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Thermal performance analysis and optimization of a cascaded packed bed cool thermal energy storage unit using multiple phase change materials

Xiwen Cheng, Xiaoqiang Zhai*

Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, Shanghai 200240, China

HIGHLIGHTS

- A cascaded packed bed cool thermal energy storage unit is proposed.
- Thermal performance is analyzed and structural parameters are optimized.
- The charging rate is improved due to the cascaded design.

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ABSTRACT

This paper proposes a cascaded packed bed cool thermal energy storage (CTES) unit using multiple phase change materials (PCM). In terms of the solidification processes, the basic heat transfer characteristics were analyzed based on an experimentally validated simulation model. Thermal performances, including cold charging rate, the quantity of cold and exergy charged, as well as the exergy efficiency of the cascaded CTES unit were compared with those of a single-stage CTES unit. In order to further achieve better thermal performance, the materials, stages and thickness of each stage were optimized. According to the results, the 24-stage CTES unit with a phase change temperature difference between the highest and lowest stage (denoted as T_d) of 6 °C has the best thermal performance, because it shows a 15.1% reduction in charging time compared with a single-stage unit, while its quality and quantity of cold charged remains almost equivalent to the single-stage unit. Moreover, 3–5 stages are recommended for an evenly distributed cascaded CTES as their thermal performances are quite close to the optimal 24-stage unit.

1. Introduction

To eliminate the mismatch between energy demand and supply, thermal energy storage (TES) devices are widely applied in heating and cooling applications [1,2]. There are generally two kinds of TES: sensible thermal energy storage (STES) which stores energy in the form of sensible heat, and latent thermal energy storage (LTES) which stores thermal energy mainly in the form of latent heat. In comparison with STES, LTES is more favorable due to the high thermal energy density and near-isothermal behavior during the thermal energy charging/discharging process of its thermal storage medium—PCMs [3]. Over the past decades, LTES devices have seen their utilization in numerous heating applications [4,5]. Besides, in the area of air-conditioning system, which accounts for almost half of the buildings' energy consumption in developed areas, PCM-based cool thermal energy storage (CTES) plays an important role in reducing the annual energy consumption [6], stabilizing the operation of solar cooling system [7], shifting the electricity peak load [8], and increasing thermal inertial of passive cooling buildings [9].

However, limited by the low thermal conductivity of PCMs, the heat transfer performance in PCM-based TES is poor. In terms of the CTES, where the available temperature difference is smaller than the heating application, the requirement for thermal performance enhancement is further accentuated [10]. Until now, a lot of methods have been employed for enhancing PCM's thermal conductivity, such as the dispersion of high thermal conductive nanoparticles in PCMs [11], the insertion of metal foams in PCMs [12] and the mixture of expanded graphite with PCMs [13]. Additionally, innovative design and optimization of the heat exchangers for LTES are also effective ways of overcoming the shortage of PCMs [14].

Recently, the concept of cascaded LTES with multiple PCMs has attracted extensive interest of the energy sector researchers, owing to its better heat transfer performance and energy utilization efficiency compared with single-stage LTES. The earliest studies on cascaded LTES

* Corresponding author.
E-mail address: xqzhai@sjtu.edu.cn (X. Zhai).

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Nomenclature

a_p	superficial capsule area per unit bed volume (m^{-1})
c	specific heat ($J\cdot kg^{-1}\cdot K^{-1}$)
D	diameter of packed bed (m)
Ex	exergy (J)
h	heat transfer coefficient ($W\cdot m^{-2}\cdot K^{-1}$)
H	enthalpy of phase change material ($J\cdot kg^{-1}$)
k	thermal conductivity ($W\cdot m^{-1}\cdot K^{-1}$), or time steps
L	bed height (m)
m	mass (kg)
$\dot{m}$	mass flow rate ($kg\cdot s^{-1}$)
Nu	Nusselt number
Pr	Prandtl number
$\dot{q}$	cold charging rate (W)
Q	accumulated cold stored (J)
r	radius (m)
R	radius of PCM capsule (m)
Re	Reynolds number
T	temperature (°C)
t	time (s)
u	mean velocity of heat transfer fluid ($m\cdot s^{-1}$)
$\dot{v}$	volume flow rate ($m^3\cdot s^{-1}$)
x	distance along the flow direction (m)

Greek symbols

ε	void fraction
ρ	density ($kg\cdot m^{-3}$)
η	efficiency

Subscripts

des	exergy destruction
f	heat transfer fluid
i, j	space node
in	inlet of heat transfer fluid
ini	initial state
out	outlet of heat transfer fluid
p	phase change material
sup	exergy supplied
stored	exergy stored
S-M	solid to mushy zone boundary
L-M	liquid to mushy zone boundary

Acronym

TES	thermal energy storage
STES	sensible thermal energy storage
LTES	latent thermal energy storage
PCM	phase change material
CTES	cool thermal energy storage
PCT	phase change temperature
HTF	heat transfer fluid
C-L/O	Capric-Lauric acid eutectic with Oleic acid mixture
DSC	differential scanning calorimeter
RSME	root-mean-square error
MAPE	mean absolute percentage error

traceable in the literature were presented by Farid and Kanzawa [15,16], in which they proposed the arrangement of PCMs with different melting temperatures in a cascaded way, and demonstrated numerically and experimentally the advantages of the cascaded arrangement. Since then, some studies on the cascaded LTES for different applications were presented, concerning the heat transfer performance and energy utilization efficiency. Peiró et al. [17] experimentally compared the thermal performance of a pilot scale two-stage LTES with a single LTES. The result showed that two-stage LTES has introduced a first-law energy effectiveness enhancement of 19.36%. Shabgard et al. [18] simulated a cascaded LTES with embedded heat pipes for solar power application, concluding that approximately 10% more exergy was recovered by cascaded LTES during a 24-h charging–discharging cycle in comparison with the best non-cascaded LTES. Wu et al. [19] numerically studied the thermal performance of single-stage, 3-stage and 5-stage packed bed TES with molten-salts as PCM. The results indicated that the cascaded system showed faster charging and discharging rates, and the 5-stage cascaded TES could reach a repeatable state after a charging-discharging cycle.

To date, most of the investigations on cascaded LTES mainly focus on heating applications, whose phase change temperatures (PCTs) are usually higher than 80 °C [20–22]. Given different temperature range may results in different heat transfer characteristics, and thus results in different application scenarios, it is necessary to conduct studies on cascaded CTES. However, only a few works that deals with cascaded LTES for cooling application were seen in the literature. Chiu and Martin [10] numerically studied and analyzed the performance of a fin-tube CTES unit with 3 kinds of PCMs. The result showed that the thermal performance of the cascaded unit could be improved by 10–40% compared with a corresponding single-stage unit whose PCT equals to the average PCT of the cascaded unit. Mosaffa et al. [23] conducted an energy and exergy analysis of a 2-stage LTES integrated in a free cooling system and concluded that the exergy efficiency tends to be more significantly influenced by inlet air temperature than the air flow rate during the charging process. However, the limited researches were in an initial stage for the concept validation to the thermal performance enhancement techniques through implementing multiple PCMs on CTES [10]. As Chiu and Martin [10] stated that "Future work will be carried out to study an array of different heat exchanger geometries, distribution and choice of PCMs at various phase change temperatures", the study of cascaded CTES with different types of heat exchangers and further on optimization for these heat exchangers are necessary, but such investigations are rare in the literature. Till now, only two types of cascaded CTES heat exchangers were involved. So the primary task is to conduct more studies on other types of cascaded CTES heat exchangers because different structure may also results in different heat transfer characteristics. For example, the packed bed CTES with encapsulated PCMs has been frequently used in cold storage air-conditioning system due to its simple structure, large heat transfer area and high capacity of the storage unit [24–26]. However, the analysis of a cascaded packed bed CTES with multiple PCMs remains absent from the literature until now, let alone the optimization of such cascaded CTES.

Therefore, the present research proposed a cascaded design of a packed bed CTES unit with multiple spherical PCM capsules. Using an experimentally validated simulation model, the basic heat transfer characteristics and thermal performance inside the cascaded unit were analyzed in the solidification processes, and compared with those of a single-stage packed bed CTES unit. In addition, a structural optimization analysis was also performed, including the selection of materials, stages, and thickness (or mass distribution) of PCM in each stage.

2. Physical model of the cascaded packed bed CTES

Fig. 1 schematically shows the structure of a 3-stage cascaded packed bed CTES unit. As it can be seen, three kinds of PCMs with different PCTs are equally packed in three sections of a vertically standing cylindrical tank. The height, L, and inner diameter, D, of the tank are 0.912 m and 0.19 m, respectively. The PCMs are filled