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A Critical Review of Solid-liquid Phase Change for Thermal Energy Storage Applications#

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ABSTRACT

The use of phase change materials (PCMs) in various applications, such as brick walls, cold thermal energy storage systems, solar water heating, and photovoltaic-thermal (PVT) systems suggests significant potential for improving energy efficiency and thermal performance. This review discusses key findings from recent studies on optimizing PCM use in different scenarios. Studies emphasize the importance of comprehensive evaluations to determine the economic viability and environmental impact of brick PCM systems. Further investigations are recommended to develop composite PCMs suitable for year-round use and improve thermal performance in brick wall applications. For cold thermal energy storage systems, enhancing heat storage density, solidification rates, and operational efficiency is essential for PCM-based systems to effectively replace fossil fuels. Meanwhile, incorporating tracking systems and nano-enhanced PCMs in solar water heating systems can lead to enhanced performance and sustainability. In PVT systems, refining the preparation of nanoparticle PCMs and integrating efficient thermal transfer fluids prove to be key areas for improvement. Additionally, the utilization of enhanced PCMs (EPCMs) in PV modules has demonstrated improved temperature control and increased photoelectric conversion efficiency. Findings highlight the potential of PCM integration in various systems and emphasize the need for further research to optimize performance, enhance efficiency, and address environmental considerations. Overall, this review provides key insights for professionals working in the field of PCM-based thermal energy storage.

Keywords: thermal energy storage, solid-liquid phase change, solar thermal, thermal management

1. CONCEPT OF THERMAL ENERGY STORAGE

Efforts to reduce carbon emissions in global energy consumption is an important priority, but reliance on fossil fuel sources, the use of conventional heating/cooling in public sectors have fallen short in this regard, necessitating the presence of alternative fossil fuel burning. One way to replace fossil fuel with solar thermal systems can address CO2 emissions by more efficiently storing thermal energy. Thermal energy storage has three categories as depicted in Figure 1. Sensible heat storage (SHS) leverages the temperature difference and specific heat capacity of materials to store energy. Latent heat storage (LHS) utilizes the enthalpy of a materials during changing of physical state to more efficiently store energy at constant temperature. Thermochemical heat storage takes advantage of chemical reactions and kinetic processes to store and discharge thermal energy and is best suited for interseasonal storage. Sensible heat storage (SHS) systems have low costs and low storage densities, necessitating larger storage units to compensate for the reduced storage capacity. Inorganic PCMs in latent heat storage (LHS) systems have low thermal conductivities, though conductive inserts are a potential solution as they can cut the duration for charging and discharging in half. In chemical heat storage (CHS) systems, the employment of reversible chemical reactions to store thermal energy provides indications of high efficiencies. Meanwhile medium to large scale systems such as buildings and commercial centers can capitalize on LHS systems, further integrated into industrial processes to reduce heat loss and enhance heat storage. Further applications of LHS systems include use in batch processes in food industry through drying process.

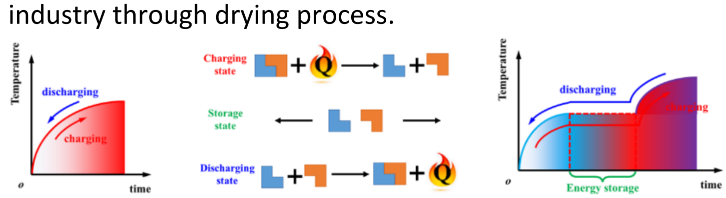

Fig. 1 Classifications of thermal energy storage [1] Reproduced with permission from Elsevier.

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2. PHASE CHANGE MATERIALS

When utilizing thermal energy storage in LHS system [2], phase change materials (PCMs) are typically involved. PCM is such a substance that charges and discharges thermal energy during the phase transition process for the aims of heating or cooling, without changing its temperature a lot during period of heat storage or release. According to the respective compositions, PCMs can further be separated into three sub-categories (see Figure 2) [3].

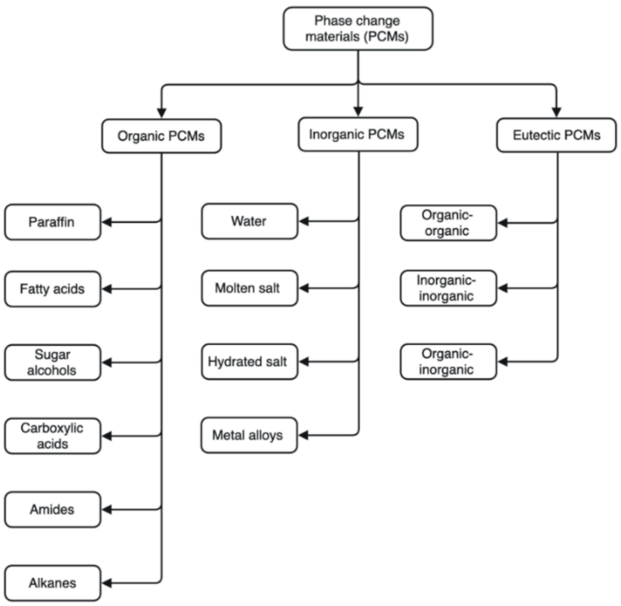

Fig. 2 Classification of phase change materials

Organic PCMs are made of hydrocarbons and include paraffin, fatty acids, sugar alcohols, carboxylic acids, amides, and alkanes. Organic PCMs benefit from low undercooling, less distinct phase change separation, limited corrosion, and an economic nature. In turn, they suffer from low thermal conductivity, low latent heat values, and poor storage efficiency. They often have a larger fusion range, high volatility in reactions, high combustible. Inorganic PCMs include inorganic materials and substances such as water, molten and hydrated salt, and metal alloys. Inorganic PCMs boast high latent heat values, high conductivity, as well as cost-efficiency. Nevertheless, inorganic PCMs are restricted by issues of corrosion with metals, supercooling, and phase separation. The latter two drawbacks can be solved by mixing salts with other crystal structures as a potential solution to this problem. By changing the ratios of the components involved, eutectic phase change materials (EPCMs) can adjust phase change temperature and other physical characteristics. The kinds of PCM that make up eutectic PCM range from inorganic to organic, inorganic to organic, and inorganic to organic. They exhibit high heat storage densities, high latent heat values, and cost-efficiency. However, the use of EPCMs in commercial applications is restricted by issues like their low conductivity, high supercooling, as well as phase separation problem. Table 1, 2, and 3 indicate the properties of select organic, inorganic, as well as eutectic compounds respectively. Both organic and eutectic compounds have a high range in temperature and energy density, at the expense of considerable cost as indicated by cost per unit heat storage capacity. Despite its reduced range of temperatures (when compared to organic compounds) and energy densities, salt hydrates present itself as a more economical alternative.

3. MATERIAL AND METHODS

The subsequent section will discuss various engineering applications of PCMs, their functionalities, importance, and real-world contexts. These include refrigeration and cold storage systems with incorporated PCMs, PCM based bricks and construction materials for buildings, photovoltaic (PV) modules with PCMs, solar water heating systems, battery thermal management systems (BTMS) with PCMs, and solar salt in the power cycle. General comments and references will be provided, alongside figures and illustrations to enhance descriptions. The summary is described in Figure 3.

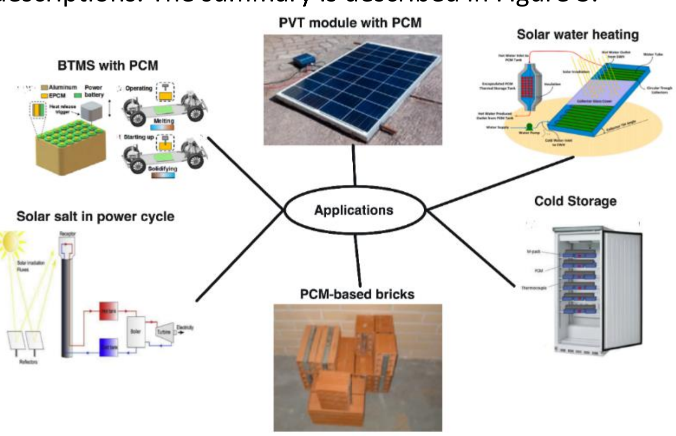

Fig. 3 Engineering applications of TES with PCMs

3.1 Refrigeration and cold storage

Figure 4(a) shows a refrigeration system to investigate the room temperature and energy consumption with and without EPCMs. Data showed that [14] use of EPCMs in the freezer cut down on temperature fluctuations by a respectable amount (40.59%). The energy consumption of the freezer was also lowered with an energy saving of 8.37%, in contrast to ordinary refrigerators.

Table 1 Thermophysical properties of representative organic PCMs

Compound	T_m	ΔH_m	$C_{p,s}$	$C_{p,l}$	ρ_s	λ_s	λ_l	Refs.
	℃	kJ/kg	kJ/kg K		kg/m3	W/m K		
Paraffin wax	0-90	150-250	3.00	2.00	880-950	0.2		[4, 5]
Formic acid	8	277	1.00	1.17	1227	0.30	0.27	[5]
Acetic acid	17	192	1.33	2.04	1214	0.26	0.19	[5, 6]
Lauric acid	44	212	2.02	2.15	1007	0.22	0.15	[5, 6]
Stearic acid	54	157	1.76	2.27	940	0.29	0.17	[7, 8]
Palmitic acid	61	222	1.69	2.20	989	0.21	0.17	[7, 9]
Acetamide	82	260	2.00	3.00	1160	0.40	0.25	[5]
Erythritol	117	340	2.25	2.61	1450	0.73	0.33	[10]
Urea	134	250	1.80	2.11	1320	0.80	0.60	[6]
Hydroquinone	172	258	1.59	1.64	1300			[5]

Table 2 Thermophysical properties of representative inorganic PCMs

Compound	T_m	ΔH_m	$C_{p,s}$	$C_{p,l}$	ρ_s	λ_s	λ_l	Refs.
	℃	kJ/kg	kJ/kg K		kg/m3	W/m K		
Water	0	333	3.30	4.18	920	1.60	0.61	[5]
Calcium chloride hexahydrate	30	125	1.42	2.20	1710	1.09	0.53	[4, 5]
Sodium sulphate decahydrate	32	180	1.93	2.80	1485	0.56	0.45	[5]
Sodium thiosulfate pentahydrate	46	210	1.46	2.39	1666	0.73	0.38	[5, 11]
Sodium acetate trihydrate	58	266	1.68	2.37	1450	0.43	0.34	[12]

Table 3 Thermophysical properties of representative eutectic PCMs

Compound	T_m	ΔH_m	$C_{p,s}$	$C_{p,l}$	ρ_s	λ_s	λ_l	Refs.
	℃	kJ/kg	kJ/kg K		kg/m3	W/m K		
CaCl2·(H2O)6 MgCl2·(H2O)6	25	127	1661	1620	2270	930	550	[5, 11]
Urea CH3COONa·(H2O)3	30	200	1750	2210	1370	630	480	[11, 13]
Mg(NO3)2·(H2O)6–MgCl2·(H2O)6	59	132	2290	2810	1610	670	530	[5, 11]
Urea–NaNO3	83	187	1600	2030	1502	750	590	[13]
LiNO3–KCl	160	272	1260	1350	2196	1310	590	[5]

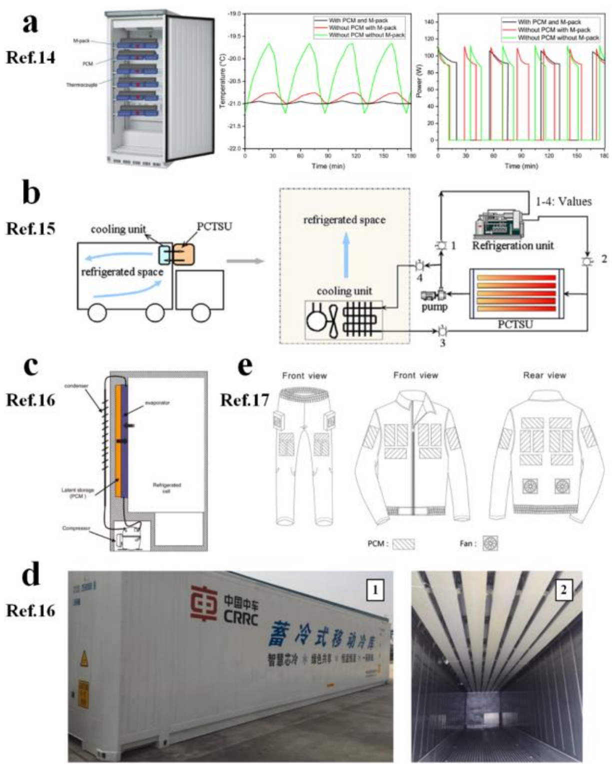

Fig. 4 (a) Schematic diagram of low temperature household cold storage filled with EPCMs and comparison of temperature fluctuation and energy consumption [14]. Reproduced with permission from Elsevier. (b) Configuration of the refrigeration system with PCMs [15]. Reproduced with permission from Elsevier. (c) a household refrigerator with PCMs [16]. Reproduced with permission from Elsevier. (d) PCMs-based shipping container [16]. Reproduced with permission from Elsevier. (e) Clothes containing PCMs and ventilation fans [17]. Reproduced with permission from Elsevier.

Figure 4(b) depicts the configuration of a refrigeration system with PCMs. Liu et al. [15] modeled a mobile transport refrigeration system that incorporated PCMs into its design. Flat containers were stacked in parallel and filled with PCMs, with the PCMs being charged by an off-vehicle refrigeration unit. It was surmised that PCM-based systems had reduced energy consumption and emissions and were more efficient compared to conventional systems. Figure 4(c) illuminates the addition of eutectic aqueous solution as PCM to the refrigerator evaporator. Azzouz et al. [16] examined the efficiency of a refrigerator with an incorporated PCM storage system. PCMs led to a higher evaporating temperature and would cool the refrigerator when it was necessary, safeguarding the system efficiency. PCM was incorporated into the design of a shipping container in China for fruit and produce delivery [16]. The PCM is charged outside of the container, and once placed inside the container to maintain a suitable internal temperature over 120 hours (see Figure 4(d)). The extensive distances traveled by the container in different modes of transport without using additional energy supplies suggests the viability of switching between the different modes. Employing PCMs in vest cooling technology ensures the regulation of skin temperatures and the efficient absorption of excess thermal energy, facilitating comfort in high-intensity physical activities. This has led to PCM usage in vest cooling the clothes incorporating fans as well as PCM. A weight of 3 kg can maintain less than 22 ℃ for cooling (see Figure 4(e)).

3.2 PCM based bricks for building construction

There are three main ways to incorporate PCMs into the design of brick structures: encapsulation, filling, and stabilization [18]. Each way has its own strengths and weaknesses, which should be accounted for. It is known that the type of PCM, its quantity, and how it is implemented in a brick PCM system is capable of affecting the system efficiency. Therefore, proper optimization is needed to have high efficiency and thermal performance. It is also known that by reducing energy consumption and minimizing emissions, PCM brick walls are an environmentally friendly option in construction.

The first way to integrate PCMs into brick is encapsulation, which can prevent leakage for usage. There are two types of fabrication by macroscopically and microscopically encapsulations. Gupta et al. [19] examined the effect of using different tubular, square, and rectangular macro-encapsulated PCMs in clay brick, molded from various wood designs (see Figure 5(a)). Silva et al. [20] also examined how the incorporation of PCM can thermally impact the clay bricks in Figure 5(b). Besides, Gupta et al. [21] compared the performance of conventional bricks and fabricated bricks prepared using polyethylene, a material boasting strong thermal stability, as shown in Figure 5(c). Abdulhussein and Hashem [22] carried out a study where a paraffin wax and coconut oil-based eutectic PCM, enclosed in iron containers, was inserted into brick walls, as shown in Figure 5(d). The PCM successfully coped with increases in temperature and achieved a considerable decrease in heat flow, with the PCMs inserted into brick holes boasting the strongest performance. Similarly, the cement brick design with PCMs is depicted in Figure 5(e)

[18]. The microencapsulated PCM MEP29 is directly filled into the brick holes near the outer wall [23]. Filling brick holes and cavities with PCMs is another method to produce PCM bricks. Clay, concrete, aluminum, and more materials were used in the fabrication of bricks to fill using PCMs, as shown in Figure 5(f). Zhang et al. [24] and Tenpierik et al. [25] studied the thermal inertia of bricks fabricated from sugar-beet-pulp and starch composite, with the bricks filled with a BP/S mixture, air, stabilized PCM gel. The incorporation of PCMs into the design of concrete bricks was further investigated. Zhang et al. [26] inspected the thermal performance of building walls that incorporated PCMs into their design, filled with microparticle-based PCMs. Similar attempts can be found in the work by Gao et al. [27]. Another way depicted in Figure 5(g) to fabricate PCMs-based bricks is to form stable PCMs which is produced by incorporating PCM into porous supporting. Mixtures of cement mortar [28], sand, water [29], and fumed silica [30] are also developed to store thermal energy, reduce thermal load of buildings, peak shifting.

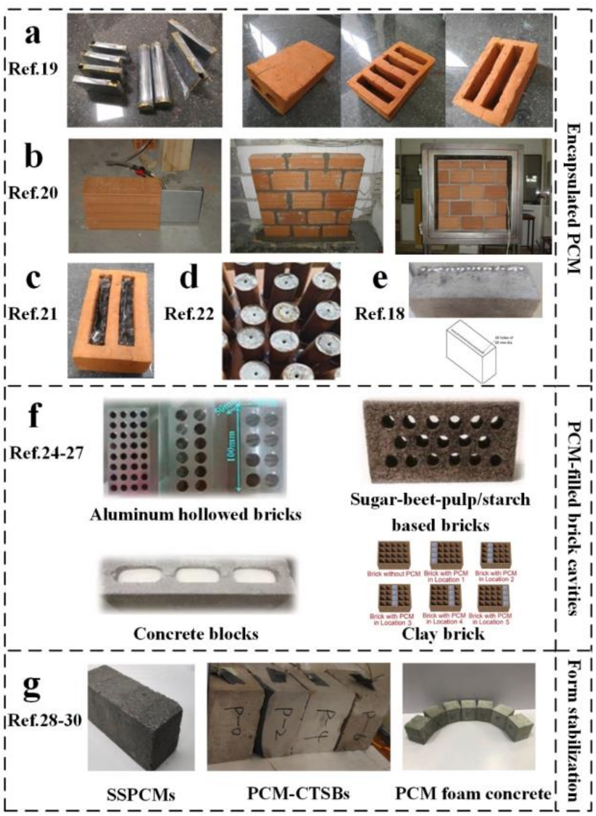

Fig. 5 (a) PCMs are filled in different bricks [19]. Reproduced with permission from Elsevier. (b) Metal-steel macro-encapsulation [20]. Reproduced with permission from Elsevier. (c) PCMs-based polythene bags [21]. Reproduced with permission from Elsevier. (d) PCMs-based cylindrical capsulations [22]. Reproduced with permission from Edizioni ETS. (e) Micro-encapsulation [18]. Reproduced with permission from Elsevier. (f) PCMs-based bricks [24-27]. Reproduced with permission from Elsevier. (g) Shape-stabilized PCMs [28-30]. Reproduced with permission from Elsevier.

3.3 PVT module with PCM

EPCMs can be used in photovoltaic (PV) systems for the purpose of thermal management, courtesy of its temperature-stabilizing properties. Photoelectric conversion efficiency will suffer from excessive temperature in a PV panel, thereby the need to control the temperature is critical.

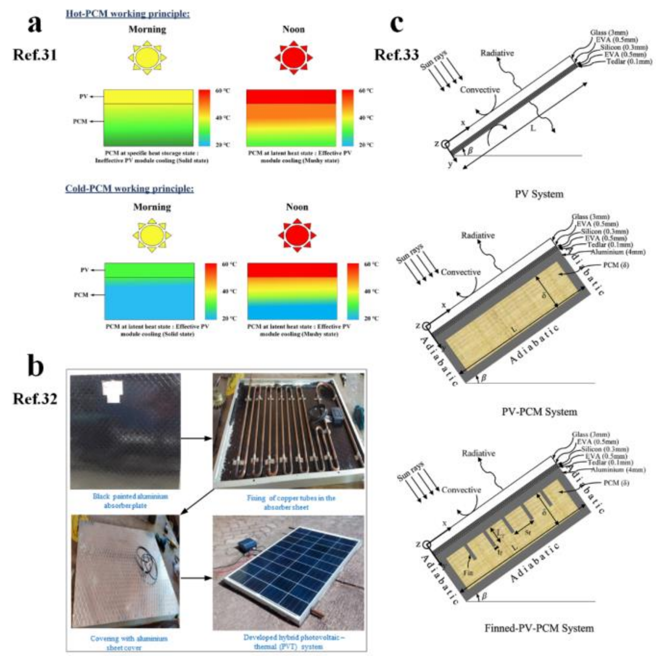

Fig. 6 (a) Heat transfer process between PV and PCMs [31]. Reproduced with permission from Elsevier. (b) PVT system with PCMs [32]. Reproduced with permission from Elsevier. (c) Inclination PVT system [33]. Reproduced with permission from Elsevier.

Figure 6(a) demonstrates heat transfer process between PV and EPCMs. EPCMs were able to control the temperature of PV modules by absorbing the heat dissipation of the modules in daytime and solidifying in nighttime. Results indicated that the EPCM enhanced the output power and reduced the module temperatures [31]. The assembly photos of various components of PVT system are shown in Figure 6(b). Combining the nano-PCM and twisted absorber tubes enhanced the thermal performance. Menon et al. [32] examined the performance of a PVT system that used a water and nanofluid-based heat absorber in coil configuration. Nanofluid and water-cooling methods decreased the panel temperature, improving the system efficiency compared to the original design. Khanna et al. [33] found the optimal depth of the PCM vessel and explored the influences of fin dimensions upon the optimal depth, incorporating three systems over the course of the study, as shown in Figure 6(c). Such an approach suffers from several factors: obstructing buoyancy flow of molten PCM, increasing the technical burden, and decreasing the PCM's latent heat capacity. Metal fins were used to manage cell temperatures. Khodadadi et al. [34] argued that melting was dramatically accelerated by incorporating fins into PCM-PVT modules.

A module known as a macro-encapsulated phase transition panel manages the solid to liquid phase change, preventing leakages during the solidification process [35]. The improvements have been proved by Modiano et al. [36] and Nasef et al. [37] in terms of experimentations involving filling acrylic heat exchanger tubes with PCM.

3.4 Solar water heating system

Water heating applications are much desired due to their low costs, design practicality, strong performance, and increased lifespan [38]. To overcome the fluctuating and intermittent nature of solar energy, TES has been successfully integrated into solar thermal energy in energy conservation and utilization.

Figure 7(a) illustrates four types of solar water heater (SWH). Their performance comparison is as follows [39]: Flat plate collectors (FPCs) feature a simple manufacturing process with low prices, and are widespread across the world in their capacity as SWH in hot water production. Evacuated tube collectors (ETCs) boast improved thermal performance when compared to FPCs and can be broken down into three categories: thermosyphon based ETCs, U-tube based ETCs, and heat-pipe based ETCs. A PV/T based SWH is known that a high cell temperature can affect performance of a single cell. Therefore, the solar collector is used to mitigate the effects on efficiency. The solar collector itself takes in thermal energy to heat the water, and large-scale usage of collectors are found in power generation and other industrial sectors. SWH systems are active or passive. An active system moves the fluid via forced circulation, while a passive fluid uses a thermosiphon effect to circulate the fluid. Flare plate solar collectors are abundant and low priced, boasting a strong performance [42]. They use direct, indirect, and diffused sunlight to heat water. FPCs are made up of a metal absorber plate and heat transfer medium that absorbs the heat imparted onto the absorber plate. A solar collector and thermally insulated water tank are used to properly store thermal energy throughout days. The efficiency of the FPC system is further enhanced by integrating PCMs and NE-PCMs, as depicted in Figure 7(b).

Figure 7(c) depicts the system schematic design of employing PCMs to guarantee stable temperature for output water. Avargani et al. [40] explored the contributions of PCM in SWH as well the ones of temperature changes in PCM and water flow rate to the whole system. Solar thermal energy is then more efficiently stored in PCM to keep a stable temperature, thus improving the overall efficiency of the system. Similar attempts have been carried out by Abdallah et al. [41] in terms of studying the influences of passive air cooling as well as SWH involving integrated PCMs upon thermal efficiency under hot weather scenarios. Figure 7(d) showcases the principle of solar chimney in improving heat transfer for a composite SWH system with PCMs. It has been proven that such composite structure does favor to high efficiency in low flow rate.

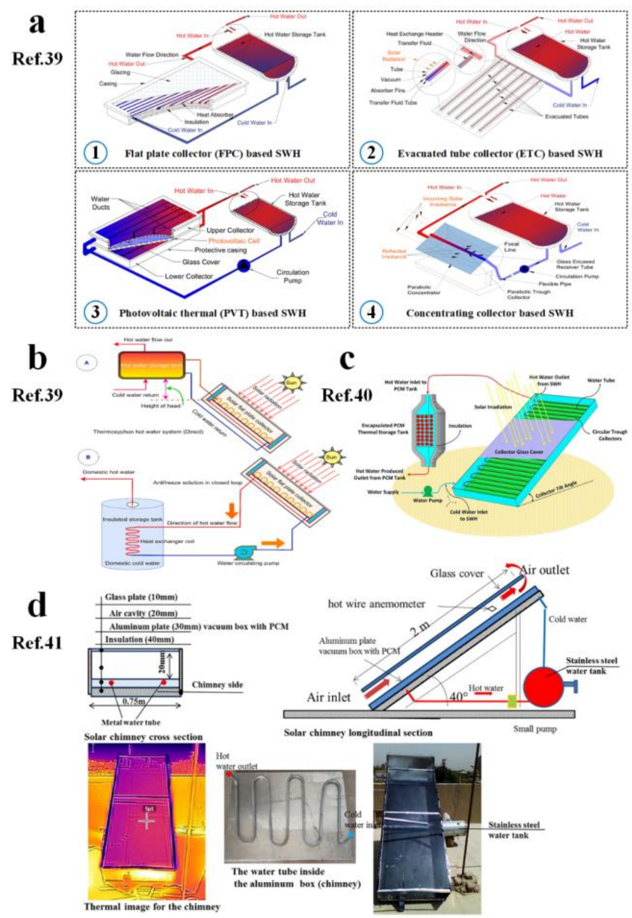

Fig. 7 (a) Four representative types of SWH [39]. Reproduced with permission from Elsevier. (b) Direct and indirect-contact SWH system [39]. Reproduced with permission from Elsevier. (c) Schematic diagram *of the system for adjusting temperature changes using PCM [40]. Reproduced with permission from Elsevier. (d) Solar chimney enhanced SWH with PCMs [41]. Reproduced with permission from Elsevier.*

3.5 BTMS with PCM

The performance of power battery can be impacted by its temperature, necessitating the presence of an efficiently thermal controller. PCMs are capable of absorbing heat without changing their temperature. Battery thermal management systems (BTMS) who use PCMs to passively control the temperature benefit from low costs and thermal stability.

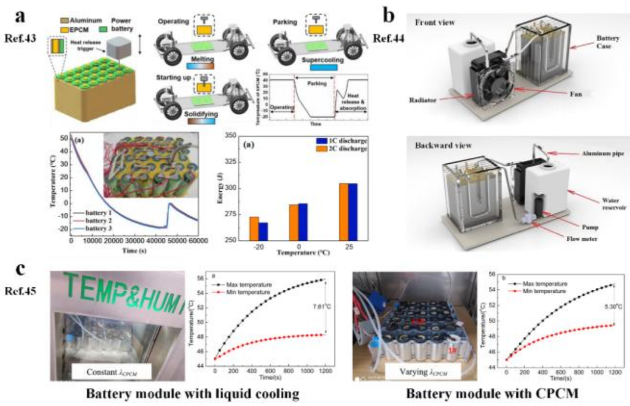

Fig. 8 (a) Working principle and performance of the EPCM for BTMS on EV [43]. Reproduced with permission from Elsevier. (b) Water circulation system and its components [44]. Reproduced with permission from Elsevier. (c) Snapshot of battery module having liquid cooling with EPCM [45]. Reproduced with permission from Elsevier.

Figure 8(a) illustrates working principle and performance of the EPCM for BTMS on EV. It has been proven that the battery increases output power by 5% under a condition of 2C discharge rate. A system's cooling efficiency can be enhanced by coupling different cooling modes. Hekmat et al. [44] found that by embedding a liquid channel into PCMs and utilizing a fan, a hybrid system's cooling performance could be greatly augmented, in addition to the maximum temperature and temperature range being better controlled, as shown in Figure 8(b). Zhang et al. [46] discovered that a passive cooling effect can be reached by leveraging the cooling performance of PCM and HP. Zhang et al. [47] employed a synergy of PCM, HP, and liquid cooling methods to enhance and optimize the cooling capacity of a system and ascertained that an optimized system better controlled the temperature compared to a non-optimized system.

Figure 8(c) describes the thermal management of power batteries and its temperature difference during working period. A cylindrical battery module employing a liquid cooling method was wrapped in shape-stabilized CPCM made from Polyolefin Elastomer (POE), PW, and EG [45]. It was found that under high temperatures, the CPCM underwent a melting process and subsequently lost its thermal management characteristics. The ability for liquid cooling to keep the range of battery temperatures within the standard operating range is thus essential. Experimentation was carried out investigating the impact of the melted CPCM on controlling battery temperature. It was discovered that such design significantly improved the thermal stability of the batteries.

4. CONCLUSIONS AND FUTURE PROSPECTIVES

This paper introduces the fundamental concepts on thermal energy storage and its related engineering applications. Three kinds of thermal storage approaches have been compared regarding their feasibility, stability, and economic features. Concerns have been paid to the understanding on the design, utilization and operation of latent heat phase change materials in real applications of six categories. The research fronts and prospectives are discussed as follows:

1. An efficient, high-performance thermal energy storage (TES) system is desirable for many, whether it be on a testing scale or large-scale commercial usage. As such there are several conditions: high storage density in the materials used, good thermal conductivity, stability of storage materials over an extended period, compatibility of various sub-components used, reversibility of cycles, reduced heat loss, and operational efficiency. Besides, there are several objectives to fulfill: development and testing of PCMs and their charging/discharging process, development and testing of storage techniques, and routine analyses to optimize storage systems.

2. For the perspective of PCM, EPCMs are popular due to the modifiability of their characteristics that depends on the ratio of sub-materials. Despite this, EPCMs face challenges when it comes to large-scale commercial use due to poor heat transfer, supercooling, phase separation, and corrosion of materials. To rectify these issues, using EPCMs with high storage capacities is vital. Moreover, employing additives and encapsulating EPCMs can remedy the poor heat transfer, phase separation, and corrosion, enhancing overall performance of the EPCMs, though with the downside of higher costs. It is essential that EPCMs can be acquired

from an assortment of different materials, boasting strong thermal stability, high latent heat values, and cost-efficiency in the process.

3. For building energy conservation, PCM based bricks bring about new future for both improving building energy utilization and thermal comfort. Utilizing as the basic construction materials, PCM brick walls provides environmentally friendly solution to reduce energy consumption and minimizing emissions during the lifetime functioning of buildings. To expand on the integration of PCMs in brick walls, there are several possibilities. First, a comprehensive evaluation taking into consideration material and manufacturing costs and expenses is needed to thoroughly examine the economic viability and environmental friendliness of brick PCM systems, particularly in regards to emissions and energy savings. Second, in-depth research should be conducted in the creation of composite PCMs that work well in different seasons of the year, overcoming the shortcomings of only using a single PCM which may only be suited for one particular season. Third, the way the PCM is integrated in bricks should be investigated to understand how thermal performance and efficiency is impacted. Lastly, studies should be carried out on the fire-resistance of brick PCM walls in light of inadequate data in the area.

4. For cold storage, the heat storage density, charging and discharging rate, lifespan, heat loss, and operation efficiency of TES systems that rely on PCMs should all be improved if PCM-based TES systems are to be a viable alternative to fossil fuels in the future. The slow rate of solidification in cold TES systems is known to negatively affect thermal performance and efficiency, and existing methods to remedy the issue by adding conductive additives or solid mesh are known to cause problems in heat loss and cooling. Further studies should be carried out on ways to enhance the solidification rate of cold TES systems without negatively affecting other aspects of a system. Lastly, designs for cold TES systems should be standardized depending on which type is desired.

5. For solar water heating, employing tracking systems can result in an improvement in the performance of PCM and NE-PCM based SWH systems. Future investigations should closely examine the costs and parameters of SWH systems to ensure sustainability, while looking into the use of NE-PCMs that are known to enhance the efficiency of SWH systems. Further experimental and numerical research should be conducted on the integration of PCMs and NE-PCMs in SWH systems and the optimization of NE-PCM based SWHs by carefully studying the parameters and use of materials. Machine learning algorithms are recommended for simulations and modeling during this process. Additional studies should scrutinize the environmental costs of SWH systems.

6. For PVT system, the two-step method that is often employed in preparing nanoparticle PCMs should be improved by using a more efficient method. In PVT systems, thermal energy transfer fluids such as EG, water-EG, and oil should be utilized over water. Employing functionalized nanoparticles can lead to improved dispersion and enhanced heat transfer. Tracking systems can boost the energy output of a PCM and NE-PCM based PVT system. In-depth evaluations are needed to examine the economic viability of PCM and NE-PCM based PVT systems for large scale commercial usage. Further analyses on the life cycles of PCM and NE-PCM PVT systems should be carried out, so as to more accurately infer the environmental impact of PVT systems.

7. For battery thermal management, the use of batteries has seen a sharp increase thanks to the growing popularity of electric vehicles (EVs). Vibrations can impact the performance of the battery, so further research conducted on PCM based battery thermal management systems should be done under working conditions, such that solutions can be pinpointed readily to enhance the overall performance of the battery.

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