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Experimental and numerical study on the performance of a new high-temperature packed-bed thermal energy storage system with macroencapsulation of molten salt phase change material

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HIGHLIGHTS

- A new type of PCM capsule with molten salt as phase change material is encapsulated.
- A new high temperature packed bed thermal energy storage system is constructed.
- Experimental study on the temperature evolution of PCM capsule and HTF are carried out.
- Influences of different mass flow rates and inlet temperature on charging and discharging process are analyzed.
- A numerical modeling of PBTES to elucidate its performance is presented.

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ABSTRACT

In this paper, a new high-temperature packed-bed thermal energy storage system (PBTES) with macro-encapsulation of molten salt phase change material has been established. A new phase change material (PCM) capsule is designed and constructed with the macro-encapsulated molten salt as its PCM. The ternary carbonate Li_2CO_3-K_2CO_3-Na_2CO_3 (32–35–33 wt%) has been selected as the optimal option of PCMs. The melting point is 395.1 °C and the energy storage density is 174.7 kJ·kg^{-1}. Moreover, the thermal performances such as the temperature evolution of heat transfer fluid and that of PCM capsule, average charging/discharging rate and overall heat storage efficiency are investigated in detail. Finally, a mathematical model is presented complementarily to simulate the thermal performance of PBTES. The results are concluded as follows. (1) The temperature variation of the heat transfer fluid and that of the capsule in the PBTES are obtained. There is a certain temperature difference between the capsule and the heat transfer fluid. Moreover, the convection heat transfer resistances of the capsule and the heat transfer fluid are the main influential factors in the heat exchange process. It can be improved by the inlet temperature and mass flow rate of the fluid. (2) The improvement of inlet temperature and mass flow rate in PBTES can increase its charging and discharging efficiencies. The overall efficiency of the system can be increased to 86.1% from 77.4% through increasing inlet temperature from 425 °C to 465 °C. The efficiency will up to 83.6% from the level of 80.6% by the rise of mass flow rate. (3) To compare the shell and tube thermal storage system, the charging and discharging rates of PBTES are 1.8–3.2 times that of the former one. The overall efficiency of PBTES is 1.9–2.4 times that of shell and tube thermal storage system. (4) According to the numerical simulation results, the good agreements of temperature evolution are achieved between the numerical results and experimental data, and the shorter diameter is optimal to the PBTES because a larger diameter will increase the charging time. In summary, the PBTES is an efficient method of heat storage. The study proposes a design of such the PBTES for a first step implementation of the technology and the improvement of thermal performance optimization.

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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 efficiency
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
down	tank downwards
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
up	tank upwards

Abbreviations

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

1. Introduction

The utilization of renewable energy is widely considered as an efficient solution to the global environmental pollution caused by the overuse of fossil fuel [1,2]. As a clean and environmental-friendly renewable energy, solar energy has advantages of huge reserves and a wide range of sources. Therefore, the related research on solar thermal utilization has been rapidly developed [3–5]. Concentrating solar power (CSP) and photovoltaic (PV) are two main types of solar energy utilization. The CSP technology is more adjusted to being integrated into electrical networks [6]. Because of the unstable and intermittent nature, the integration of thermal energy storage (TES) system in the CSP systems plays an important role to improve the stability of the power generation system and the energy utilization efficiency [7,8].

TES can be divided into the two tank heat storage system and the single-tank heat storage system. The two tank heat storage system is most widely adopted in the commercial market but its disadvantages include high consumption of molten salt, large plot area and more investment costs. Compared with the two tank system, solid particles are adopted in the single-tank heat storage system as the thermal storage medium that leads the single-tank heat storage system has lower investment costs and good application prospects [9,10]. The thermal storage mediums normally are sensible thermal storage materials including quartz sand, rock, ceramic etc. Comparing with sensible thermal storage materials, phase change heat thermal materials have higher energy storage density, which can effectively reduce the volume of thermal storage devices and reduce the cost of construction. Moreover, the characteristic of phase change process is approximately isothermal that can maintain the stability of output power. Therefore, the packed-bed thermal storage system (PBTES) composing phase change materials, one of the single energy storage tanks, has attracted wide attention in recent years [11,12].

Molten salt, as an important PCMs, has a large latent heat of transformation and low price. It is widely used in solar thermal power plants [13,14]. However, the thermal conductivity of most molten salt is low that affects the charging/discharging rate of thermal energy storage with PCMs. Therefore, it is necessary to enhance the thermal performance of its charging and discharging behavior. For instance, the addition of particles with high thermal conductivity [15], the implement of finned tubes [16,17], heat pipe [18], capsule encapsulation [19] and cascaded latent heat energy storage materials [20,21] etc. Among these methods, encapsulating the phase change thermal storage material in the capsule can enlarge the heat transfer area and increase the heat transfer rate. It is an effective method to enhance heat transfer and can solve the leakage problem of phase change thermal storage material [22].

The PBTESs composing phase change materials have been studied in a decade, and it can be separated into the numerical analysis and experimental study that is presented as follows. In the respect of numerical analysis, Wu and He [23] established a two-dimensional mathematical model of PBTES. Numerical simulations were carried out to study the influence of different design parameters including the melting point of the PCM, the diameter of the capsule, and the inlet velocity of the heat transfer fluid. They presented that it effectively improves the discharging efficiency of the system through increasing the melting point of PCM, decreasing the flow rate of heat transfer and shortening the diameter of PCM capsule. Another model of cascade phase change packed bed thermal storage was further framed by Wu and He [24], and they found that the heat storage rate and charging efficiency of cascade thermal storage system is greater than that of non-cascaded thermal energy storage. Xia et al. [25] proposed an effective model of packed bed storage system. They obtained the temperature distribution in the PCM capsule and the air flow in the void part of the packed bed. Based on the model, the influence of heat accumulation method to heat transfer has been further analyzed. Karthikeyan et al. [26] compared three different numerical models of phase change packed bed thermal storage. They concluded that mathematical models should be matched with exchange fluids because of requirements of different calculation precisions. Xu and He [20] adopted the exergy analysis to investigate the influence of inlet temperature and the number of heat transfer units