OPINION
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Perspectives on Low-Temperature Packed Bed Latent Heat Storage Systems

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INTRODUCTION

Thermal energy is stored in a packed bed thermal energy storage (PBTES) system by raising the temperature of the packing elements. This simple mechanism and economic feasibility (Gautam and Saini, 2020) make the PBTES promising for applications such as solar thermal power plants, building cooling systems, and waste heat recovery (Nallusamy et al., 2007). The traditional PBTES is based on sensible heat transfer and is therefore limited by a low energy density and temperature stability (Mawire et al., 2020). Compared with the traditional system, a packed bed latent heat storage (PBLHS) system based on phase-change materials (PCMs) (Wang H. et al., 2018; Wang J. et al., 2018) offers advantages such as a higher energy density, higher temperature stability, and few safety issues (Li et al., 2018; Kumar and Saha, 2021; Wang et al., 2021) and therefore is considered a promising solution for thermal energy storage (Yang et al., 2017; Zhang et al., 2020; Grabo et al., 2021).

This study reviews recent progress on low-temperature PBLHS systems with phase-change points below 100°C. A brief discussion of the working principle and impact factors of the PBLHS system is presented based on results from recent studies (Alptekin and Ezan, 2021). The performance and applications of PBLHS systems are also discussed.

CHARACTERISTICS OF THE PACKED BED LATENT HEAT STORAGE SYSTEM

Structure and Working Principle of the Packed Bed Latent Heat Storage System

A typical low-temperature PBLHS system (Liu and Zhao, 2021; He et al., 2022) consists of a heat storage tank, a heat transfer fluid (HTF), and heat storage media (HSM). The structure of a PBLHS system is shown in **Figure 1A**. Capsules containing low-temperature PCMs constitute the HSM, which is supported by a screen in the lower portion of the heat storage tank. The heat storage tank is surrounded by a layer of insulation material to reduce thermal energy loss. During the charging and discharging process, the HTF percolates through the HSM (Singh et al., 2010). The HSM packing is a porous medium with a high surface-to-volume ratio at the macroscopic level, which enhances heat transfer (Yang et al., 2019; Yang et al., 2020). Heat transfer between the HSM and HTF enables the charging and discharging of the PBLHS system (Guo et al., 2021). The buoyancy effect causes the high-temperature HTF to enter the top of the heat storage tank during the charging process (Zanganeh et al., 2012). The HSM near the inlet is heated first. The temperature gradient across the HSM from the inlet to the outlet results in the lower portion of the HSM also being heated by the upper portion of the HSM (Qin et al., 2012). During the discharging process, the thermal energy

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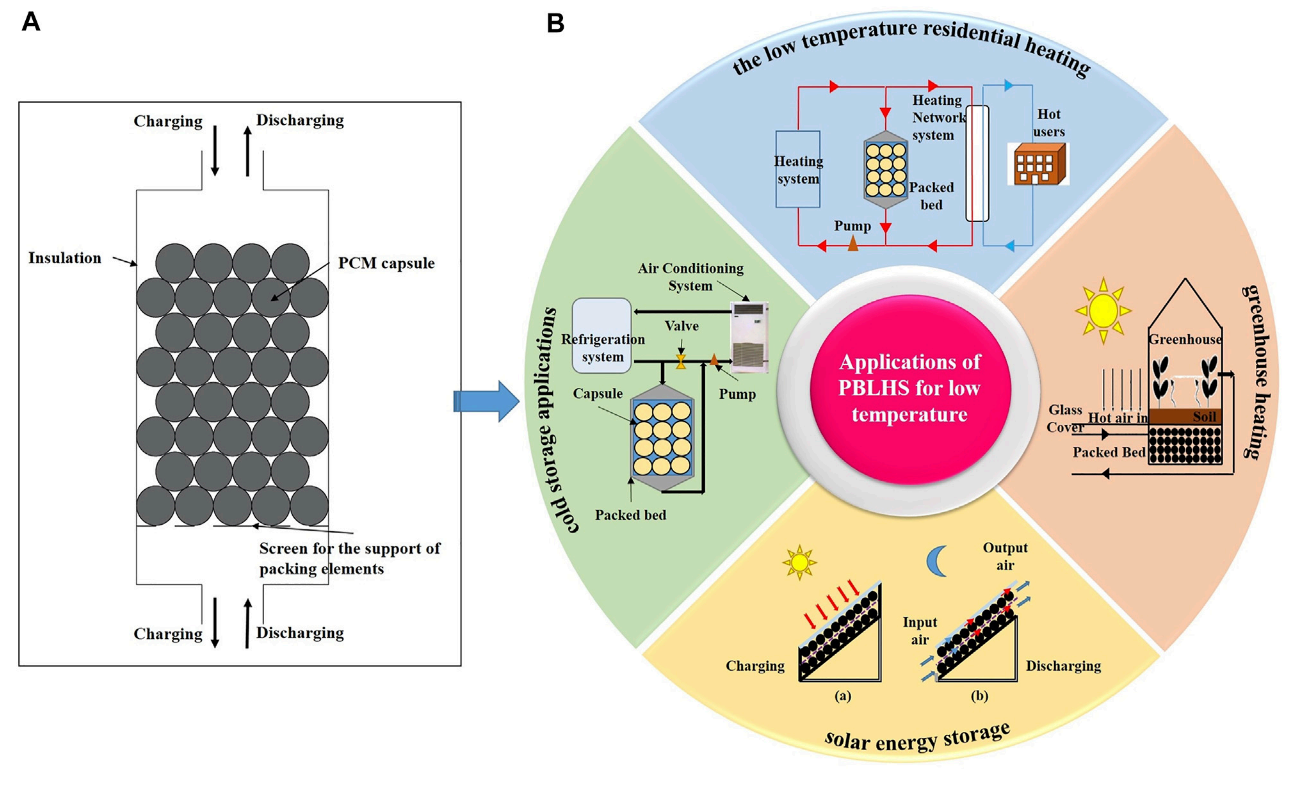

FIGURE 1 | Structure and applications of a low-temperature PBLHS system. **(A)** Structure; **(B)** Applications.

stored in the HSM is released by heat transfer between the low-temperature HTF and the high-temperature HSM.

Materials of the Packed Bed Latent Heat Storage System

HSMs in the form of spherical capsules have been found to exhibit superior thermohydraulic performance (Singh et al., 2013). In a low-temperature PBLHS system, the HSM consists of spherical capsules filled with PCMs, such as paraffin (Nallusamy et al., 2007; Wang et al., 2017), water (Fang et al., 2010), n-tetradecane (Wu et al., 2010), and composite materials (Cheng and Zhai, 2018). The macro-encapsulated PCMs can be made by filling a pre-made shell with liquid PCM (Liu et al., 2018). The micro-encapsulated PCMs can be fabricated by physical, chemical, or physicochemical methods, that is, spray drying (Alva et al., 2017), interfacial polymerization (Milián et al., 2017), and droplet microfluidics (Chen et al., 2013; Han et al., 2020). The use of large PCM capsules results in poor thermal performance and low energy loss. However, small PCM capsules induce a large pressure drop across the HTF (Li et al., 2018; Alptekin and Ezan, 2021). Therefore, the PCM capsule size should be determined based on a comprehensive evaluation of the thermal performance and pumping power of the PBLHS system (Pakrouh et al., 2017).

Both liquids and gases, that is, water (Cheng and Zhai, 2018), ethylene glycol (Fang et al., 2010), and air (Arfaoui et al., 2017), can be used as the HTF in the PBLHS system. A liquidus HTF has a large heat transfer ecoefficiency and can be used to fabricate a PBLHS system with a high charging/discharging rate (Felix Regin et al., 2009). However, the large flow resistance of a liquidus HTF produces a large pressure drop across the PBLHS system. Air is typically used as a gaseous HTF because of its low cost and high-temperature resistance. However, the low thermal conductivity of a gaseous HTF results in a low charging/discharging rate for the PBLHS system. Thus, a HTF should be selected by considering the influence factors for the system, including the HTF cost, estimated charging/discharging rate of the PBLHS system, and pumping power (de Gracia and Cabeza, 2017).

Factors Affecting the Packed Bed Latent Heat Storage System Performance

The various factors affecting the performance of the PBLHS system can be categorized into structural and material factors. As a PBLHS system can be treated as a porous medium at the macroscopic level, the effect of the packing structure determines the heat transfer between the HSM and the HTF, as well as the pressure drop in the PBLHS system (Deng et al., 2017). In order to maintain a balance between the heat transfer and pressure drop, the size and aspect ratio of the HSM should be optimized. A high void fraction, that is, a high ratio of the volume of the voids in the bed to the total bed volume, enhances the thermal conductivity of the HSM but induces a large pressure drop across the PBLHS system.

The thermal properties of the materials in the PBLHS system determine the heat transfer in the system, including convection and conduction. Specifically, heat transfer within the PBLHS system combines conduction between the wall and HSM, convection between the HSM and HTF, convection between the wall surface and HTF, and even radiation from the HSM. The effective thermal conductivity is used as a comprehensive measure of the heat transfer within the PBLHS system.

PERFORMANCE EVALUATION OF THE PACKED BED LATENT HEAT STORAGE SYSTEM

Energy efficiency is typically used to evaluate the energy storage performance of a PBLHS system and is expressed as the ratio between the energy recovered from the PBLHS system and the energy delivered to the PBLHS system (Yang and Garimella, 2010). Arfaoui et al. used a PBLHS system with air as the HTF and $CaCl_{26}H_2O$ as the PCM to increase the efficiency of a solar air collector. The maximum absorbed energy reached 730 kJ, and the daily energy efficiency was approximately 47% Arfaoui et al. (2017).

However, irreversible losses were not considered in the energy analysis. The exergy efficiency, the ratio of the total exergy recovered from the PBLHS system to the total exergy delivered to the PBLHS system, is preferred as a measure of the comprehensive system performance (Saha and Das, 2020; Mawire et al., 2021). Cheng et al. found that the exergy efficiency decreases from 83.1% to 79.4% as the capsule size increases from 9.5 mm to 47.5 mm (Cheng and Zhai, 2018).

As applications of the PBLHS system are sometimes limited by the large capital investment involved, it is important to consider the cost of a PBLHS system. The levelized cost of electricity (LCOE) is the most commonly used indicator of the economic feasibility of a PBLHS system. Tehrani et al. performed a techno-economic comparative analysis on a PBLHS system and a shell-and-tube latent storage system based on the thermal storage capacity for a 19.9 MWe solar power plant. The cost of a PBLHS system with a wall thickness of no more than 0.1 mm is ~10 US$ kWh_{th} Mostafavi Tehrani et al. (2019).

APPLICATIONS OF LOW-TEMPERATURE PACKED BED LATENT HEAT STORAGE SYSTEMS

A low-temperature PBLHS system can be integrated with residential heating (He et al., 2019b; Xu et al., 2020), greenhouse heating (Baddadi et al., 2019), and solar collectors (Desai et al., 2022). Baddadi et al. (2019)designed a greenhouse with a PBLHS system, utilizing $CaCl_2.6H_2O$ as the PCM and air as the HTF. The system was found to enhance the greenhouse microclimate. Cheng and Zhai (2018) reported a cascaded packed bed based on cool thermal energy storage, with water and a composite material (C-L/O) as the HTF and PCM, respectively. The most efficient 24-stage unit had a 15.1% lower charging time than a single-stage unit and a similar thermal performance to a 3–5 stage system. He et al. (2019a) designed a PBLHS system integrated with a water tank to enhance the electric power load regulation capacity and the heat-supply capacity. The energy storage capacity increased by 29.62% theoretically. Wu et al. (2022) also discussed the application and optimization of the PBLHS system in hot-water supply, theoretically and experimentally. The system has better thermal stratification when the PCM units are placed at a higher place and near the inlet of the high-temperature water, and the flow rate is 3 L/min. The PBLHS system can also be used for the drying process (Atalay, 2020), with an average energy efficiency of 68.55%.

CONCLUSION AND PROSPECTS

This study presents a brief introduction to the structure and the working principles of the PBLHS system. The impact factors and performance of the PBLHS system have been discussed. The packing structure of a PBLHS system significantly affects thermal performance. The PBLHS system performance is commonly evaluated using the energy efficiency and exergy efficiency, between which the exergy efficiency is more accurate and therefore preferred. In addition, applications of low-temperature PBLHS systems, especially for buildings, are introduced. However, a few studies have been carried out on the economic aspects of low-temperature PBLHS systems. Further investigations on optimizing the design and economic feasibility of low-temperature PBLHS systems are encouraged.

AUTHOR CONTRIBUTIONS

CZ and SW developed the concept of the study. DC wrote the first draft of the manuscript. CY revised the manuscript. All authors revised the manuscript and read and approved the submitted version.

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