cut-off temperatures can effectively improve the cost competitiveness of the molten-salt packed-bed TES integrated into concentrating solar power plants.

1. Introduction

Current commercialized concentrating solar power (CSP) tower plants integrated with a two-tank thermal energy storage (TES) using molten-salt can provide dispatchable electricity output, regardless of the intermittency of sunlight [1]. However, the two-tank TES carries a

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Nomenclature

a	specific surface area, m^{-1}
C	specific heat, $J\,kg^{-1}\,K^{-1}$
C_F	resistance coefficient
D	diameter, m
f_D	Darcy's coefficient
G_m	mass flow rate, $kg\,s^{-1}$
G_v	volume flow rate, $m^3\,s^{-1}$
H	height, m
h_c	specific enthalpy of fillers, $kJ\,kg^{-1}$
h_{latent}	specific latent heat of PCM, $kJ\,kg^{-1}$
k	thermal conductivity, $W\,m^{-1}\,K^{-1}$
K_p	permeability, m^2
L	length, m
M	mass, kg
Nu	Nusselt number
p	pressure, MPa
Pr	Prandtl number
P_e	electric power, MW_e
P_{th}	thermal power, MW_t
Q	heat, MWh_t
r	radial direction
R	radius, m
Re	Reynolds number
S	cross sectional area, m^2
t	operating duration, h
T	temperature, K
TR	thermal resistance, $K\,W^{-1}$
u	velocity, $m\,s^{-1}$
z	axial direction

Subscripts

ava	available
bot	bottom
c	capsule
conv	convection
dis	distributor
e	external
esti	estimated
eff	effective
f	heat transfer fluid
HT	high temperature
HTP	high-temperature pump
i	internal
in	inlet
l	liquid state
LT	low temperature
LTP	low-temperature pump
m	mean
ori	orifice
out	outlet
pb	packed-bed
PB	power block
rec	receiver
s	solid state
SG	steam generator
tot	total
w	capsule shell

Greek symbols

α	convective heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
β	relax factor
ΔP	pressure drop
ε	porosity of the packed bed
ρ	density, $kg\,m^{-3}$
η	efficiency, %

Abbreviations

CSP	concentrating solar power
ESD	energy storage density
HH	hybrid-heat
HT	high temperature
HTF	heat transfer fluid
LH	latent-heat
LT	low temperature
OC	operating cost
PCM	phase change material
PCT	phase change temperature
SH	sensible-heat
TES	thermal energy storage
TUC	total unit cost

high capital cost and lacks the potential for cost reduction because of its large consumption of costly molten-salt and tank structural materials [2]. The packed-bed TES has been regarded as a promising alternative TES method because it can reduce the capital cost by over 30% with respect to an equivalent-scale two-tank TES [3]. The cost reduction relies on two main factors. The first factor is that the packed-bed TES takes advantage of the thermocline technology to isolate hot and cold storage mediums within a single tank [4]. The second factor is that the packed-bed TES can employ a low-cost sensible-heat packed-bed [5] or encapsulated phase change materials (PCMs) [6] as a solid storage medium to substitute for a mass of costly liquid storage medium (the molten-salt).

A packed-bed TES is charged by injecting hot heat transfer fluid (HTF) at the top of the tank while extracting cold HTF at its bottom. Oppositely, the system is discharged by injecting cold HTF at the bottom of the tank while extracting hot HTF at its top. A thermocline is then formed by natural thermal diffusion at the interface of the hot and cold HTF and periodically travels up and down along the axial direction of the tank during charging-discharging cycles. A large number of experimental works have been carried out to verify the operational feasibility and characteristics of the packed-bed TES. Pacheco et al. [7] tested the discharging process of a 2.3–MWh_t pilot-scale packed-bed TES system using quartzite rocks and sands as the packed-bed storage mediums and obtained a stable thermocline distribution during the operation. Bruch et al. [8] built an oil/rock thermocline packed-bed TES system and performed multiple charge/discharge cycles of the system. The results confirm that the thermocline is controllable and predictable. The authors also investigated the influence of occasional perturbations during multiple charge/discharge cycles of the system in their subsequent work [9]. Bellan et al. [10] presented a lab-scale experimental setup of a high temperature latent thermal energy storage system using sodium nitrate as a encapsulated PCMs and air as an HTF, and studied the heat transfer characteristics of the device. Zanganeh et al. [11] designed and tested a lab-scale packed-bed TES system with encapsulated $AlSi_{12}$ located on the top of a sensible heat packed-bed consisting of sedimentary rocks. The outflow temperature of HTF was successfully stabilized at 575 °C for over an hour. Oró et al. [12] established a latent heat packed-bed TES system used for district cooling and characterized the HTF stratification during charges and discharges. The experimental results show that the encapsulated PCMs contributes