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Research Paper

Numerical and Experimental study on the performance of a new two-layered high-temperature packed-bed thermal energy storage system with changed-diameter macro-encapsulation capsule

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HIGHLIGHTS

- A new two-layered PBTES system with changed-diameter capsules is established to improve the thermal performance.
- A numerical modeling of PBTES is constructed to investigate the influence of PCM capsule diameter on the thermal performance.
- Experimental study on the temperature evolution of PCM capsule and HTF of two-layered PBTES are carried out.
- Influences of different mass flow rates and inlet temperature on the charging process are analyzed.

ARTICLE INFO

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Diameter-changed two-layered PBTES system
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Numerical analysis
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ABSTRACT

In this paper, a new two-layered high-temperature packed-bed thermal energy storage system (PBTES) with changed-diameter macro-encapsulation capsule has been established to improve the thermal performance of PBTES. The effects of different diameters on thermal energy storage (TES) charging rate and TES density are numerically analyzed primarily. Second, the optimized hierarchical structure of PBTES is further constructed based on the proposed optimal comprehensive index called TES rate density. The optimal diameter pair of capsules exists when one of the diameters is fixed to obtain the optimized TES charging rate and TES rate density. Moreover, the thermal performance of diameter-changed two-layered PBTES is obtained compared to that of single-layered PBTES system. Finally, thermal performance of two-layered PBTES is experimentally examined. The influence of different inlet temperature and mass flow on the thermal performance of the system are investigated. The results are concluded as follows. (1) The phase change material of the lower-layer is melted faster by adopting the two-layered PBTES system. The improvement of heat transfer performance and enhancement of uneven heat transfer temperature can further increase the thermal performance of the system. (2) When the air inlet temperature increases from 425 °C to 465 °C, the TES charging rate can be increased by 60.5% and the heat storage efficiency rises from 84.8% to 91.1%. The TES charging rate is raised by 23.5% when the mass flow rate increases from 180 $kg\cdot h^{-1}$ to 260 $kg\cdot h^{-1}$ and the heat storage efficiency is decreased slightly. (3) With the same inlet temperature and mass flow, the TES charging rate of diameter-changed two-layered PBTES is better than that of single-layered PBTES. The maximum TES charging rate of the former system can be increased by 12.4% compared to that of the latter system, and TES rate density of two-layered PBTES can be improved by 13% as well. In summary, the new diameter-changed two-layered PBTES is an optimized system of heat storage. The study provides a design of such the PBTES for a first step implementation of the technology and the improvement of thermal performance optimization.

1. Introduction

In recent decades, the shortage of energy and environmental pollution are more severe with the over-exploitation and inefficient utilization of conventional fossil fuels. Thus, renewable energy is rapidly developed [1,2]. As the clean and pollution-free renewable energy

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Nomenclature

C_p	specific heat/(J·kg^{-1}·K^{-1})
d	capsule diameter/mm
D	diameter/mm
E	energy stored in capsule/kJ
H	height/mm
h_p	heat transfer coefficient/(W·m^{-2}·K^{-1})
$\dot{m}$	mass flow rate/(kg·h^{-1})
P	heat storage rate/W
P_r	Prandlt number
Q	heat storage capacity/kJ
R	thermal resistance/(m^2·K·W^{-1})
r	radial direction/mm
Re	Reynolds number
T	temperature/°C
V	volume/m^3
ΔH	enthalpy/(kJ·kg^{-1})

Greek symbols

δ	thickness/mm
Δ	difference value
ε	porosity of packed bed region
η	heat storage effiency
λ	thermal conductivity/(W·m^{-1}·K^{-1})
ρ	density/(kg·m^{-3})
τ	time/min

Subscripts

ave	average value
bed	packed bed
bot	bottom capsule
charge	charging process
discharge	discharging process
f	heat transfer fluid
l	liquid phase
m	melting
in	inlet
ini	initial
out	outlet
p	phase change material
s	solid phase
shell	stainless steel shell
tank	thermal energy storage tank
top	inlet capsule
total	total quantity

Abbreviations

EPCM	encapsulated phase change material
HTF	heat transfer fluid
PBTES	packed bed thermal energy storage
PCM	phase change material

source, solar energy is the most prevalent which attracts extensive attention [3–5]. Normally, thermal storage system plays a vital role in solar thermal power plants because of the intermittency and instability of solar energy. Thermal storage technology is significant to solve the above-mentioned problems, improve generation efficiency and reduce generation costs [6–9].

The thermal storage technology contains sensible heat storage, latent heat storage and chemical energy storage. The latent heat storage is also called phase change heat storage, which is widely adopted in the thermal storage system due to its high thermal energy storage density, stable process temperature and low costs [10–13]. The research of thermal storage system mainly contains the following four items including the enhancement of thermal performance of phase change material (PCM), the technology of macro-encapsulation, the technology of cascade heat storage and thermal performance index of a thermal storage system.

In the respect of enhancing the thermal performance of PCM, various methods have been proposed such as the addition of carbon materials (carbon fiber, graphite powder, carbon nanotubes), nano metal materials, etc. Many scholars put forward ways to enhance the heat storage performance through adding carbon materials (carbon fiber, graphite powder, carbon nanotubes), adopting nano metal materials, using metal fins and cascade heat storage, etc. Tao et al. [14] from our research group investigated the effects of adding four different kinds of carbon nanomaterials on the PCM including single-walled carbon nanotubes (SWCNT), multi-walled carbon nanotubes (NWCNT), graphite and C60. The results provided that the graphite is the optimal choice to increase the specific heat capacity of composite PCMs by 18.57%. SWCNT is proper to improve the thermal conductivity of composite PCMs by 56.98%. Parameshwara et al. [15] added silver particles with the mass fraction of 0.1–5.0% into organic PCMs. They further analyzed the influence of silver particles on the latent heat, thermal conductivity and thermal energy storage (TES) charging rate of composite PCMs. The result presented that the latent heat of composite PCM is decreased by 7.88–8.91%, but the thermal conductivity is increased by 10–67% to the range of 0.284–0.765 W·m^{-1}·K^{-1}. Tao et al. [16] from our team further investigated the effects of tube structure on the heat transfer enhancement of fluid side in the PCM storage system. The intensified tubes include d-tube, tapered finned tube and spiral finned tube. All the three tubes can effectively shorten the melting time of the PCM and improve the TES charging rate. The best thermal performance has caused by spiral finned tube. The melting time of phase change material is reduced by more than 30%.

In the respect of the technology of macroencapsulation, Li et al. [13] designed and constructed a new high-temperature packed-bed thermal energy storage (PBTES) with a new type of PCM capsule with high-temperature molten salt. The ternary carbonate Li_2CO_3-K_2CO_3-Na_2CO_3 (32–35–33 wt%) is adopted as the PCM of the macro-encapsulation. We further analyzed the thermal performance including temperature evolution of heat transfer fluid and that of capsules, average charging/discharging rates and overall heat storage efficiency. The results presented that the macro-encapsulation can effectively prevent the leakage of molten salt and the new system has been proved as an efficient method of heat storage. The charging/discharging thermal performance of this PBTES is better than that of shell and tube thermal storage system and finned-tube thermal storage system after comparison. The charging/discharging rate of PBTES is 1.8–3.2 times that of shell and tube thermal storage system. Nomura et al. [17] constructed a high-temperature capsule with a melting point of 577 °C. The aluminum–silicon alloy is adopted as the PCM of the capsule and the aluminum oxide is applied as the macro-encapsulation material. The experimental results indicated that the PCM of microcapsule has a high melting point, good thermal conductivity, high specific heat capacity and merit cycle stability.

Speaking to the technology of cascade heat storage, Li and He et al. [18] conducted an investigation on the thermal performance of two-stage thermal storage system with different melting points by applying exergy analysis. It presented that the exergy of the two-stage thermal storage system is 19.0%-53.8% higher than that of the single-stage thermal storage system. Wu and He et al. [11] established a one-

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