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Upgrading sensible-heat storage with a thermochemical storage section operated at variable pressure: An effective way toward active control of the heat-transfer fluid outflow temperature

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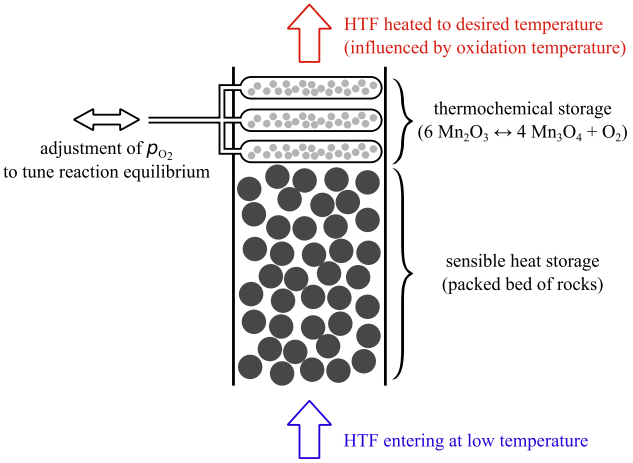
HIGHLIGHTS

- A novel combined sensible-heat/thermochemical storage concept is proposed.
- The outflow temperature of the heat-transfer fluid can be actively controlled.
- The energy/exergy efficiencies are compared to sensible-heat storage.

GRAPHICAL ABSTRACT



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ABSTRACT

This article introduces a novel thermal-energy storage concept that allows the outflow temperature of the heat-transfer fluid to be controlled during discharging. The concept is based on placing a thermochemical-storage section on top of a sensible thermal-energy storage section. The thermochemical-storage section comprises tubes that house gaseous and solid reactants undergoing reversible endo/exothermic cycling. Because the reactants are physically separated from the heat-transfer fluid, the reaction pressure can be independently adjusted using a compressor. As a result, the equilibrium reaction temperature can be tuned to reach the rate and temperature of the exothermic reaction that allow the heat-transfer fluid passing the tubes to be heated to a desired temperature during discharging. Transient simulations of such a combined sensible/thermochemical thermal-energy storage confirm that during discharging the heat-transfer fluid can be heated to a constant outflow temperature that is equal to or higher than the inflow temperature during charging. The calculated cycle efficiency of the combined storage accounts for the parasitic losses introduced by the reaction pressure swing and is compared to the cycle efficiency of a sensible storage operating under equal inflow conditions.

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Nomenclature

Latin symbols

a_v	surface-to-volume ratio [1/m]
c_p	specific heat capacity [J/kg K]
d	diameter [m]
k_h	interphase heat-transfer coefficient [W/m^2 K]
$\dot{m}$	mass-flow rate of HTF [kg/s]
p_{O_2}	oxygen pressure in tube [Pa]
$p_{O_2,\mathrm{storage}}$	pressure in oxygen storage [Pa]
Q	energy [J]
R	reaction rate [mol/m^{3}s]
S	pitch between tube layers [m]
T	temperature [K]
t	time [s]
V	volume [m^3]

Greek symbols

ΔH_{rxn}	reaction enthalpy [J/mol]
Δz	grid spacing in fluid phase [m]
ε	void fraction [–]
η_{TES}	cycle energy efficiency of TES [–]
Φ	exergy [J]
ρ	density [kg/m^3]
τ	charging/discharging duration [s]
Ψ_{TES}	cycle exergy efficiency of TES [–]

Subscripts

A	axial
c	charging
captured	energy/exergy captured by TES during charging
cell	control volume in TCS section (occupied by HTF and tubes)
compr,O_2	energy/exergy needed to generate electricity for oxygen compression in TCS section
d	discharging
eff	effective property
eq	thermodynamic equilibrium
f	fluid phase
HTF	heat-transfer fluid
i	inner diameter
j	tube layer index
ideal	maximum energy/exergy transferred from HTF to adiabatic TES during charging
in	storage inlet
internal	internal exergy consumption
l	efficiency loss
MnOx	mixture of Mn_2O_3 and Mn_3O_4
m	melting
net	energy/exergy taken from TES that is used to generate net electricity output
o	outer diameter
out	storage outlet
PCM	phase-change material
p	particle
particles	particulate phase in tubes
pump, HTF	energy/exergy needed to generate electricity for HTF pump
recovered	energy/exergy transferred from TES to HTF during discharging
STES	sensible thermal-energy storage section in the combined storage
s	solidification
T	transversal
TCS	thermochemical storage section in the combined storage
t	tube
uncaptured	uncaptured energy/exergy not captured by TES during charging
void	void space in tubes, occupied by oxygen
wall	tube wall

Superscripts

target	target temperature at storage outlet during discharging

Abbreviations

CS	combined sensible/thermochemical thermal-energy storage
CSP	concentrated solar power
HTF	heat-transfer fluid
PCM	phase-change material
STES	sensible thermal-energy storage
TCS	thermochemical storage
TES	thermal-energy storage

1. Introduction

The integration of thermal energy storage (TES) into concentrated solar power (CSP) plants is a cost-effective option to decouple the electricity generation from the intermittent solar insolation [1,2]. TES systems used in current CSP plants are usually two-tank systems using molten salts or synthetic oils as the sensible thermal-energy storage (STES) medium and heat-transfer fluid (HTF) [2,3]. Compared to these systems, packed beds of rocks that are operated with air as the HTF offer the advantages of lower storage material costs and a wider operating temperature range [4–7]. During periods of high insolation, a fraction of the HTF that has been heated in the solar field transfers thermal energy to the power block to generate electricity, whereas the remainder of the HTF is used to charge the TES by entering the vertically oriented packed bed of rocks from the top. As the HTF passes through the packed bed, its temperature gradually decreases due to the heat transfer to the rocks. As a result, axial temperature gradients are established in both the solid phase and the HTF, and the HTF leaves the packed bed at temperatures that are close to the initial temperature of the rocks. To generate electricity in the absence of solar irradiation, cold HTF enters the packed bed from the bottom and is heated by the rocks, thereby discharging the TES. The hot HTF leaving the packed bed at the top is then directed to the power block.

Packed beds are usually designed and operated to maintain the rocks at the top and the bottom of the bed at high and moderate temperatures, respectively, throughout the charging/discharging cycle. However, the axial temperature gradients cannot be perfectly steep and flatten over time [8,9]. As a result, the HTF outflow temperature during discharging $T_{f,d,out}$ decreases to a value below the HTF inflow temperature during charging $T_{f,c,in}$. This decrease in $T_{f,d,out}$ and the associated transients in the thermal output of the storage can lead to decreased efficiencies of the power block. Therefore, this temperature drop is considered to be a drawback of packed-bed STES compared to conventional two-tank STES, which can maintain almost constant HTF outflow temperatures if the tanks are well insulated.

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