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Review Article

Phase change materials in building integrated space heating and domestic hot water applications: A review

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ABSTRACT

Thermal energy storage (TES) using phase change materials (PCM) has been widely investigated for various applications from very low to very high temperatures due to its flexible operating temperature range, high energy storage density, and long-life cycle at a reasonable cost. The use of PCM in building components and hot water production can reduce the building energy demand, indoor temperature fluctuation, and better demand-side management by utilising available renewable energy and off-peak electricity. This paper presents a state-of-the-art review of the application of PCM domestic thermal heating. The classifications of TES systems, advantages of PCM over other TES systems, and the methods to overcome shortcomings of PCM are discussed in brief. Then the various novel techniques employed in underfloor heating, wall heating, PCM integration in domestic hot water tanks, and developing latent heat thermal energy storage units are extensively reviewed and the major findings of the research works reviewed are tabulated. Based on the extensive review conducted, the important factors to be considered for selecting a suitable PCM for these applications are summarised, and the commercially available PCM for the above applications are listed with their major thermo-physical properties and supplier details in the appendix.

1. Introduction

The economic development and prosperity of a nation largely depend on the availability of energy. However, ever-growing energy demand has led to a significant depletion of fossil fuel resources, the use of which has also increased environmental pollution (for example acid rain) and climate change [1,2]. Over the past few decades, there has been considerable research to increase the contribution of renewable energy sources and technologies to reduce energy consumption so that independence from carbon-based fuels can be achieved. However, the intermittency of renewable energy resources, especially solar and the wind is the major challenge in utilising energy throughout the day [3–5].

In Europe, households account for 24.7 % of the total energy consumption. Sanitary hot water and space heating represents >80 % of total domestic energy consumption. The major share of this is covered by heaters operated either by gas, oil, or electricity, [6–10].

It has been predicted that the worldwide energy demand of the domestic sector energy is forecasted to increase to 50 %, 200 %, or even 300 % of the total demand by 2050 [11,12]. However, the recent intergovernmental panel for climatic change assessment report 6 (IPCC AR6) report linked residential energy growth to growth in global residential floor areas. With the economic upheavals due to the Covid-19 pandemic and the potential repurposing of existing buildings, this

Abbreviations: AC, air conditioning; Al, aluminium; ASHP, air source heat pump; ASHRAE, American Society of Heating, Refrigeration and Air-Conditioning Engineers; BS, British standards; CFD, computational fluid dynamics; COP, coefficient of performance; CPCM, composite phase change material; Cu, copper; CuO, copper oxide; DHW, domestic hot water; EG, expanded graphite; EWGLI, European working group for legionella infection; FEA, finite element analysis; FPSWH, flat plate solar water heater; HDPE, high-density polyethylene; HP, heat pump; HTF, heat transfer fluid; HWT, hot water tank; IPCC AR, Intergovernmental Panel for Climatic Change Assessment Report; LHTES, latent heat thermal energy storage; MEPCM, macro encapsulated phase change material; MP, melting point; MPCM, micro encapsulated phase change material; Ni, nickel; PCM, phase change material; RECC-LED, resource efficiency and climate change-low energy demand; RMB, Ren Min Bi (Chinese currency); RT, rubitherm; SAT, sodium acetate trihydrate; SHS, sensible heat storage; SiO_2, silica; SSPCM, shape stabilized phase change material; TES, thermal energy storage; XPS, extruded poly styrene.

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growth has been moderated to 100 % growth under current policies or a 50 % reduction under the IPCC's resource efficiency and climate change-low energy demand (RECC-LED) scenario [13,14]. The RECC-LED scenario requires decarbonization of this sector through renewable energy market penetration and significant energy efficiency measures. Heat pumps (HP) are one such measure that can effectively utilize off-peak electricity to solve the mismatch between the supply and demand of energy and provides significant economic benefits [15–17]. Another solution is efficient thermal energy storage (TES) to bridge the mismatch between renewable energy supply and demand. This is achieved through storing surplus thermal energy at the time of high renewable energy availability for use when renewable energy is unable to meet demand [18–20]. In 2020, 12.1 % of wind in Ireland and Northern Ireland, 1909 GWh, could not be dispatched to the electricity grid, while there was 8.7 GWh of curtailment from Irish solar resources, representing 6.3 % of solar available solar energy. Therefore, increasing the utilization of renewable energies is essential in achieving a net-zero emission energy market by 2050. On the island of Ireland, the curtailment of wind tends to be overnight and by utilising energy storage consumers can take advantage of off-peak electricity price variations for building heating applications [21].

Thermal energy storage (TES) technology has gained great popularity as an effective method for demand-side management of energy of heating. TES has the potential to harvest, store and save thermal energy for short or longer periods. Scientists and energy technologists are investing their efforts to develop efficient, reliable, and cost-effective TES systems which can be integrated with heat pumps (HP) and solar panels to store off-peak renewable energy and deliver thermal energy to decarbonise the heating sector [22–24]. Among the various energy storage methods, the thermal energy storage system (TES) is achieving greater acceptance and a large volume of research activities are undergoing due to its low cost, simple design considerations, ease in integrating with HP and solar panels to retrofit the houses.

1.1. *Classification of TES*

TES materials can be broadly classified into sensible, latent, and thermochemical materials based on the nature of the heat storage mechanism. Fig. 1 illustrates the classification of existing TES technologies in detail [26]. The selection of TES mainly depends on the storage period required, operating conditions, and economic viability [27–29].

1.1.1. *Sensible heat storage materials (SHS)*

Sensible heat storage materials are the most widely employed methods for TES. These materials store or release heat by virtue of the temperature change; the energy is stored as a function of its heat capacity and the temperature difference between initial and final states [30]. Water, bricks, high-temperature mineral oils, stones, metals, molten salts, and concrete are the most suitable materials for sensible heat storage. Among the above-mentioned materials, the high heat capacity of water makes it one of the most popular candidates for domestic heating applications [27,31,32]. Most domestic systems store the energy in a water tank which is heated via an electrical heating element, converting electrical energy to thermal energy, or a heat exchanger loop within the tank, the thermal energy in this loop is acquired from a boiler, heat pump, solar thermal panel, or other thermal energy sources. The thermal energy in the tank can either be utilised through direct draw-off or via a separate heat exchanger loop. The ability of the tank to store the heat will be dependent upon its surface area to volume ratio and the insulation around the tank, both of which influence sensible heat losses from the store. Heat can be actively stored in solids by means of air or a liquid flowing through the solid with direct contact, allowing the transfer and storage of the thermal energy [31,33]. However, the lower energy density and higher energy loss of the sensible heat storage systems have led to research into more compact and efficient methods, albeit the sensible heat storage is cheap, well understood and materials are abundant [26,31,33].

1.1.2. *Latent heat storage (LHS) materials*

LHS materials stores a large quantity of thermal energy across a narrow temperature range at the phase change enthalpy of the material. LHS materials are classified into solid-solid, solid-liquid, and liquid-gas as shown in Fig. 1[25,31,33]. Solid to liquid and liquid to gas LHS materials undergo molecular rearrangement during the phase change, whereas solid to solid LHS materials store and release heat by a phase transition between crystalline or semicrystalline and amorphous states [25,34,35]. Among these LHS materials, solid-liquid materials are the most used and commonly available in the market for TES applications and is the focus of this research. Compared to solid-to-solid materials they exhibit high phase change enthalpy, high energy storage density,

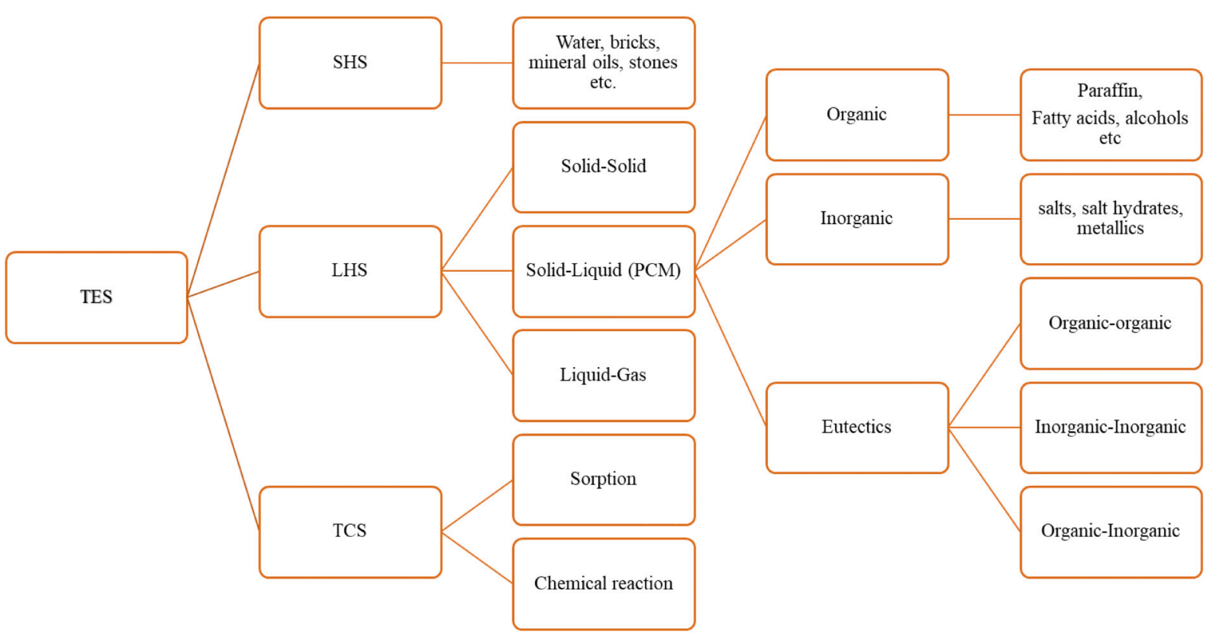


Fig. 1. Classification of popular TES materials [25,26].

availability in a wide temperature range, and material stability. Further, the solid-liquid materials have significantly low volume change during phase change compared to liquid to gas materials, which makes them easier to incorporate into most of the TES applications. Solid to liquid LHS materials are commonly referred to as phase change materials (PCM) [25,26,33]. The total energy stored/discharged during the heating/cooling process includes both sensible and latent heat. When the temperature of the material is below the phase change temperature, the temperature will rise linearly as a sensible store when heat is added. At the phase change temperature of the material, the heat will be stored due to the change in enthalpy of the phase change. Once the material has changed phase, the store's temperature will rise again in line with the specific heat capacity of the material in that phase state. Fig. 2 illustrates the ideal phase transition of a solid to liquid LHS material. In this figure, there is a sharp change in the temperature/thermal energy stored profile at the phase change. However, in practice, most LHS materials are not pure, and there is a transition both into and out of the phase change period. The width of the transition can influence the choice of material for a specific application.

1.1.3. Thermochemical storage (TCS) material

Thermochemical materials store or release energy during reversible chemical reactions. These are classified into sorption materials and thermochemical materials [5,37]. Sorption storage materials store a large amount of energy during the sorption (adsorption/desorption) of gases or water vapor from materials such as silica [38], zeolites [39], etc. There is no formation of permanent chemical bonds, rather the process occurs by the formation or braking of temporary Van der Waals bonds or hydrogen bonds. Whereas in thermochemical materials, permanent chemical bonds are formed during reversible reactions as in the case of the hydration of salts [40,41]. Since the thermochemical storage materials store heat during a reversible reaction without any temperature change, it is not subject to heat loss through heat transfer to the surroundings – a problem for both sensible and latent energy storage systems. So, thermochemical storage materials are widely discussed as suitable for seasonal TES systems. Although thermochemical storage systems possess high energy densities and longer periods of energy storage without much loss, their cost, slower kinetics, operational conditions, etc., limit their application [2,32,40].

1.2. Scope of the review article

There are a number of review articles available on types of PCM, PCM thermophysical property enhancement, and application of PCM in very low to high-temperature applications such as cooling, thermal management, heating, demand-side management, waste heat recovery, and power generation. Table. 1. gives an overview of major review articles published since 2015 on the application of PCM in building heating including active and passive building integration and domestic hot water (DHW) application in comparison with the objectives of the present paper. As can be seen from Table. 1. most of the review papers covered either the application of PCM in a large temperature range from very low to high-temperature applications or focussed only on specific applications such as passive and active building heating or DHW application. There are no review papers available that cover both PCM integrated building heating systems, DHW production using PCM integrated hot water tank (HWT), and PCM TES unit development. Moreover, there are not enough details on the optimum melting point (MP) range for each application and potential commercial PCM database to support researchers in selecting a suitable PCM for a particular application. Whereas, the main objective of this study is to present an extensive review of the research activities and development of PCM-based TES in domestic heating applications including the PCM underfloor, PCM wall, PCM in HWT, and the PCM TES units for DHW applications in the recent decade. The review commences with a brief overview of the important aspects of PCM, their desirable properties, limitations, and the commonly studied methods for overcoming the shortcomings of PCM systems. Then the major research works published in the last ten years on PCM integrated under floor heating, building walls, DHW tanks, and PCM TES units for hot water production are extensively reviewed. Based on the literature review conducted, suitable temperature ranges of PCM for these applications are summarised and the commercially available PCM for the above applications are listed with their major thermophysical properties and supplier details.

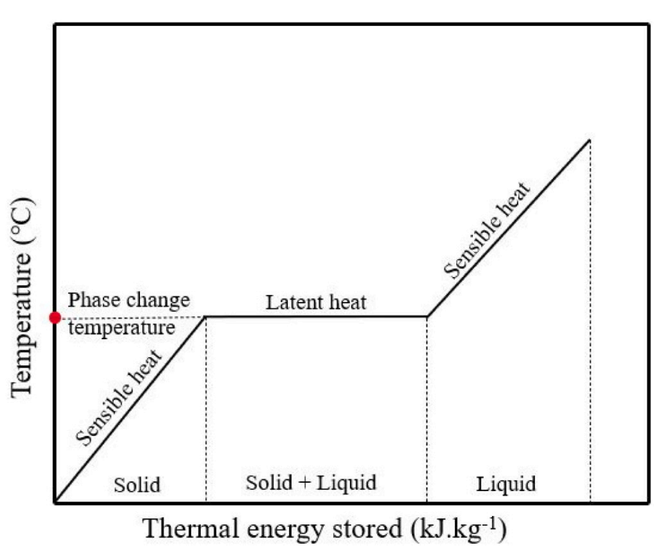


Fig. 2. ideal phase transition diagram of a solid to liquid LHS material [36].

2. Phase change materials

Among the three TES, PCM has the most flexible operating range [26]. PCM possesses higher energy densities than sensible heat stores and is available in wide temperature ranges from very low to very high temperatures. PCM is classified into organic, inorganic, and eutectic materials. Fig. 1. lists the various types of PCM commonly used in studies. PCM stores or releases heat during the phase change process at an almost constant temperature. The total energy stored/released during the charging/discharging process is the sum of solid sensible heat, phase change enthalpy, and liquid sensible heat [31,33].

Suitable phase change temperature, high latent heat and specific heats, high energy density, thermal and chemical stability, thermal reliability, good thermal conductivity, little or no supercooling, small volume change during the phase change, compatibility with the containment material, low vapor pressure, low price, and good recyclability are the desirable properties of PCM which make them a suitable candidate for applications such as building integration for thermal management [63], space heating, and hot water production [64], demand-side management to utilize off-peak electricity [64], concentrated solar power plants [65], and so on. Table. 2. summarises the advantages and disadvantages of each type of PCM [28,31,33]. Despite the advantages, most PCM exhibit low thermal conductivity, leakage, corrosive nature, phase separation, and supercooling, which hamper their wide application and acceptance [28,54,67].

Among the different TES methods, PCM materials offer the most flexible operating ranges, comparatively high energy density, and high durability at a reasonable cost, which has opened wide the market for PCM. Despite the cost of the PCM being high compared to the SHS, the number of industries producing promising PCMs and PCM products has increased significantly in the last decade, with the expectation that the world will shift towards low carbon emission technologies. Thus the demand for potential TES would increase irrespective of the cost of the system, which could result in a reduced price of latent heat thermal energy storage (LHTES) systems [68,69].

Table 1
Details of the review articles published in the last five years in comparison with the objectives of the current paper.

Review article	Objectives of the current review paper								
	PCM performance enhancement methods	Building-integrated active heating				PCM in domestic hot water production			
		Underfloor	Wall	PCM selection	List of commercial PCM for the application	PCM integrated HWT	LHTES units for DHW	PCM selection	List of commercial PCM for the application
Shah et al 2022 [42]	X	✓	✓	X	X	X	X	X	X
Wang et al. 2022 [20]	✓	✓	X	X	X	X	X	X	X
Faraj et al. 2021 [43]	X	✓	✓	X	X	X	X	X	X
Osterman and Stritih 2021 [29]	X	X	X	X	X	✓	✓	X	X
Al-Yasiri and Szabo 2021 [36]	X	X	✓	X	X	X	X	X	X
Teamah 2021 [44]	X	X	X	X	X	✓	✓	X	X
Douvi et al 2021 [22]	X	X	X	X	X	✓	✓	✓	X
Naghavi et al 2021 [45]	X	X	X	X	X	✓	✓	X	X
Li et al. 2020 [204]	✓	✓	✓	X	X	X	✓	X	X
Romdhane et al. 2020 [47]	X	✓	✓	X	X	X	X	X	X
da Cunha and de Aguiar 2020 [48]	✓	X	✓	X	X	X	X	X	X
Rathore et al. 2020 [49]	✓	X	✓	X	X	X	X	X	X
Drissi et al 2019 [50]	✓	✓	✓	X	X	X	X	X	X
Zayed et al 2019 [51]	X	X	X	X	X	✓	✓	X	X
Nazir et al 2019 [26]	✓	✓	✓	X	X	✓	✓	X	X
Zhu et al 2018 [52]	✓	✓	✓	X	X	X	X	X	X
Song et al 2018 [53]	X	✓	✓	X	X	X	X	X	X
Du et al 2018 [54]	X	✓	✓	✓	X	X	✓	✓	X
Lin et al. 2018 [55]	X	X	X	X	X	X	✓	X	X
Kee et al 2018 [56]	✓	X	X	X	X	✓	✓	X	X
Reddy et al 2018 [57]	✓	✓	✓	X	X	✓	✓	X	X
Kasaeian et al 2017 [58]	X	✓	✓	X	X	X	X	X	X
Pardinas et al. 2017 [59]	X	X	X	X	X	✓	✓	X	X
Khan et al. 2016 [60]	✓	X	X	X	X	✓	✓	X	X
Navarro et al. 2016 [61]	X	✓	✓	X	X	X	X	X	X
Seddegh et al. 2015 [4]	X	X	X	X	X	✓	✓	✓	X
Sharif et al 2015 [62]	X	X	X	X	X	✓	✓	X	X

3. Methods to enhance the thermal performance of PCM systems

PCM possesses very low thermal conductivity, corrosive in nature, supercooling, and volume expansion. These require resolution so that they may be successfully commercialised. This can be done either by modifying the design of heat exchangers or by modifying the thermo-physical properties of PCM. Fig. 3 shows the various heat transfer enhancement methods investigated widely by researchers for achieving higher efficiency and better performance of TES units [26,70].

3.1. Design modifications

An efficient heat exchanger transfers the maximum possible heat in a short period with high heat transfer and minimum heat loss [70]. Shell and tube heat exchangers [71] and concentric tube heat exchangers [72] are the two most commonly studied heat exchangers in latent heat systems. During charging of PCM, convection dominates as the PCM melts, while conduction is the major heat transfer mechanism during solidification. A vertical orientation of the LHTES system is preferred for both charging and discharging because the strong convection current

Table 2
list of advantages and disadvantages of various types of PCM [28,66].

Organic PCM		Inorganic PCM		Eutectic PCM	
Advantages	Disadvantages	Advantages	Disadvantages	Advantages	Disadvantages
Available in a large temperature range	Low thermal conductivity	High energy storage density	Corrosive	Sharp melting point	Limited thermophysical property data available
No supercooling	Large volumetric change	Congruent melting	Large supercooling	Can be prepared to match specific requirements	Costly
No phase separation	Flammability	Good thermal conductivity	Phase separation	High energy storage density	
High phase change enthalpy		Low cost			
Chemically inert		Low volumetric change			
Low vapour pressure		Non-flammable			
Chemically stable		Recyclable			
Recyclable					

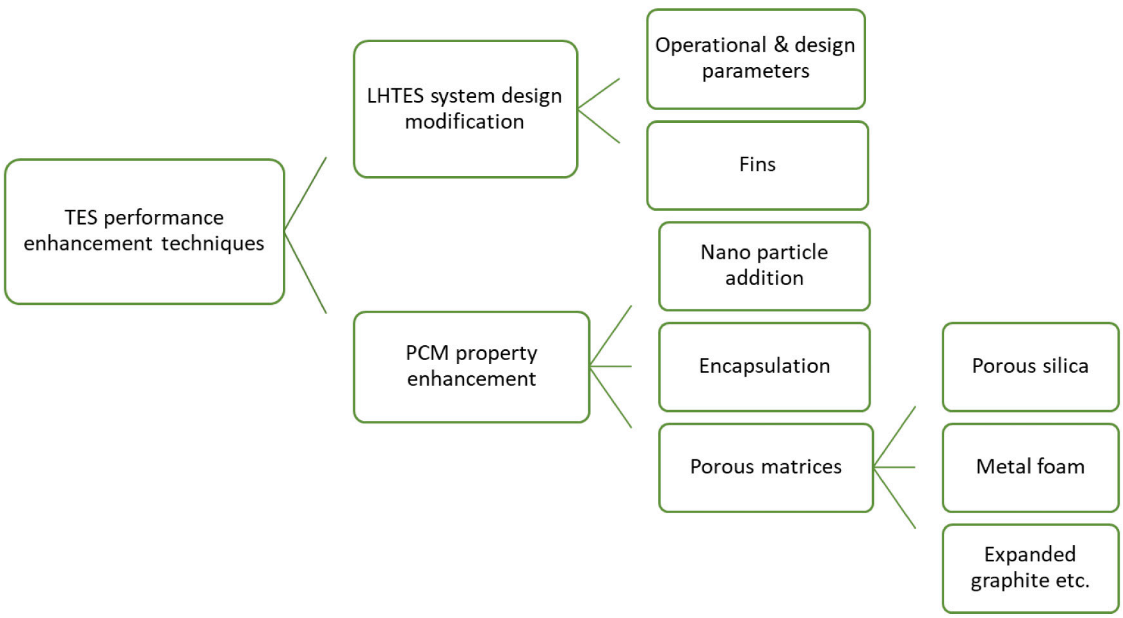


Fig. 3. Type of heat transfer enhancement methods used in LHTES systems [26].

caused by the buoyancy effects increases the heat transfer rate [73,74]. The inlet temperature of the heat transfer fluid (HTF) has a larger impact on the heat transfer rate than an increase in the mass flow rate [75,76]. Compared to PCM thermophysical property enhancement methods, fins are a simple, economical, and most widely used technique for heat transfer enhancement. However, it results in reduced energy storage capacity [70,77]. Longitudinal fins [71] and radial or transverse fins [78] are commonly used types for heat transfer augmentation, whereas systems with longitudinal fins have better heat transfer rates than radial finned systems [75,78]. Design modifications of heat exchangers affect only the thermal performance of the LHTES system, but to account for the other issues related to the PCM, thermophysical property modifications are required.

3.2. Nano particle addition

Dispersion of suitable nanoparticles into the PCM has been studied widely by researchers as a method to enhance melting and solidification rates [79] and to reduce the supercooling by creating nucleating sites to initiate solidification [80]. Nano particles of graphene [79], alumina [81], titanium dioxide [82], and copper oxide [83] are the most commonly used nanoparticles for the modification of the thermophysical properties of the PCM. However, the addition of nanoparticles compromises the overall thermal storage capacity and enhances the dynamic viscosity of the composite, which inhibits the effect of natural convection [79,84]. Most of the nanoparticles are metallic which may react when added to inorganic salt hydrates. The high-density difference between the nanoparticle and the liquid PCM may result in the aggregation of particles at the bottom during repeated charging and discharging cycles.

3.3. Encapsulation

Encapsulation is the process of enclosing the PCM inside a coating material made of non-reactive stable polymers or containers to form a capsule of spherical, oval, or even irregular shape. This can improve the thermal conductivity, thermal stability, supercooling, leakage of PCM, and the corrosion of containment material [26,85]. Depending on the size of capsules, the encapsulation process is classified into macro [86] micro [87,88], and nano encapsulation [89]. As the size of the capsules decreases more surface area can be achieved which leads to better heat transfer enhancement [87,90]. Despite the high heat transfer, reduced leakage, and less corrosion, its complex preparation method, high cost of production, and chances of leakage over a larger number of thermal cycles hamper the wide acceptability compared to other types of enhancement methods [26].

3.4. Porous matrix

Infiltrating the PCM into the porous sites of matrices to form shape stable PCM (SS-CPCM) is an effective way to replace the expensive encapsulation methods [26]. When PCM is impregnated into the porous matrices, the capillary force of the porous network structure will hold the molten PCM even if it is heated above the melting point of the PCM [91]. This approach has been widely studied to improve thermal conductivity, supercooling, leakage, and corrosion issues associated with PCM [92]. Several porous matrices have been investigated as matrices for SS-CPCM preparation such as porous silica [91,93] metal foams [94], expanded graphite [95]. The high specific area, large pore volume, high capillarity, thermal and mechanical stability, and chemical inertness are the favourable properties that have attracted the attention of researchers.

3.4.1. Porous silica

Being highly porous with a strong network structure and chemically inert, porous silica (SiO_2) is a potential candidate for SS-CPCM application and is suitable for organic PCM composites [96]. The melt blending and impregnation method is widely used to prepare silica/PCM composites [97]. Despite the high thermal and mechanical stability, chemical inertness, and porous network structure possessed by porous silica being promising, it is hindered by the low thermal conductivity of silica [97,98].

3.4.2. Porous metal foams

Metal foam-PCM composite is a promising method to improve the thermal performance of PCM systems and has been widely employed by researchers due to its high thermal conductivity and strong porous structure. Highly conductive metallic foams manufactured from copper (Cu) ([99,100], nickel (Ni) [101], and aluminium (Al) [94] are widely studied to improve the thermal conductivity of PCMs. Metal foam/salt hydrate composite possess high energy storage densities, high thermal conductivities, and better supercooling. However, the corrosion induced by the salt hydrates on metal foams can cause serious damage [26,102].

3.4.3. Expanded graphite (EG)

EG is a potential candidate for composite PCM (CPCM) preparation due to its chemical inertness, high thermal conductivity, mechanical and thermal stability, large porous network, and high specific surface area [103,104]. Being chemically inert, it is compatible with both organic and inorganic PCM [104,105]. PCM/EG composites exhibit high thermal stability. Even after a large number of operations cycles, it retains the thermophysical properties without significant change [95,105]. PCM/EG composites can achieve 10 to 100 times enhancement of the thermal conductivity when a 10 to 30 wt% of EG is used [106,107].

4. Phase change materials for building integrated heating and DHW application

Improving the energy efficiency of buildings has a profound impact on reducing energy consumption and carbon footprint. Integrating a suitable PCM in buildings and DHW storage can reduce the heat demand of the building and provide better demand-side management by storing available renewable energy and electricity during off-peak periods.

4.1. Scope of phase change materials in building integrated heating

Many buildings have been constructed with materials such as concrete, brick, and rock to utilize the natural thermal mass of these materials for maintaining thermal comfort [108]. Building constructions with lightweight materials of low thermal mass [109] have also been used, however, the indoor temperature of the latter is more prone to outdoor weather fluctuations and large amounts of energy can be required to maintain indoor thermal comfort [110,111]. PCM integrated into buildings is a feasible choice for enhancing thermal mass to decrease energy demand, reduce indoor temperature fluctuation, and maintain thermal comfort under all-weather conditions [23]. PCM infiltrated building materials such as concrete, bricks and porous rocks are being researched widely to enhance the thermal mass of the building without much increase in mass. The artificial enhancement of the mass is through the absorption of energy in the phase change. So, for example, a wallboard with a PCM that melts at 26 °C can maintain the temperature of an office below 28 °C by absorbing thermal energy from the air [112]. However, volume expansion and associated leakage limit the application [113–115]. Whereas PCM incorporated building components such as the wall, ceiling, and floor are smart ways of maintaining thermal comfort and reducing energy consumption without consuming extra space ([48]; Y. [116]). Building-integrated TES systems are classified as active and passive systems. Active heating systems require an additional fluid loop or electric heating element to transfer the energy available from sources. Such systems bring better control over indoor thermal comfort [61,117], whereas passive heating systems operate naturally without the assistance of any mechanical or electrical components. PCM infiltrated building materials, ceilings, roofs, and chimneys are classified into passive systems [118,119].

4.1.1. Radiant underfloor heating system

Over the past few decades, radiant underfloor heating systems have received considerable attention due to their ability to distribute the heat uniformly, save living/workspace, and reduce the head and foot temperature difference in buildings. Radiant underfloor systems with suitable phase change materials can reduce indoor temperature fluctuations, bring better thermal comfort and reduce energy consumption [120,121].

A PCM enhanced radiant underfloor system comprises five main layers from bottom to top viz. base floor layer, an insulation layer, heating layer, PCM storage layer, and a floor surface layer as shown in Fig. 4 [122–124]. However, the number of floor layers varies with the type of heating source employed. Electric heat mats are employed with five-layer flooring whereas in systems with hydronic circuits coupled with a heat pump or solar collector, the hydronic pipes can be immersed in the concrete layer below the floor surface are used as illustrated in Fig. 5 [125].

Electric radiant floor heating system with a suitable PCM is an effective method of shifting the electricity peak load by connecting either to a heat mat or to a HP [126]. Lin et al. [120] formulated an enthalpy model for the numerical simulation of paraffin encapsulated in polyethylene then integrated into a five-layer radiant under-floor electric heating system. The effects of exterior climatic conditions, the heat load of the room, the thickness of the air layer and wooden layers were extensively studied.

Later, the simulation results were validated with the experiments conducted in a test house in Beijing. Although the system could maintain a uniform indoor vertical temperature distribution, the high phase change temperature (52 °C) caused the indoor temperature to be above comfort level. However, more than half of the peak electricity shift was achieved [123].

PCM/underfloor heating systems are more efficient in minimizing the indoor temperature fluctuations than systems using sensible heat

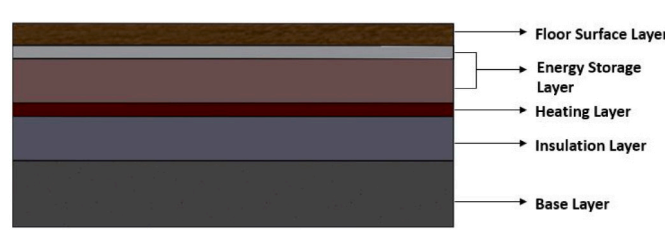


Fig. 4. Structure of the basic five-layer flooring system [120].

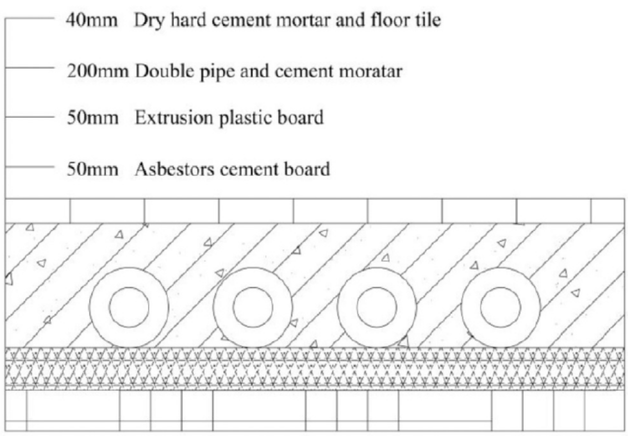


Fig. 5. Structure of floor system with PCM pipe immersed in concrete layer [125].

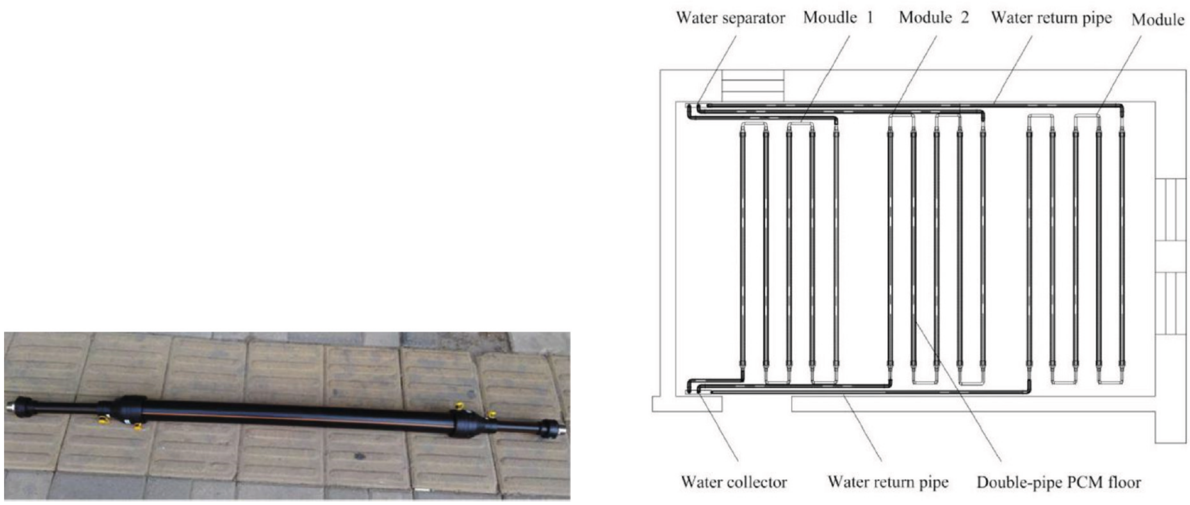
storage materials such as sand and concrete. Zhou and He [121] compared the heat storage and release performance of a floor heating system with PCM and sand experimentally. Four different combinations of two storage materials (sand and PCM) and two heating pipes (polyethylene and capillary mats) were employed for the experiments. Fig. 6 illustrates the capillary mat floor and polyethylene floor employed for the study. The system with capillary mat and PCM attained a uniform average indoor temperature in the vertical direction and had a heat release period, two times longer than that with sand.

In a recent study, Lu et al. [125] has employed paraffin wax in the annular cavity of polyethylene double pipe immersed in a concrete mortar layer for an under-floor heating system. The double pipe PCM unit and the floor heating network system design are shown in Fig. 7a and b, respectively. Three independent PCM modules were used for better control of the room temperature. The feasibility of the system was extensively investigated under four operating strategies and found that the average indoor temperature swing was controlled within 3.2 °C with a minimum fluctuation of 1.8 °C.

An effective PCM underfloor heating system should be capable of reducing indoor temperature fluctuations in summer by buffering the solar gains while maintaining the room temperature within the thermal comfort range in winter. Jin and Zhang [127] conducted a numerical study of radiant floor heating systems with two PCM layers of different melting point for all the year-round thermal comfort. An effective heat capacity-based finite-difference model was formulated to study the feasibility of the system and the results showed that compared to a floor without PCM, the PCM floor system could transfer 41.1 % and 37.9 % more energy during heating and cooling respectively when a PCM with the latent heat of 150 $kJ.kg^{-1}$ was used. As a continuation of the work, Xia and Zhang [128] experimentally investigated the two-layer PCM system and validated the numerical results. Two test rooms were built with a five-layer flooring system, where the first room has a low-temperature PCM layer above the high-temperature PCM layer and the second room had the reverse order. Under the same test conditions, test room 2 exhibited higher room temperatures and temperature variation, whereas the floor temperature variation of room 1 was below 2 °C during both heating and heat release periods. In a similar study Ansuini et al. [129] conducted an experimental study of an underfloor heating system with metal boxes containing granular RT27 in mineral particles. The results of experiments were validated with a finite element analysis (FEA) model and found that the system was efficient in maintaining thermal comfort during both summer and winter climatic conditions. Barzin et al. [130] has evaluated the performance of a house integrated with PCM boards in an underfloor heating system and Dupont Energain wallboards to achieve thermal comfort in both winter and summer. Through the control strategy employed the underfloor system was charged during the off-peak period and maintained the room temperature at 23 °C during morning peak hours while at the same time the PCM wallboards, having a melting point of 21.7 °C, get fully charged. As the PCM in the floor system discharges completely, the room temperature drops, and PCM wallboards keep the room warm. Thus, better thermal comfort can be achieved even during evening peak hours. By setting the control temperature to 20 °C the summer gain of the building can be effectively buffered. An extension of this work has been performed by Devaux and Farid [131] by using an additional Dupont layer ceiling along with the previous system configuration. EnergyPlus simulations were performed for energy and heating cost savings optimization strategy and achieved 32 % energy savings and cost savings of 42 %. Faraj et al. [122] investigated the feasibility of coconut oil as PCM in an underfloor heating system for electricity peak load shifting. A modular test house with PCM incorporated underfloor combined with passive PCM wall and roof has been fabricated and evaluated the thermal performance of the test house for two different PCMs under different weather conditions. Total energy consumption and economic benefit of the PCM test house were compared with that of a test house without PCM. HTF pipe configuration in the modular test house floors and the macro encapsulation units for the PCM are displayed in Fig. 8. It was found that system A with PCM in floor, wall and roof resulted in the complete shifting of the load from high peak (unshaded part in graph) to

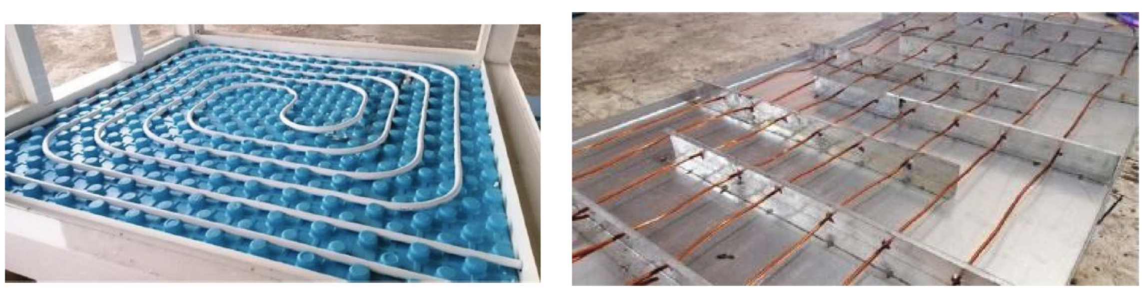
(a) **(b)**

Fig. 6. Images of (a) Test room floor with capillary mat; (b) Sand + PE coil floor [121].



(a) (b)

Fig. 7. (a) Double pipe PCM storage; (b) Schematic diagram of double pipe PCM floor system design [125].



a b

Fig. 8. (a) HTF pipe configuration on the modular test facility floor; (b) the macro encapsulation unit for the PCM with copper wires for heat transfer enhancement [132].

low peak load (shaded part) period as shown in Fig. 9, although, the system with paraffin wax having a MP 60 °C resulted in high indoor temperature, beyond the thermal comfort. Also, the room heating period was enhanced by 53.7 % with PCM. Furthermore, the economic analysis of the system for climatic conditions of Lebanon revealed that the system can achieve an annual energy cost reduction of 58.9 % [132].

Even though the encapsulation avoids the leakage and increases the heat transfer rate to an extent, PCM diffuses to the shell surface and can cause leakage and property degradation over continuous cycle operations. To overcome the drawbacks of conventional form stable PCMs, shape stabilized PCM (SSPCM) is widely investigated in building integration. Li et al. [133] has prepared a novel composite by blending microencapsulated PCM with high density polyethylene (HDPE), wood floor composite (350 μm), and micro mist graphite (particle size <38 μm). A simulation model based on the effective heat capacity method was developed to study the temperature control and cost reduction

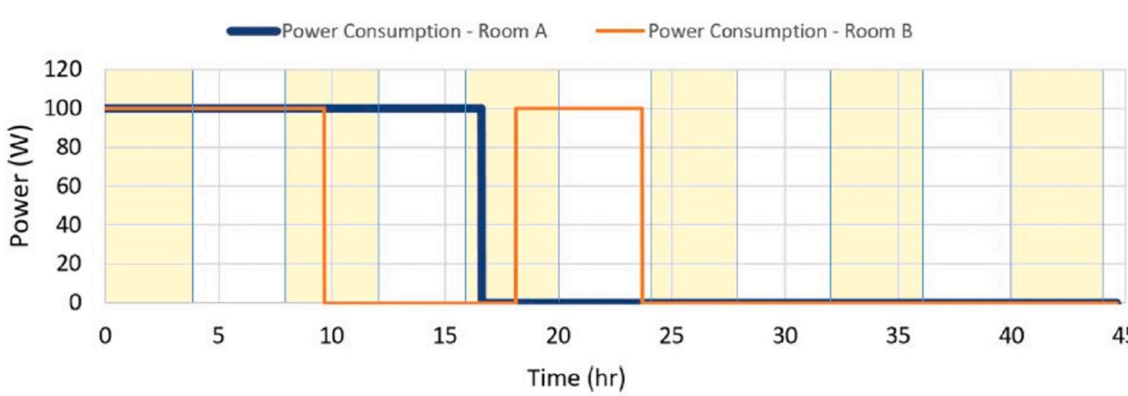


Fig. 9. Power consumption of systems A and B during peak and off-peak load period [132].

effect of the novel composite PCM layer with electric radiant heating systems. The simulation results were validated with experimental results conducted with the same composite PCM floor system. Indoor temperature variation results obtained from both studies were in good agreement. In a similar study, Cheng et al. [134] has used compressed paraffin/polyethylene/EG composite tiles with electric heating films arranged below the floor surface as shown in Fig. 10. The performance comparison of the proposed system with a non-PCM system and a conventional air conditioning (AC) system indicated an increased energy efficiency with the thermal conductivity of the composite PCM. However, thermal conductivities above 1 Wm^{-1} K^{-1} did not have any significant influence. The phase change energy storage system can recoup the cost within four years compared to a non-PCM system. Fang et al. [135] has conducted a similar study and evaluated the thermal performances of the PCM room. Fig. 11. displays the indoor temperature variation of the simulation room with and without the PCM layer. The floor surface temperature reached 45 °C without PCM, which is beyond the indoor comfort level. Whereas the room with PCM/EG layer had a longer thermal comfort time of 12.65 h with floor temperature in the comfort range.

A passive underfloor heating system with MPCM mixed concrete layer for the utilization of daylight entering dwellings in the moderate Dutch climate was proposed by Entrop et al. [136]. Four experimental test houses were developed, two with MPCM mixed concrete layer and two without PCM. Indoor temperature fluctuation of all the four test houses was evaluated for different types of insulation material. The PCM concrete layer successfully buffered the diurnal solar gain and heated the room during cold nights. Plytaria et al. [137] investigated the energetic and economic feasibility of a solar-assisted heat pump underfloor heating system with PCM using TRNSYS software. The energetic performances of two floors of $100m^2$ area with and without PCM connected to a heat pump operated by three types of solar panels namely, flat plate solar collector, thermal photovoltaic, and photovoltaic collector were compared and concluded that the building with PCM floor layer achieved 40 % reduction in heating load. Moreover, 42 to 67 % of grid electricity consumption can be reduced by using a solar-driven system with a 20 % reduction in variable cost. Thermal photovoltaic seems to be the most viable system due to its low grid electricity consumption. However, the payback period of a PCM system with a flat plate collector is 18.3 years which is much greater than the one without PCM (10.2 years) [138]. In a similar work, the author has used the TRNSYS software to conduct a parametric analysis and optimization of the same building for various indoor temperatures, cost and auxiliary load required for various PCM, the volume of the storage tank, area of collector, and thickness of insulation. The simulation estimated a 65 % reduction in auxiliary load with a PCM layer and the optimum insulation thickness was found to be 0.03 m [139].

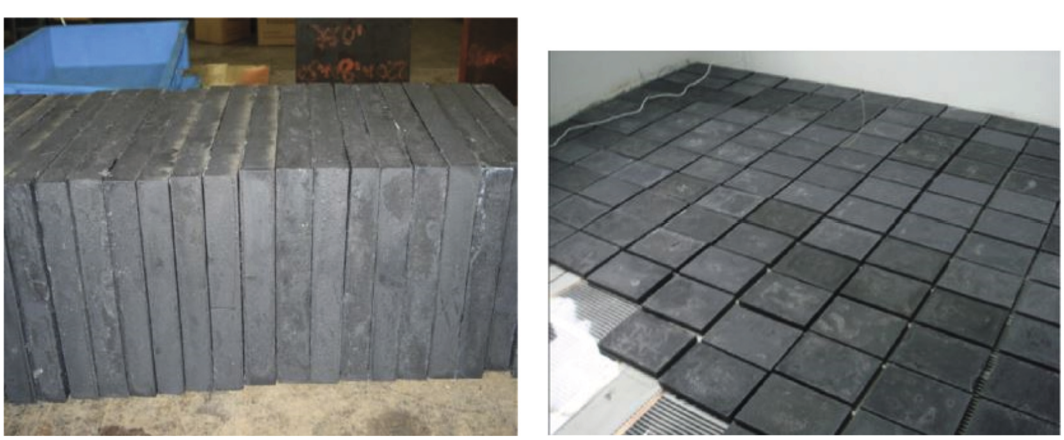
Larwa et al. [140] investigated a hydronic circuit radiant underfloor system integrated with PCM for maintaining the thermal comfort of a lightweight building. The effect of various combinations and positions of S27 and S21 microencapsulated in HDPE on the temperature distribution and heat flux at different locations of the floor and rooms were numerically studied. The experimental and numerical analysis data showed an overheating condition during sunny days due to the combined heating effect of PCM layer and solar radiations. Thus Cesari et al. [141] suggested a weather forecast based control strategy to improve the internal thermal comfort and achieve better energy savings in the same light weight building with the PCM underfloor heating system and evaluated its impact on the energy savings and indoor air temperature using TRNSYS. About 4 % additional energy savings on heating was achieved with the control strategy.

The major studies on PCM integrated radiant underfloor heating systems in recent years are summarised in Table. 3. It gives an overview of the state of the art that has been reviewed, including the information on the PCM used with integration methods and key results. Although a large volume of experimental and numerical studies is available, most of the works focussed on the evaluation of indoor temperature fluctuation, only very few dealt with thermal comfort.

4.1.2. Wall board

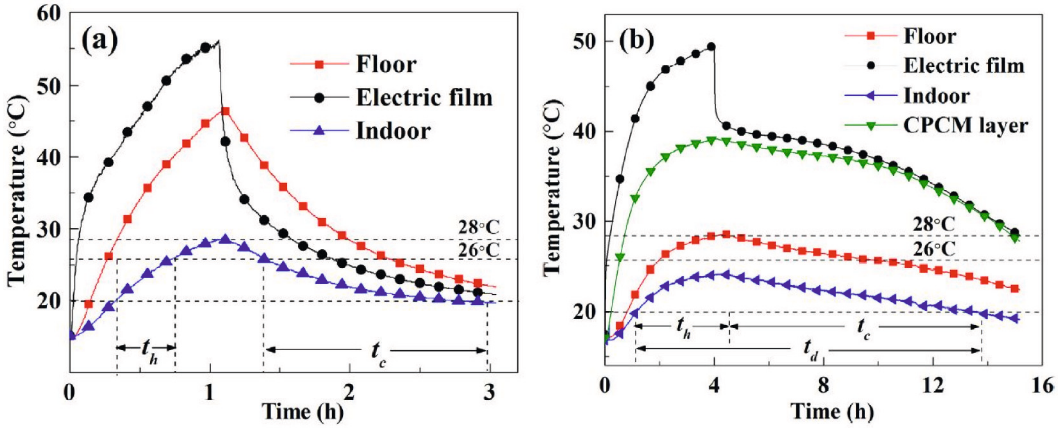
Energy consumption of a building indicates how effective the building envelope is in losing or gaining energy through it. Typically a building will lose 25 % of energy through walls, 30 % by windows, 22 % through the roof and others account for 30 % [154]. PCM integrated building envelopes and wallboards can increase the thermal efficiency and achieve a significant reduction in energy consumption instead of using thicker walls, to save the cost of maintaining thermal comfort [149,155]. PCM wallboards are an easy way to retrofit an existing building to minimise the energy consumption, indoor temperature swing and to enhance thermal comfort. Moreover, it offers better leakage control and saves living and working space without affecting the mechanical strength [146].

Borreguero et al. [142] formulated a mathematical model of one-dimensional heat conduction based on effective heat capacity to study the effect of mass content of PCM on the thermal performance of gypsum walls. A simple experimental setup was designed to validate the simulation result and studied the effect of three mass percentages of microcapsules (0, 4.6, and 6.4 %). The heat was supplied at one side of the gypsum wall to simulate the heat transfer characteristic of the wall under passive heating conditions. To avoid PCM leakage through the shell material and for better installation in walls, Sun et al. [143] proposed and designed a pipe encapsulated PCM system as shown in Fig. 12.



(a) (b)

Fig. 10. (a) The SSPCM modules; (b) The floor unit with electric heating film and SSPCM modules [134].



(a) (b)

Fig. 11. Temperature variation of the radiant floor (a) without PCM layer; (b) with PCM layer [135].

in which the PCM is encapsulated in copper pipes and sealed at both ends. The pipelayer was installed in the wall and investigated the heat flux reduction and time lag for various pipe sizes for various wall depths (pipe location) and the outdoor temperature. They concluded that the PCM pipes should be placed between the middle depth wall and indoor wall for a complete charging and discharging cycle. In a similar study the author has used three five-layer walls, A: with all five layers of extruded poly styrene (XPS) insulation, B: four XPS layers and a cavity integrated sheet at inner surface and C: with four XPS layers and one macro encapsulated PCM sheet at the middle layer and found that a maximum annual average energy savings of 23.1 % were obtained with the PCM at the third layer [144].

Compared to macro/microencapsulated PCM/gypsum wallboard, SSPCM with suitable supporting materials such as EG offers better leakage protection and high heat transfer performance. Biswas et al. [63] evaluated the indoor thermal comfort of a room fitted with novel EG nanosheets PCM integrated gypsum wallboard under US climatic conditions over several months. A 2-D finite element numerical model was developed to study the system extensively for yearly weather data to evaluate the impact of the system on heating and cooling load and found that the system maintained an interior temperature between 20 and 30 °C during summer days and above 18 °C during winter days. Zhou et al. [145] has used a 1-D enthalpy model-based finite difference method to analyse the effect of using SSPCM wallboard on indoor temperature distribution under sinusoidal heat flux outdoor conditions. The results were compared with that of brick, foam concrete and expanded polystyrene and concluded that the PCM wall resulted in larger time lag and lower decremental factor than the other building materials. In a similar study, Zhou et al. [146] performed a numerical simulation of a wall system with exterior and interior PCM walls and evaluated the effect of thermal properties of PCM walls on the inner surface temperature history and storage of diurnal thermal energy. Interior PCM wall with a melting point of 23 °C and latent heat of at least 50 kJ.kg^{-1} would be required for a stable internal temperature history. Zhou et al. [147] studied the performance of a PCM Trombe wall using a TRNSYS model under summer and winter climatic conditions of Wuhan, China and the numerical model was validated with experimental data available from previous literature. The double layer SSPCM Trombe wall model used for the simulation is illustrated in Fig. 13. The double layer PCM system reduced the peak cooling load by 9 % and heating load by 15 %. The optimum phase change temperature of the PCM for the wall was 30 °C for external wall and 18 °C for internal wall.

MPCM integrated geopolymer concrete walls were numerically simulated by Cao et al. [148] in a Norwegian climate using a finite-difference model. The multi-layer PCM wall employed MPCM layers at both exterior and interior with a pure PCM wall and insulation in between. The thickness of the PCM layer and insulation were optimised and found that 28–30 % annual energy reduction can be achieved with up to 32 % in summer and 23 % in winter, respectively. In a similar study using the finite difference model, Li et al. [156] considered a wall built from plaster (2 cm), clay brick (15 cm), and cement (3 cm) with and without PCM layer and optimised the effect of thermophysical properties of thirteen PCMs on the system performance. The.

PCM layer with low thermal conductivity close to the exterior wall controls the heat transfer effectively. A residential dwelling with sunspace employing a PCM wall was modelled and simulated in EnergyPlus software by Vukadinovic et al. [157]. Positions of the PCM in the wall and its relation to the sunspace are well explained in Fig. 14. Three different PCM walls with Q21, Q25, and Q29 PCM were analysed and concluded that among all the three arrangements, the Q29 PCM wall in the middle was the most energy-efficient model for a residential building. In a similar study, Liu et al. [158] investigated the influence of PCM parameters and the thermal resistance of the normal wall on the thermal performance of a lightweight building wall using a 2-D heat transfer model. The numerical simulations were repeated for various phase transition temperatures of PCM and different thermal resistance values of the wall. The results showed that the location of the PCM has more influence on the suitable phase transition temperature than the thermal resistance of the wall. The PCM layer at the middle wall was the best choice for optimum heat absorption and release efficiency.

Active PCM wall systems are designed to utilize solar energy [152] or off-peak electricity [130] to maintain indoor room comfort conditions. Koo et al. [155] performed an experimentally validated simulation to investigate the effect of design parameters such as PCM phase change temperature, heat transfer coefficient, and thickness of the wall on thermal energy stored and time shift. The simulation result indicated that energy stored in the PCM wallboard reaches the maximum when the average room temperature is nearly the same as phase change temperature.

Low-temperature PCM (18–22 °C) wall boards installed in a room with PCM underfloor heating can offer an effective indoor thermal comfort throughout the day. Such a system can maintain indoor thermal comfort during early morning peak hours through the discharge of the underfloor PCM layer and during evening peak hours, through the discharge of PCM wallboards [131,159]. Kuznik and Virgone [149] evaluated the heat transfer characteristic of the MPCM wall in all weather conditions by maintaining the summer climatic conditions using a solar simulator and a 1500 W heater to provide winter ambient conditions. For all tests, the PCM wallboard reduced the vertical temperature variation effectively by enhancing the natural convection.

Table 3
Summary of PCM building integrated heating application studies.

Study	Study type	Heat source	PCM	MP (°C)	PCM incorporation technique	Synthesized/ commercial?	Average_ indoor room temperature_°C	Energy savings (%)	Cost savings $/m^2
Lin et al. [120,123]	Numerical/ Enthalpy model Experimental	Electric	paraffin/ polyethylene	52	Macro encapsulation	Synthesized	31	54	
Li et al. [133]	Numerical/ experimental	Electric	paraffin/HDPE/ wood flour	18.5–25.9	composite matrix/micro encapsulations	Synthesized	20.15	…..	…..
Xia and Zhang et al. [128]	Experimental	Electric	Alcohol Lipids	34–35 19	Double layers of PCM	Synthesized	20	…..	…..
Jin, and Zhang [127]	Numerical/FDM	Electric	Alcohol Lipids	34–35 20	Double layers of PCM	…..	…..	…..	…..
Ansuini et al. [129]	Experimental/ FEA	Electric	RT GR 27/ mineral particle	24–29	shape stabilized	Commercial	…...	…..	….
Cheng et al. [134]	Experiment/ Numerical	Electric	paraffin/ polyethylene/ EG	30.3	shape stabilized	Synthesized	16	66.7	270.83 in 40 years
Zhou and He [121]	Experiment/ Numerical-CFD	Electric/ solar	……………….	29 ± 2	Macro encapsulation	Synthesized	22	…..	….
Barzin et al. [130]	Experimental	Electric	Paraffin Dupont wall	28 21.7	PCM impregnated Gypsum board	Commercial	22	35	44 %
Devaux and Farid [131]	Simulation/ EnergyPlus	Electric	Paraffin Dupont wall/ceiling	28 21.8	PCM impregnated Gypsum board	Commercial	23	32	42 %
Faraj et al. 2019, 2021 [122,132]	Experimental	Electric	Coconut oil	28	In Al container	Synthesized	24	…...	58.90 %
Fang et al. [135]	Experimental	Electric	SAT-Formamide/EG	38.54	Shape stabilized	Synthesized	22	…...	…...
Lu et al. [125]	Experimental	Electric	Paraffin	35.86–39.48	In double pipe	Synthesized	18.9	…...	…...
Entrop et al. [136]	Experimental	Solar passive	Micronal DS	23	Micro encapsulated and mixed with concrete	…...	22	…...	…...
Playtaria et al. ([137]; [138]; [139])	Simulation/ TRNSYS	Solar HP	Q29	29	In metallic container	…...	22.4	40 %	20 %
Borreguero et al. [142]	Numerical/ Experimental	Passive	RT27/ Polystyrene	27	Micro encapsulation	Synthesized	……	……	……
Sun et al. [143]	Experiment	Passive	RT27	27	Encapsulated in Cu pipes	Synthesized	……	32.67 W-hr/m^2	……
Sun et al. [144]	Numerical/ Experimental	Passive	Paraffin/HDPE	27–29	Macro encapsulated	Synthesized	……	23.1	……
Biswas et al. [63]	Numerical-Cosmol/ Experimental	Passive	Paraffin/EG nano sheets	21.1	SSPCM	Synthesized	19–21	……	……
Zhou et al. [145]	Numerical	Passive	……	18–22	SSPCM	……	……	……	……
Zhou et al. [146]	Numerical	Passive	……	20–25	PCM wall board	……	……	……	……
Zhu et al. [147]	Numerical/ TRNSYS	Passive	Paraffin/HDPE/ EG	18	SSPCM	…...	16.13	15	……
Cao et al. [148]	Numerical	Passive	Paraffin/ Melamine-Formaldehyde	21.9	Micro encapsulation	…...	19	28–30	……
Barzin et al. [130]	Experimental	Active/ Underfloor heating	Paraffin Dupont wall	21.7	PCM impregnated Gypsum board	Commercial/ ENERGAIN/ Belgium	22	35	44 %
Devaux and Farid et al. [130]	Simulation/ EnergyPlus	Active/ Underfloor heating	Paraffin Dupont wall	21.7	PCM impregnated Gypsum board	Commercial/ ENERGAIN/ Belgium	23	32	42 %
Kuznik and Virjone [149]	Experiment	Active/ Electric	Paraffin Dupont wall	13.6–23.5	Micro encapsulation	Commercial/ ENERGAIN/ Belgium	23	……	……
Koo et al. [149]	Numerical/ Experimental	Active	Paraffin wall board	26	Micro encapsulation	Commercial/ Knauf/ Germany	……	……	……
Kong et al. [150]	Experiment	Active/Solar	Paraffin/EP	24.5–29.05	SSPCM	Synthesized	23	59.13	……
Kong et al. [151]	Experiment	Active/Solar	Paraffin/EP/Al powder	24.92–29.05	SSPCM	Synthesized	……	44.16	……
Qiao et al. [152]	Numerical/ Experimental	Active/Solar	Paraffin/EP	25.04–27.04	SSPCM	Synthesized	25.52	……	……

(continued on next page)

Table 3 (*continued*)

Study	Study type	Heat source	PCM	MP (°C)	PCM incorporation technique	Synthesized/ commercial?	Average_ indoor room temperature_°C	Energy savings (%)	Cost savings $/m^2
Li et al. [46]	Experimental	Active/solar	MPCM12 MPCM 18 MPCM 29	12 18 29	Micro encapsulation	Synthesized	20	30	……
Li et al. [153]	Numerical	Active	……	16–28	……	…..	18	12.9	46.54
Larwa et al. [140] Caseri et al. [141]	Numerical/ Experimental/ COMSOL/ TRNSYS	Active/HP	S27, S21	27, 21	MEPCM in HDPE	Synthesized	……	……	……

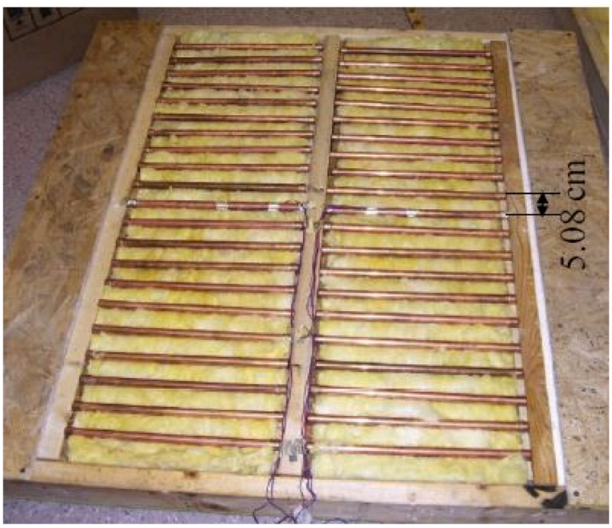


Fig. 12. PCM filled copper pipes fitted into the wooden frame [143].

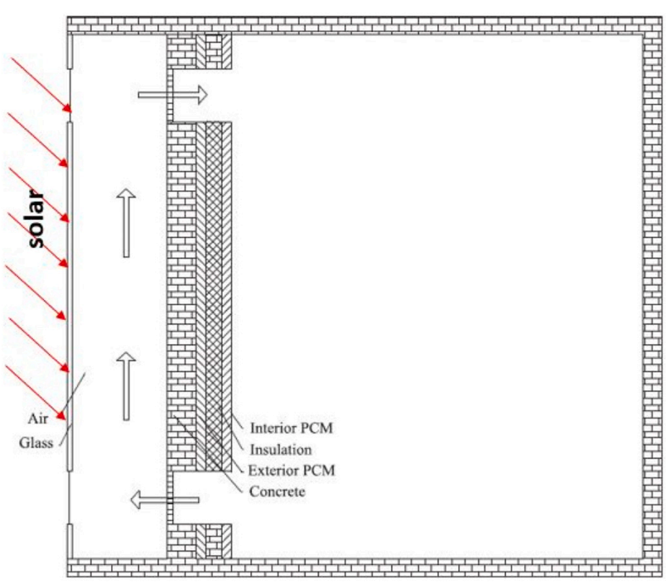


Fig. 13. PCM integrated Trombe wall [147].

Besides, it reduced the overheating of the room compared to the room with the wall without PCM. In a similar study Kong et al. [150] carried out the energetic evaluation of a CPCM wall integrated room when it is heated with a solar collector/PCM exchanger active system and compared with a reference room (with only PCM wallboard). The diurnal and night-time indoor temperature fluctuation of the active system room was less than the reference room, with an energy savings of 57.13 % as shown in Fig. 15. Later in 2020, the author designed an active PCM wall with the same composite as shown in Fig. 16. The system consisted of a series of vertical capillary tubes embedded into the CPCM layer for passing the hot water from the solar collector. The results indicated that the active PCM wallboard presented a reduced indoor temperature swing and 46.16 % reduction in energy consumption compared to the reference room [151].

A numerical simulation of the above work has been performed by Qiao et al. [152] using computational fluid dynamics (CFD) software to optimise the number and position of the capillary tube, the thickness of the composite wall, and hot water temperature for effective energy utilization. The simulation results showed that the system with nine capillary tubes close to the internal surface of the wall of 3 cm thickness with 30 °C water temperature achieved the highest efficiency at an average indoor temperature of 25.25 °C. The feasibility of combining more than one PCM in wallboards was experimentally investigated by Li et al. [46]. Two PCM wallboards were prepared for the study, namely, 1) Mode 1: wallboard in which gypsum and all the three PCMs (MPCM-12, MPCM-18, and MPCM-29) were mixed, 2) Mode 2: PCM wallboard has three layers of PCM i.e., a mixture of gypsum with each PCM separately. The boxes were examined under natural conditions with and without internal heating. The multiple PCM layers could reduce the energy consumption by 30 % while maintaining indoor thermal comfort.

In a similar study with EnergyPlus, Q.Li et al. [153] investigated the reduction in heating energy consumption, carbon emission, and the economic benefits of using PCM walls in north-eastern Chinese rural houses and found that 12.9 % energy savings were achieved for PCM close to the inner surface of the inner wall. Besides, PCM with a 16 °C phase change temperature is optimum for maintaining 18 °C indoor temperature, which resulted in the highest energy saving. Also, compared to a wall without PCM, the south facing PCM wall with suitable PCM can save around $46.54/m^2.

The relevant state of art reviewed on active and passive PCM wall systems for building heating are compiled in Table 1. Only very few studies were available on the active PCM wallboard systems for the building heating compared to passive systems. A PCM wallboard system with an underfloor heating system can maintain indoor thermal comfort throughout the day. Further studies are required to get adequate information on the implementation of the system for all-weather conditions.

4.1.3. PCM selection for building integrated heating applications

PCM integration into building envelopes such as floors and walls are promising methods to reduce energy consumption, curtail indoor temperature swing, and improve thermal comfort in new buildings and retrofitting. This section discusses the important factors to be considered when choosing a PCM for building integrated heating.

1. As per the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) standards 55–2017 for thermal environmental conditions for human occupancy, the indoor temperature should be between 21 and 24 °C in winter and 22–26 °C in

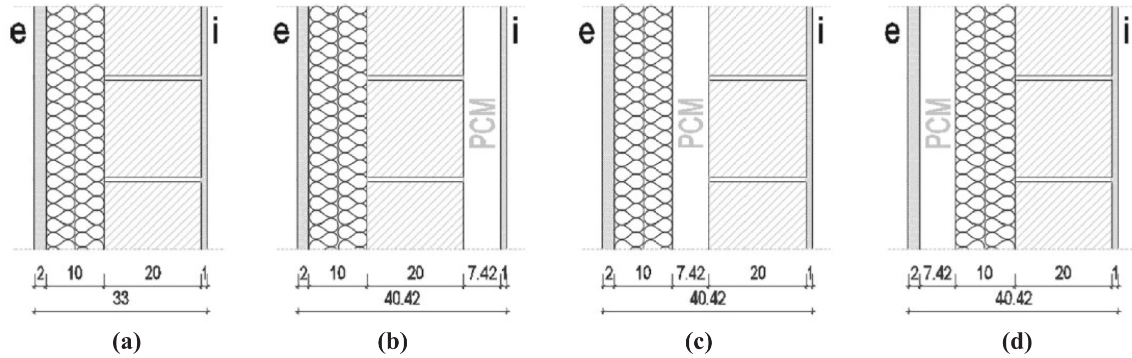


Fig. 14. Position PCM layer between Sunspace and Interior (a) without PCM; (b) PCM on the interior surface; (c) PCM at the middle layer; (d) PCM on the exterior wall surface (e- exterior, i-interior) [157].

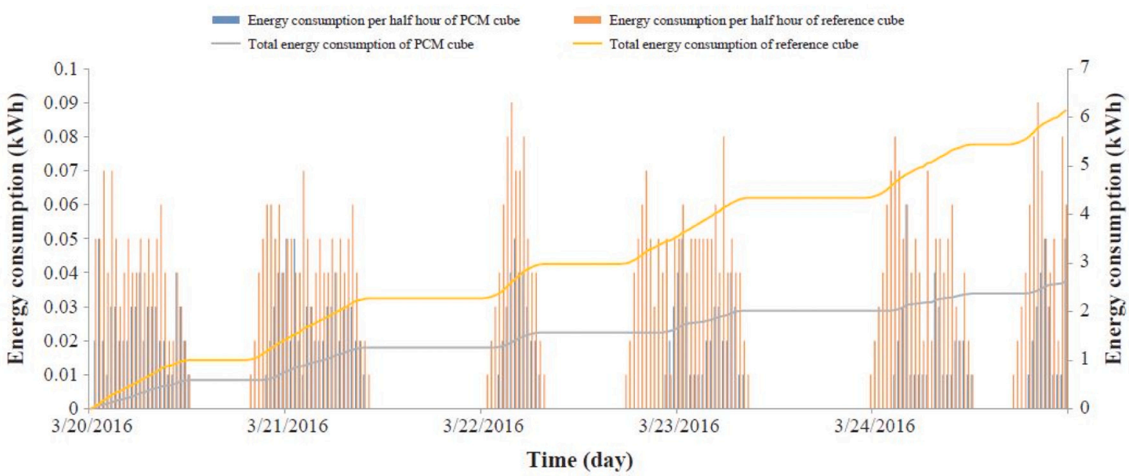


Fig. 15. Comparison of energy consumption between PCM room and reference room [150].

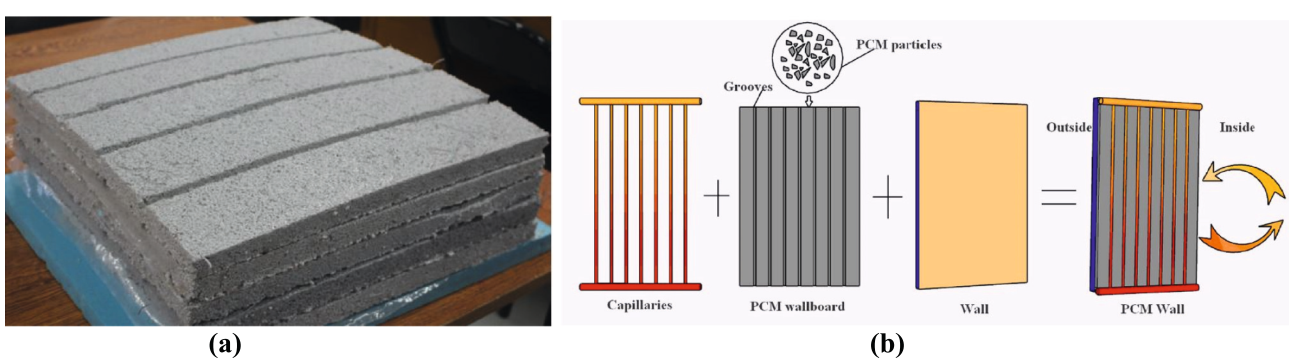


Fig. 16. (a) PCM/expanded pearlite composite wallboard; (b) structure of the active CPCM wallboard with the HTF piping [151].

summer [160,161]. However, the thermal comfort in a building varies with the cultural lifestyle of the occupant, i.e., whether the occupants wear shoes or walk barefoot on the floor or sit on a chair or the floor [162].

2. According to de Dear and Brager's adaptive thermal comfort model, outdoor air temperature should be taken into account when setting the internal thermal comfort conditions [163].
3. According to ASHRAE standards 2017, floor surface temperature between 19 and 29 °C is recommended for occupant comfort (with <10 % discomfort) and maximum allowable vertical temperature variation (between the foot and head) shall not exceed 3 °C (for 5 % dissatisfied occupants). Occupants may feel discomfort if the floor is too warm or cool [160].
4. The thermal comfort of the occupant depends on the floor surface material and to avoid discomfort due to the contact with uneven floor surface temperature, the difference between the maximum and minimum floor surface temperature should be as minimum as possible. Moreover, the maximum surface temperature should be controlled to avoid unwanted material deformations [160–162].
5. Fig. 17 displayed the melting point ranges of PCM used by various researchers for building heating applications. It can be concluded from Table. 3 and Fig. 17 that most of the researchers used PCM

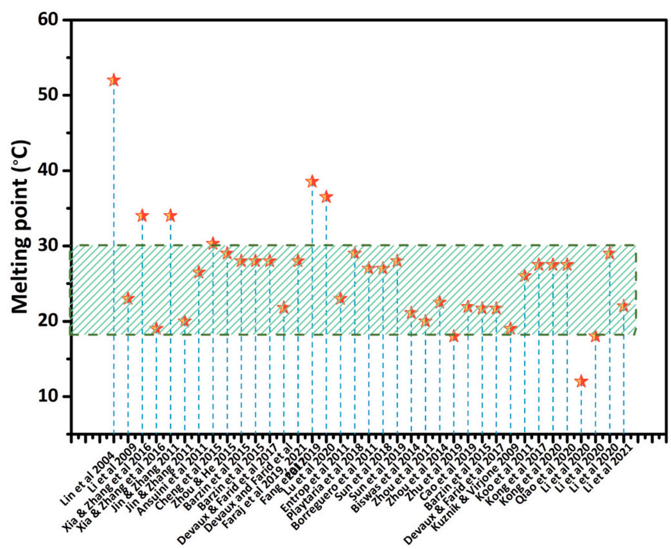


Fig. 17. Melting point range of PCM used by various researchers for the building integrated heating systems.

having melting points in the range of 18–30 °C and controlled the indoor temperature swing effectively. Whereas, from Fig. 18 it can be deduced that the use of high melting point PCM (MP = 52 °C) results in the indoor temperature above the comfort level [123].

6. For PCM wallboards with an underfloor heating system, PCM with a melting point in the range 18–23 are optimum to maintain thermal comfort throughout the day [130,131].

Based on the study conducted, a database of the commercially available potential PCMs for radiant underfloor and wall heating system integration has been created and is included in Table A.1 of Appendix A.

4.2. PCM applications in DHW production applications

Sanitary hot water is essential for daily life domestic applications and its demand is met by oil, gas, or electric heaters sometimes in conjunction with HWT. DHW tanks are simple, easy to install, and affordable for all classes of society. However, it occupies space, uses more energy to maintain a set point, and possesses relatively high standing energy losses

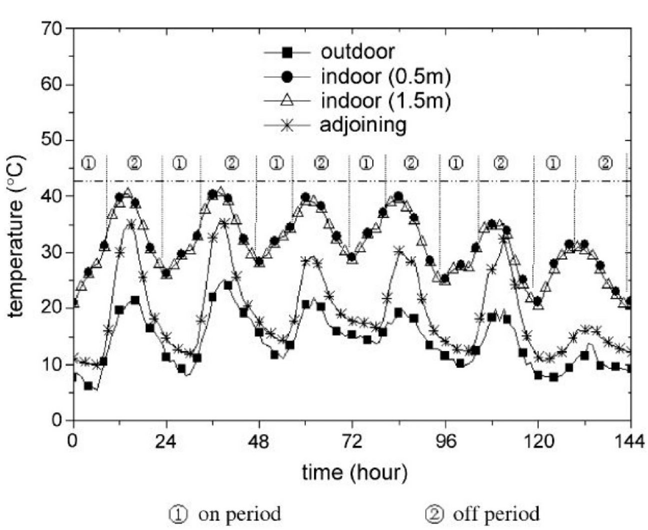


Fig. 18. Variation of indoor air temperature with electric heating during the night [123].

as it requires high storage temperatures [19,164]. Two main approaches have been followed for the PCM application in DHW production, particularly the integration of PCM modules into the HWTs and developing full-scale LHTES units [3,165,166].

4.2.1. PCM in DHW tanks

Integrating PCM modules into the hot water vessels is the most common method of PCM application in DHW production and has been widely investigated experimentally and numerically. Adding PCM modules to the top layer of the hot water storage vessel enhances the stratification effect and it maintains the upper layer hot for longer periods. Moreover, it increases the energy storage density and the hot water availability period through the efficient reheating of the water in the top layer [167,168].

Mehling et al. [168] integrated a single PCM module, of 6 % of the total volume, of the HWT at the top layer of the hot water and investigated the improvement in energy storage density and duration of hot water delivery. PCM-graphite composite with improved thermal conductivity was used in the experimental study and observed that the PCM module could hold the top layer warm from 50 % to 200 % longer with an average energy density enhancement of up to 45 %. Cabeza et al. [167] modified this system by introducing several PCM modules instead of a large single module as shown in Fig. 19. 2 to 6 SAT/10 wt% EG composite modules were used in the pilot plant system and obtained a 67.7 % increase in energy density with six modules (6.16 % of total volume) of PCM and an extra 48-min hot water delivery (36–38 °C).

Mazman et al. [169] investigated the feasibility of three different mixtures of paraffin with palmitic acid, stearic acid, and myristic acid in a DHW tank using the same configuration as Cabeza et al. [167]. The experimental results demonstrated that 3 kg of PCM could increase 14-36 L of top layer water temperature by 3–4 °C in 10–15 min after it is cooled below the utilization temperature during discharge. A combination of macro encapsulated PCM/water sensible and latent hybrid TES systems for DHW applications was developed by Frazzica et al. [165]. Two different PCMs, namely, RT65 and a mixture of salt hydrates PCM58 encapsulated in a parallel-piped polymeric capsule were employed as shown in Fig. 20. The charging and discharging performance of a HWT and PCM integrated HWT was carried out under real user conditions and achieved a 10 % increase in hot water supply with 1.3 dm^3 of PCM58. Whereas nearly double the volume of RT65 is required to achieve the same extended hot water supply.

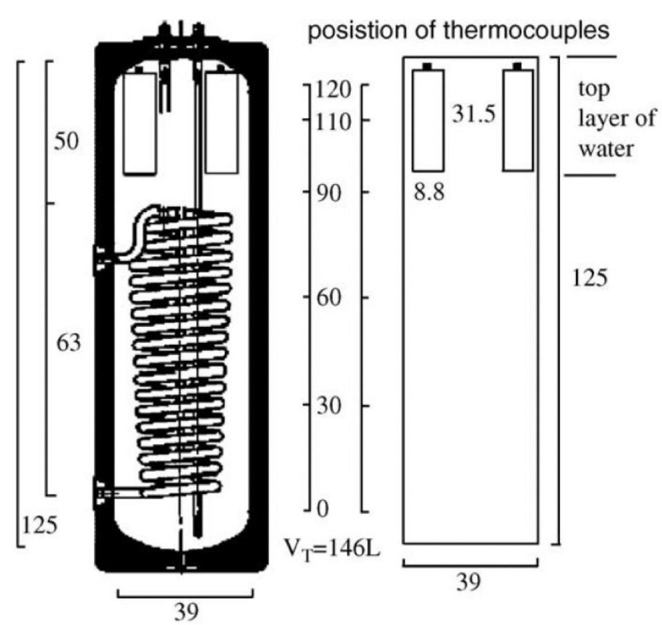
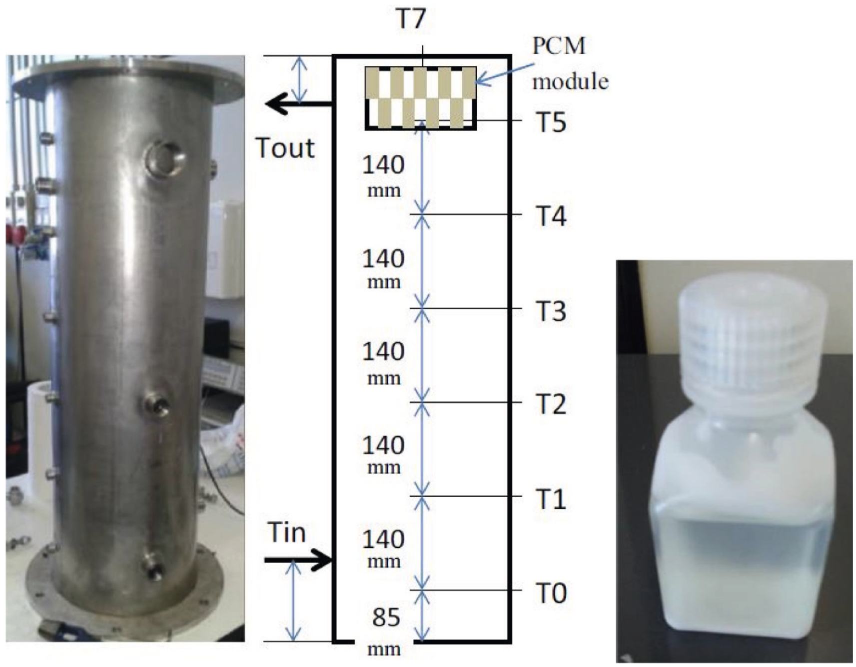


Fig. 19. HWT with multiple PCM modules [167].

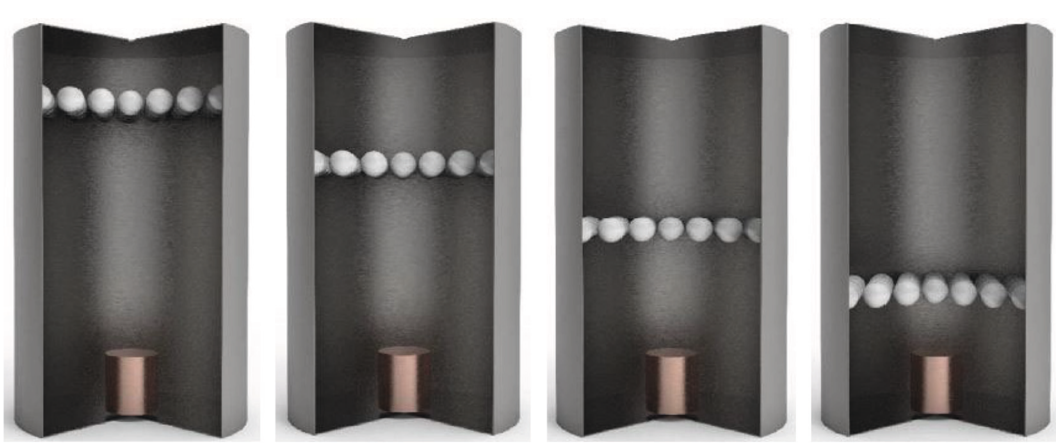


a b

Fig. 20. (a) Vertical HWT with PCM layer at the top; (b) Macro capsules of PCM employed in the HWT [165].

In a similar study, Navarro et al. [86] introduced encapsulated paraffin in high-density polyethylene spheres within a DHW tank and studied the stratification for two different masses (10.5 and 21 kg) of PCM ball layers. It was concluded from the results that 21 kg of PCM layer resulted in a 33 % increment in storage density with an extended hot water delivery period of 493 min. A problem with these spheres was that the PCM leaked from them into the water. Huang et al. [170] has studied the effect of PCM layer positions on the thermal stratification and investigated the temperature variation of the hot water at different locations during the discharge process for different flow rates by employing 13 SAT balls at four different locations from the top to bottom as shown in Fig. 21 and optimised the location of PCM layer for better stratification and utilization efficiency. For the same inlet flow rate, better thermal stratification was observed for the PCM layer close to the inlet (at the bottom of the tank). Additionally, the tank without PCM showed better stratification than the one with PCM at locations 1, 2, and 3 from top to bottom. The stratification effect was weakened with an increased flow rate due to the rapid mixing of cold and hot water. To reduce the intensity of cold-hot water mixing, Wang et al. [171] employed a three-layer equalizer at the bottom of the HWT. The three-layer equalizer displayed in Fig. 22 ensures the weak mixing of cold and hot water and observed that the equalizer not only improves stratification but also stabilizes the heat output of the water tank.

Dhaou et al. [172] proposed a novel design configuration of a solar HWT integrated with nano-enhanced PCM cylindrical capsules and a mechanical stirrer to enhance the charging and discharging process. Copper nano particle enhanced paraffin wax macro capsules of 8 mm diameter and 120 mm height were inserted into the tank. 24 such cylindrical capsules were employed for the study. With the stirrer, the total charging and discharging time was reduced by 12.5 % and 23.51 % compared to the HWT without a stirrer. In a similar study, Kozelj et al. [173] introduced macro encapsulated paraffin into a 210-l HWT and



a b c d

Fig. 21. Distribution of SAT balls in tank; (a) PCM layer at 500 mm from bottom; (b) 400 mm from bottom; (c) 300 mm from bottom; (d) 200 mm from bottom [170,171].

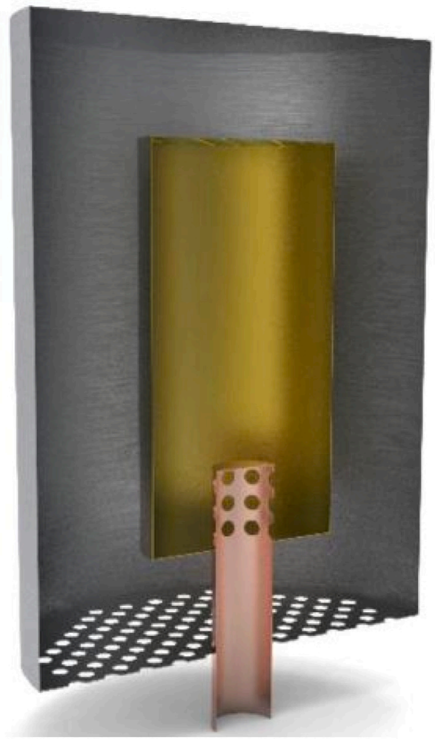


Fig. 22. Design model of Equalizer with passage for cold water [171].

compared the increase in energy storage density with a conventional HWT. With 15 % PCM addition, 70 % more energy was stored inside the tank. A similar study was conducted by Erdemir et al. [174] to investigate the effect of the volume of the PCM module on the hot water output and observed a 20 % increase in hot water output with 13 paraffin macro capsules of 5-l capacity. The charging characteristics of a 200 L hybrid modular water tank with rectangular PCM modules immersed are numerically investigated by Abdelsalam et al. [175] using 2-D CFX simulations. The volume fraction of PCM and spacing between the PCM modules on the heat transfer characteristics and charging rate were studied and compared with a HWT without PCM. The simulation results showed an 85 % increase in charging rate when PCM volume fraction was increased from 0.025 to 0.15, beyond that the charging rate remains constant. The gap between PCM modules did not have a significant effect on heat transfer performance if the thermal boundary layer did not interfere. To increase the energy storage density of the DHW tank, Zou et al. [176] filled the annular space between the outer wall of a DHW tank and the steel casing with RT44HC, and fins were welded on the outer wall of the tank to increase the heat transfer. The tank was then connected to an air source heat pump (ASHP) system in which the condenser coil passes through the PCM cavity around the tank as shown in Fig. 23. The heat storage capacity has increased by 14 % and the hot water production efficiency was improved with a 13 % reduction in operation time.

Table. 4. sums up the details of the review conducted on PCM application in DHW tanks, which demonstrates that the application of PCM modules into DHW tanks is a promising method to enhance the thermal stratification, increase the hot water availability period, and reduce the size of the tank. PCM addition in the upper layer helped in reheating the water which is critical in maintaining the hot water availability for a longer period. However, the position and amount of PCM must be optimised.

4.2.2. LHTES units for DHW

LHTES units are promising alternatives for large bulky DHW tanks and tanks integrated with PCM modules. They can possess high storage densities, save space, better utilization efficiency, and lower energy loss. In recent years, the number of research activities aiming to develop an efficient thermal store has increased substantially and industries are investing in the energy storage sector by collaborating with universities worldwide [166,189]. LHTES units can be integrated with solar collectors or with an HP for effective demand-side management [190]. An HP integrated with an LHTES unit is a future alternative for gas boilers and large HWT in reducing the CO_2 emission and yearly energy consumption when it is operating in Economy 10 tariff [191,192].

Long and Zhu [164] have developed a heat pump system in which a finned LHTES unit act as the condenser to utilize the off-peak electricity for DHW application as shown in Fig. 24. The system performance is numerically evaluated using pure conduction formulation and analysed the temperature variation and phase front transition of the PCM store. It was concluded that both experimental and numerical results were in good agreement and the coefficient of performance (COP) of the ASHP exceeded 3.08 with the LHTES condenser.

Agyenim and Hewitt [71] investigated a horizontal finned tube latent heat TES unit with 93 kg of RT58 to utilize the off-peak electricity price variation and the feasibility of this thermal store with a HP radiator system is discussed. The charging and discharging characteristics were analysed for various inlet temperatures and mass flow rates of HTF. The

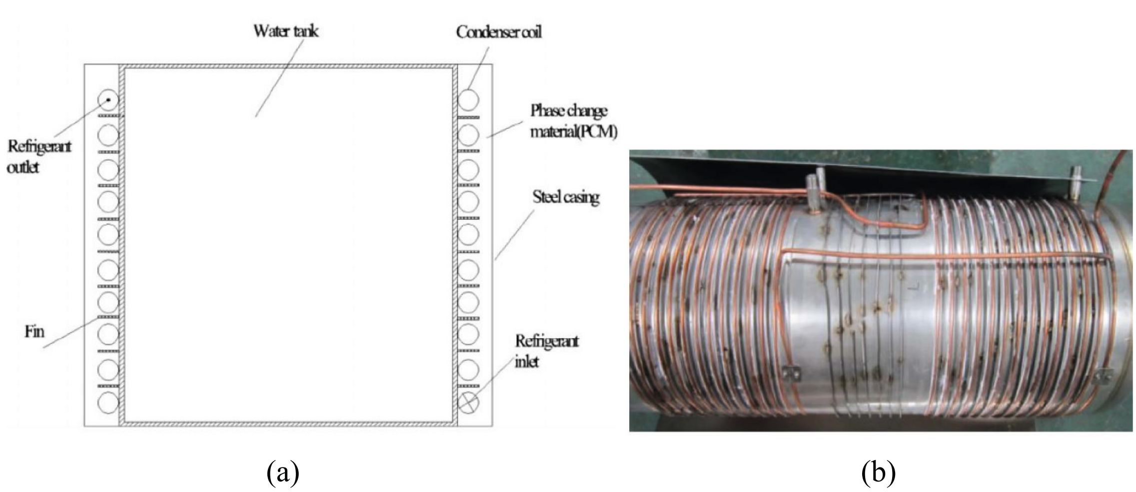


Fig. 23. (a) Schematic diagram of the HWT with PCM and condenser coil in the annular space between the water tank surface and the steel casing (b)Image of the water tank with the condenser coil [176].

Table 4
Summary of PCM application in DHW production studies reviewed, where, KCL: Potassium Chloride, CMC: DSP:

Study	Study Type	Mode of PCM integration	Heat Source	PCM	MP (°C)	PCM Incorporation Technique	Quantity of PCM	Total volume_m^3	Extended hot water period	Increase in energy density	Reduction in size with respect to HWT	Total energy stored	Useful energy released
Mehling et al. [168]	Numerical/ Experimental		Solar	RT50	54	RT50/graphite composite	6 %	0.0377	50–200 %	20–45 %	……	……	……
Cabeza et al. [167]	Experimental		Solar	SAT	58	SAT/10 wt% graphite composite	6.16 %	0.146	45 min	66.70 %	……	……	……
Mazman et al. [169]	Experimental		Solar	Paraffin/Palmitic acid Paraffin/ Stearic acid Paraffin/Myristic acid	49–53 48–52 61–65	PCM/10 wt% extended graphite	2 %	0.15	10-15 min	……	……	……	……
Frazzica et al. [165]	Experimental/ Numerical		Electric	RT65 PCM58	65.8 57.7	Macro encapsulated in polymeric shell	2.67 %	0.0486	10 %	……	……	……	……
Nevarro et al. [177]	Experimental	HWT	Solar	A58	58	Macro encapsulated in HDPE shell	19.20 %	0.12	40.70 %	33 %	……	8.124kWh	……
Huang et al. [170], Wang et al. [171]	Experimental/ Numerical		Solar	SAT	58–61	Macro encapsulated in PVC shell	7 %	0.06	……	……	……	5.372kWh	……
Dhaou et al. [172]	Experimental		Electric	Paraffin	52	Cu nano particle/ MEPCM	12 %	……	……	……	……	……	……
Kozelj et al. [173]	Experimental		Electric/HP	Paraffin	27	Macro encapsulated in polyethylene bottles	15 %	0.28	……	70 %	……	4.05kWh	……
Erdemir et al. [174]	Experimental	HWT	Electric	Paraffin	58–60	Macro encapsulation	15 %	0.45	20 %	……	……	……	……
Abdelsalam et al. [175]	Numerical		–	Lauric acid	45	PCM modules submerged water tank	……	0.2	……	……	……	……	……
Zou et al. [64]	Experimental		Electric/ ASHP	RT44HC	43	PCM filled annular cavity as condenser of HP	6 %	0.138	……	14 %	……	6.44kWh	……
Long and Zhu [164]	Experimental/ Numerical		ASHP	n-Tetracosane	56.03	Finned LHTES unit	……	……	……	……	……	……	3.08kWh
Agyenim and Hewitt [71]	Experimental/ Numerical		ASHP	RT58	58	TES unit with longitudinal fins	93 kg	0.128	……	……	30 %	5.58 kWh	52 %
Khan and Khan [178]	Experimental		Solar	RT44HC	41–44	Vertical multi-pass LHTES unit with longitudinal fins	40	0.0607	……	……	……	3.988 kWh	……
Fadl and Eames [179]	Experimental	LHTES	Electric	RT44HC	41–45	Multi-pass Cu tube heat exchanger	80	0.12	……	……	……	7.8kWh	……
Li et al. [203] Zhao et al. [180]	Experimental		Electric	Modified SAT	57.73	Finned tube heat exchanger	……	0.0977 2.09	……	2.5 times	……	7kWh 1.998MWh	6.8kWh 1.935MWh
Xu et al. [181,182]	Experimental/ Numerical		HP	Climsel C48	44–53	PCM macro encapsulated in cylindrical tubes	154 kg	0.38	……	……	……	12.8kWh	……

(*continued on next page*)

Table 4 (*continued*)

Study	Study Type	Mode of PCM integration	Heat Source	PCM	MP (°C)	PCM Incorporation Technique	Quantity of PCM	Total volume_m^3	Extended hot water period	Increase in energy density	Reduction in size with respect to HWT	Total energy stored	Useful energy released
Fang et al. [183]	Experimental		–	High carbon paraffin	50–60	micro encapsulated PCM	……	0.0023	……	……	……	……	……
Dogkas et al. [184]	Experimental		Solar/ geothermal HP	A53 A58H	53 58	Staggered finned LHTES unit	94.24 kg 93.95 kg	0.685	……	……	……	10.4 kWh 11 kWh	6.1kWh 8.5kWh
Shalabay et al. [185]	Experimental		Solar	Paraffin wax	60	Finned heat exchanger	50 kg	0.182	……	……	……	……	52 %
Wu et al. [186]	Experimental		ASHP	Paraffin wax	52–54	PCM/25wt%EG Composite unit	……	0.016	……	……	……	……	37.8 L of 40 °C water
Lin et al. [187]	Experimental/ Numerical	LHTES	ASHP	Paraffin wax	50.87	PCM/EG composite	……	0.1809	……	……	……	3.75 kWh	……
Jin et al. [188]	Experimental		Solar HP	SAT	47.8	Modified SAT with KCl, DSP. CMC and Urea	9 kg	0.0374	……	……	21 %	2.194 kWh	……

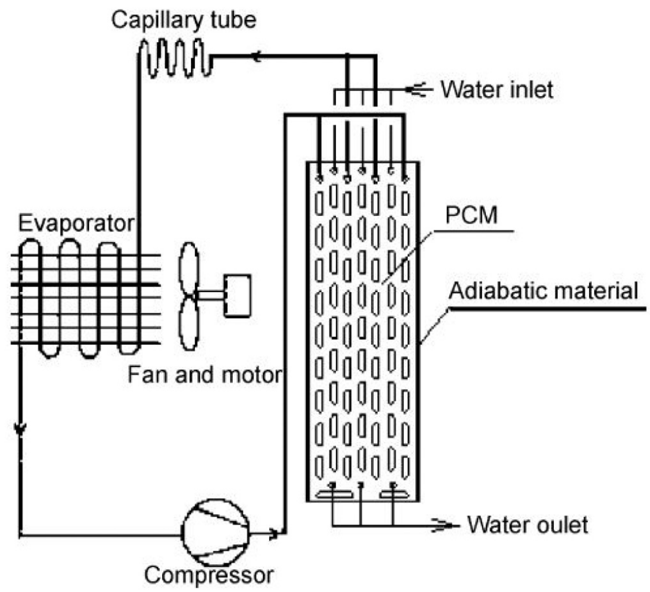


Fig. 24. ASHP system with PCM TES unit condenser [164].

result of the analysis demonstrated that 52 % of maximum energy stored was available for heating after 7 h of charging, owing to the low thermal conductivity of the PCM, and concluded that improving the heat transfer rates during charging and discharging the store size can be reduced by 30 %. In an identical study, Khan et al. [77] developed a novel vertical shell and tube LHTES unit to utilize the solar energy available and optimised the fin geometric parameters for maximum heat transfer. The experimental study has been carried out to evaluate the heat transfer rate and temperature profile of RT44HC during charging [178] and discharging [193] for different operational parameters. The unit stored 14.36 MJ of thermal energy in 3.12 h when charged at an inlet temperature of 62 °C and 12 MJ of stored energy was discharged with 10 °C inlet temperature in 1.5 h. Fadl and Eames [179] also observed a similar trend in charging and discharging rates with mass flow rates and inlet temperature of HTF when a novel LHTES unit with RT44HC was investigated for solar hot water application. Li et al. [203] has prepared a high-performance salt hydrate based PCM by modifying the SAT to overcome its phase separation and supercooling, and a LHTES unit of 7 kWh capacity has been developed for domestic heating application according to the end users' demand. The modified SAT storage unit used for the study is shown in Fig. 25(a). The storage unit was charged with an electric boiler set at 65 °C, and for discharging the unit two protocols were followed, one with city water for DHW application and in the second mode, the storage unit was directly connected to a space heating radiator and circulation pump for space heating. 6.48–6.81 kWh of storage capacity was achieved with the LHTES unit, which is 2.5 times higher than the conventional HWT. The heating power of the hot water supply was around 10.3–18.6 kW, and the system could heat the indoor air to 16–19.5 °C when the ambient temperature is between 5 and 10 °C as illustrated in Fig. 25(b). This work has been extended to a distributed building heating level by Zhao et al. [180] and performed a multilevel approach, which includes i) preparation, characterization, life cycle assessment, and market price study of industrial-grade SAT ii) design and fabrication of 120 kWh a storage unit and testing it, and finally iii) integration of several such units with an electric boiler and its techno-economic analysis. The distributed building heating system with 17 storage units provided nearly half of the heat required to meet the total demand with an operational cost of 0.371 RMB (5.2 US cents) per kWh. In a similar study, Lee et al. [194] investigated the load shifting capability of a 244.8Mcal PCM TES unit in a district heating network to meet the daily hot water demand of >126 homes in South Korea. Three PCM units of 1200 kg PCM each was connected in parallel to get the required

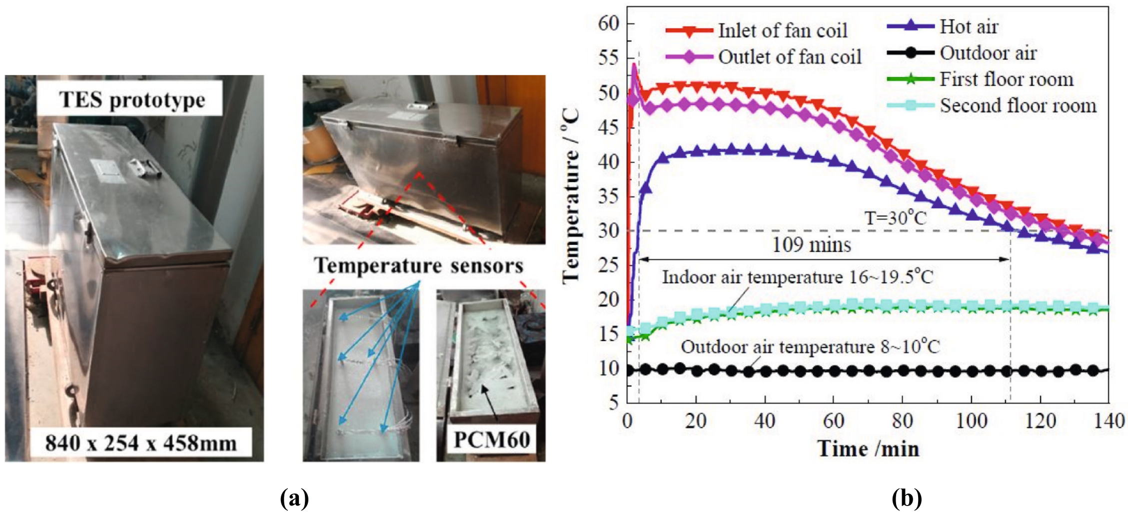


Fig. 25. (a) Modified SAT LHTES unit; (b) Thermal performance of TES unit for space heating @10 L/min [203].

heat capacity. During the off-peak period the TES units were charged with the hot water from Korea District Heating Company, and this charged energy was used for the peak hot water hours from 6.00 to 9.00 am and 19.00–23.00 pm. The average demand response time for the daily peak load was approximately 2.1 h. The total heat flow and its deviation with PCM TES units were lower than that without PCM TES units.

Xu et al. [181,182] developed a large-scale LHTES unit with cylindrically macro-encapsulated Climsel C48 and investigated its suitability for space heating application numerically and experimentally. Both horizontal and vertical orientation of the LHTES units were compared for different HTF mass flow rates and inlet temperatures. 154 kg of PCM was used in the unit with a total energy storage density of 30 kWh/m^3. The results showed that, though both orientations reduced the charging and discharging time of the storage unit, vertical orientation reduced it by 20 %, and due to the phase separation, the thermal storage capacity of the system was reduced by 8.2 % in the vertical orientation. Fang et al. [183] studied the thermal response and energy storage performance of MEPCM based LHTES unit for the DHW application. MEPCM and carbon fibres are glued together using epoxy resins to a solid half-cylinder storage unit and to avoid the contact resistance between the HTF pipes and the PCM, thermal conductive silicon was used. Each TES unit consists of four half cylinders which can be assembled into one large cylinder and studied the effect of mass fraction of MEPCM particles in TES unit, mass fraction of PCM in each particle, and the mass fraction of carbon fibre on the system performance and observed that the latent heat can be fully retrieved from the TES unit effectively during the consecutive charging-discharging cycle. Dogkas et al. [184] designed and fabricated an TES unit with a staggered finned heat exchanger immersed in A53 and A58 PCM and studied the thermal performance of the system when it is connected to a solar collector or a geothermal heat pump. The TES unit consists of three circuits, one for charging with solar thermal, the second is for charging with HP, and the third one for discharging. Charging and subsequent discharging of the thermal store were performed to evaluate the PCM store temperature, energy stored, and the amount of hot water available at 40 °C and obtained 164 l of 40 °C hot water at 12 lit/min flow rate. Shalaby et al. [185] developed a fin and tube LHTES unit to overcome the low thermal conductivity offered by paraffin wax, where the PCM core is divided into ten slices by the heat exchanger. A water tank, PCM unit, and a combination of both were tested with a FPSWH having a 2.37 m^2 collecting area. The PCM/water tank system attained the highest daily efficiency of 65 % among the studied systems with 50–60.4 °C hot water availability 24 h/day. Jin et al. [188] investigated the compatibility of a modified SAT based LHTES unit with solar HP and evaluated the performance of the LHTES unit when it is operated with a solar collector, solar HP and dual source. Fig. 26. illustrates the system designed for the study. The energy storage unit developed consists of macro encapsulated PCM in 18 cylindrical tubes and the HTF passes through the shell side. The storage unit had an energy storage density of 211.13 MJ/m3 and 1.81 to 1.94 kWh of energy was recovered during the discharging process. There was 57.5 % improvement in average efficiency of the coupled solar heat pump system compared to HP alone system.

In discharging the material around the HTF tube solidifies first and as the discharging continues the thickness of the solid PCM increases and the effect is equivalent to increasing the thermal resistance applied to the extraction of the remaining energy. Egea et al. [195] designed a novel concentric tube heat exchanger with scraper blades to remove the solidified PCM layer from the HTF wall to enhance the discharging process. Four sets of scraper blades were employed for the present study as shown in Fig. 27. All four sets of blades are attached to the central shaft, which can be rotated with an external motor. The scraper blade effectively removed solidified PCM layer from the inner wall and the latent heat was completely extracted in a short time compared to the TES unit without the blades. Besides, the heat release rate was two to three times higher than the system without scraper blades.

Along with the novel heat exchanger designs, researchers have devised LHTES units with various thermal conductivity enhancement

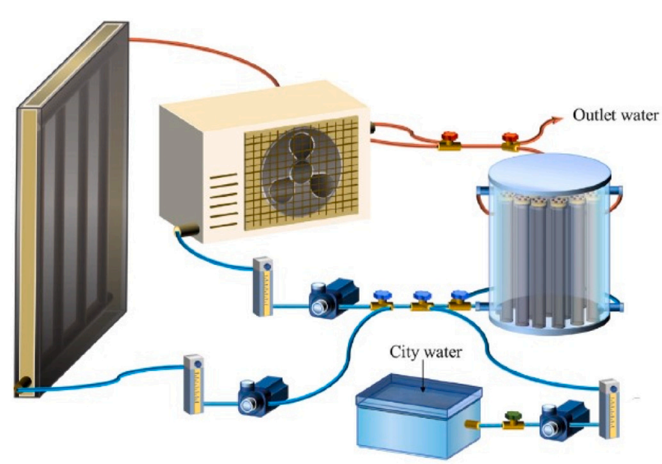


Fig. 26. The schematic diagram of the solar heat pump LHTES unit system configuration [188].

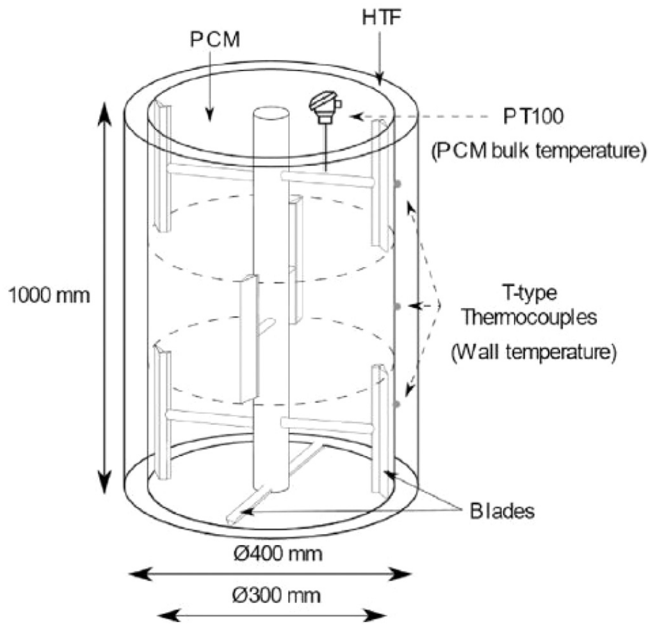


Fig. 27. Schematic diagram of the novel scrapped blade concentric tube heat exchanger [195].

techniques such as PCM/EG and PCM/metal foam TES unit for DHW applications. Meng and Zhang [100] fabricated a LHTES unit using paraffin infiltrated Cu foam and investigated its thermal performance experimentally and numerically. Fig. 28. depicts the paraffin/Cu foam TES unit developed for the study. A three-dimensional enthalpy-porosity model is developed to study the heat transfer mechanism of the TES unit. The dependence of heat transfer rate on inlet temperature and mass flow rates of HTF showed a usual trend. A large storage capacity system can be realized by assembling several small units so that it can meet the domestic heating demand. Wu et al. [186] developed a paraffin/EG composite LHTES unit to replace the conventional HWT and investigated its feasibility as a condenser in the instantaneous ASHP. Four PCM modules were stacked to get the required capacity and the structure of the system is shown in Fig. 29. The volume expansion and the temperature distribution studies revealed that for different values of inlet flow rates, there was an expansion of 6.25 wt% at 73.5 °C. 47.1 l of hot water at 40 °C was available when discharged at a flow rate of 0.5 L·min^{-1}. With five 16 L TES units in parallel the discharge flow rate can reach 6 kg.min^{-1}, which shows the potential of the system over the conventional water tanks.

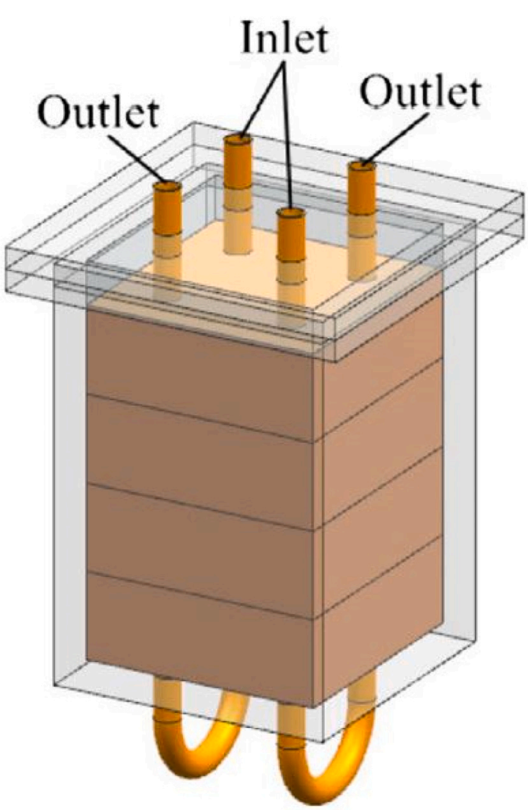


Fig. 28. Schematic representation of the paraffin/Cu foam TES unit [100].

Lin et al. [187] designed and fabricated a novel TES unit with paraffin/EG CPCM in annular tubes, and two flow systems in shell side and runner tubes of a shell and tube system as detailed in Fig. 30. The thermal performance of the system was studied experimentally and numerically and found that around 7.5 to 13.5 MJ of energy was stored during the charging process, of which 7 to 10.1 MJ of energy was recovered.

Table 4. summarises the key results of the extensive review conducted on LHTES units for DHW application. Most of the research works focussed on the development of a laboratory-scale TES unit and studied the effect of operational parameters and system design on charging and discharging characteristics of the system. The laboratory-scale studies with various LHTES units showed promising energy savings and cost-saving potential. However, long-term economic benefits and thermal performances should be studied.

4.2.3. PCM selection for DHW application

LHTES units and HWTs with PCM modules are being widely investigated for effective demand-side management in the domestic sector. The choice of PCM and the system design play vital roles in developing an efficient storage unit. Before using a random PCM, it is important to carefully analyse and compare the thermophysical properties of the PCM available in the market. This section summarises the details of commercially available PCM for the DHW application in Table. A.2. (appendix) based on the comprehensive review performed in the previous sections and the important points to be followed to sort the PCM.

- ➢ As per British standards (BS) 8558:2015 [196] and European working group for legionella infection (EWGLI) Technical Guidelines 2011 [197], to ensure effective Legionella bacteria management in the building sector, the hot water stored should be stored at or above 60 °C and the temperature of the distributed water should not be <55 °C [198,199].

Fig. 29. Image of the paraffin/EG TES unit for instantaneous hot water production [186].

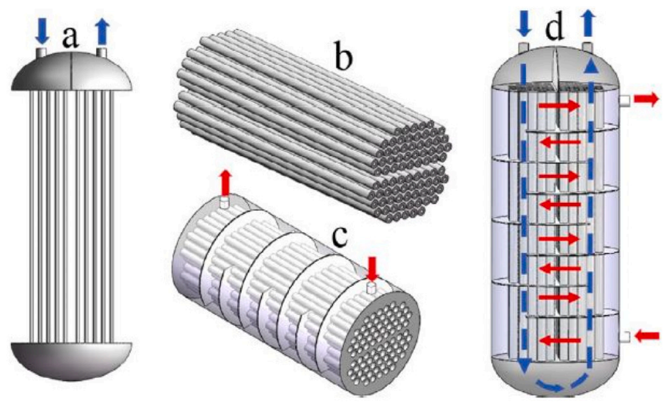


Fig. 30. Structure of the TES unit (a) inside tube runner; (b) annular tubes; (c) shell side; (d) flow direction [187].

- ➢ The temperature of supply water to any thermostatic valve should be at least 50 °C from the hot water delivery line [200,201].
- ➢ Since the quantity of water stored in LHTES units is less compared to large HWTs, the risk of Legionella bacteria is significantly reduced. Therefore, the PCM storage temperature can be less than that required for the hot water vessels. But it should be able to maintain the hot water temperature at the thermostatic mixing valve [202].
- ➢ To meet the above criteria and the European Union and UK standards, PCM with phase change temperature in the range 55–70 °C are recommended for PCM addition in the HWT and 50–70 for developing a PCM energy storage unit [62,167,169]. Fig. 31 presents the range of melting points of PCM commonly used by researchers in DHW applications. It is clear from Fig. 31 that, most of the researchers have used PCM with a melting point above 50 °C for DHW applications and obtained satisfactory results in terms of the extended period of useful hot water (Table. 4).

Based on the study conducted the commercial PCM for DHW application are listed in Table. A.2 in Appendix A.

5. Challenges and future scope

The PCM is a potential candidate for reducing building energy consumption and building heating decarbonisation. The following

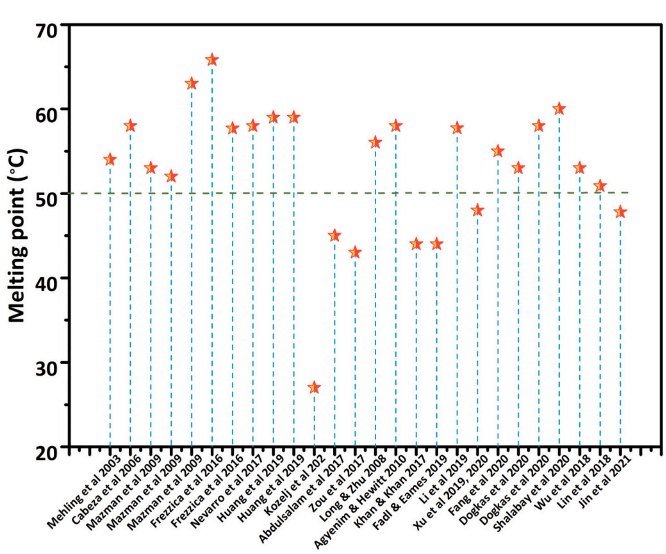


Fig. 31. Range of melting points of PCM used by researchers in DHW applications.

challenges require further research for the effective integration of PCM into the above-discussed applications.

- ➢ Paraffin-based PCM is the most investigated and commercially available type of PCM. However, the low heat transfer kinetics of the organic PCM requires a permanent and effective solution.
- ➢ Most organic PCM are highly flammable. There has been an increase in regulatory oversight and public concern since the Grenfell fire (in London) concerning the use of organic materials in construction and building systems. Irrespective of the excellent characteristics of organic PCMs, solutions for effective containment in the event of fire may be required when utilising such materials in buildings.
- ➢ A large degree of supercooling, phase separation, and corrosive nature of the salt hydrate PCM limits their application irrespective of their good thermal conductivity and high energy storage density. More research should be carried out to develop an effective salt hydrate based PCM.
- ➢ long term thermal cycle stability of most of the PCM is always a concern. This has implications where the material is buried/combined with construction material, less so if the PCM is in a module that can be easily replaced.
- ➢ Cost of nanomaterial, instability, and sedimentation due to density difference are the limiting factors of nano enhanced PCM.
- ➢ The complex preparation methods, associated cost, and leakage of PCM from the shell over many thermal cycles hamper the widespread application of micro and nanoencapsulation.
- ➢ PCM/EG or similar composites have high thermal performance in small-scale systems, and significantly control the volume expansion of the PCM. However, the details of the long-term effect of such composites in real-time practical systems are not well studied.
- ➢ A combination of various heat transfer enhancement methods such as fins/nanoparticles, fins/encapsulation, fins/porous materials, etc., must be investigated so that shortcomings of using a single method can be avoided.
- ➢ Although a large volume of research articles is available on experimental and numerical studies on PCM underfloor and wallboard systems, most of the works are limited to laboratory scale, with very few focused on real-life scenarios. Therefore, building integrated systems should be studied in detail under real weather and internal load conditions, over the long term, to ensure thermal comfort all year round when utilising renewable energy and off-peak electricity. Long term techno-economic feasibility of PCM integrated underfloor and wallboard system operated with HP should be investigated extensively both experimentally and numerically.
- ➢ There is still a lack of knowledge to optimise the choice of PCM, its quantity, and the position of the PCM module in a hot water tank. Further experimental and numerical studies need to be carried out to get adequate information on efficient system design. Moreover, the techno-economic analysis of the PCM system over the conventional system needs to be investigated.
- ➢ The PCM battery research should be extended from small-scale studies to real weather, longer period scenarios, by implementing the systems into occupied dwellings and analysing the system performance in maintaining the thermal comfort and thermal energy storage using control strategies. A general numerical model should be developed to optimise the system performance for various operating parameters.
- ➢ A generalized standard procedure for PCM integration in building components and LHTES units for space heating and hot water production, including the PCM selection, system design, and testing of the system should be developed to enhance the penetration of these technologies into the global market.
- ➢ Finally, there are no papers exploring the use of PCM in building systems with AI controls.

6. Conclusions

Residential heating and hot water production accounts for most of the energy consumption all around the world, and thus an appropriate choice of active and passive energy storage system integrated with buildings can significantly save the energy consumption of the building, reduce the carbon footprint, and provide economic benefits. PCM underfloor and wallboard systems for energy-efficient buildings and PCM applications in DHW production are extensively reviewed and commercially available PCM for each application are listed with their details.

A combination of PCM under-floor heating with wallboard systems can maintain the indoor temperature within the thermal comfort range throughout the day if the selected PCM is appropriate. PCM with meting points 18–30 °C are preferred in building integrated heating applications to maintain indoor thermal comfort. The addition of PCM into the HWT is an effective method to enhance the energy capacity, operating time under a temperature range and stratification. The reheating of the water by the PCM used extended the hot water availability time. The suitable phase change temperature of PCM for DHW application is in the range 50–70 °C and 50–70 for developing a PCM energy storage unit. Compared to PCM incorporated underfloor heating and wall heating techniques, PCM TES units can be easily retrofitted into building for space heating and domestic hot water applications. Since the PCM modules are fitted inside the walls or under the floors, any leakage of PCM will leads to high maintenance costs in the case of building integrated PCM systems.

This paper has taken an objective overview of the current research state of the art of PCMs and has outlined where the research directions required for the future development of this technology in aiding society's shift to zero carbon, low energy, sustainable technologies to enhance the usefulness of buildings for human habitation. While the paper demonstrates that considerable work has been achieved, there is a continued need for sustained research in this field if PCMs are to be of economic, environmental, and societal benefit.

CRediT authorship contribution statement

Ajay M Nair: Conceptualization, methodology, extensive literature review, material collection, and writing-original draft. **Christopher Wilson:** Reviewing and editing. **Ming Jun Huang:** Supervision, reviewing and editing, **Philip Griffiths:** Supervision, reviewing and editing, **Neil Hewitt:** Project administration and Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Based on the literature review conducted on PCM application in building integrated heating and domestic hot water production application and PCM selection criteria developed, details of the commercially available PCM are listed in the following tables. Table 1A listed the potential commercial PCM suitable for building integrated heating and Table 1B represents the details of commercial PCM for domestic hot water application.

Table A.1
List of commercial PCM suitable for building integrated heating.

Manufacturer	PCM	Type	Phase change Temperature_°C		Latent heat kJ/kg	Specific heat kJ/kg-K	Thermal Conductivity W/m-K	Density kg/m^3
			Melting point	Freezing point	ΔHl/ΔHs	Cps/Cpl	Ks/Kl	ρs/ρl
Rubitherm Tech GmbH www.rubitherm.com	RT 18HC	Organic/Paraffin	17–19	19–17	260	2	0.2	880/770
	RT 21		18–23	22–19	155	2	0.2	880/770
	RT 21HC		20–23	21–19	190	2	0.2	880/770
	RT 22HC		20–23	23–20	190	2	0.2	880/770
	RT 24		21–25	25–21	160	2	0.2	880/770
	RT 25HC		22–26	26–22	230	2	0.2	880/770
	RT 26		25–26	26–25	180	2	0.2	880/770
	RT 28HC		27–29	29–27	250	2	0.2	880/770
	SP21EK	Inorganic	22–23	21–19	170	2	0.5	1500/1400
	SP24E		24–25	23–21	180	2	0.5	1500/1400
	SP25E2		24–26	24–23	180	2	0.5	1500/1400
	SP26E		25–27	25–24	180	2	0.5	1500/1400
	SP29Eu		29–31	28–26	190	2	0.5	1500/1400
Climator www.climator.com	ClimSel C21	Salt Hydrates	21–26	……	134	……	0.93/0.75	1400
	ClimsSel C4		24–27	……	140	……	0.74/0.93	1400
	ClimSel C28		27–31	……	170	……	0.98/0.72	1400
PCM Energy pvt Ltd. www.pcmenergy.com	T18	Salt Hydrates	18	……	175	……	……	1500
	T21		21	……	175	……	……	1500
	T24		24	……	175	……	……	1500

(continued on next page)

Table A.1 (*continued*)

Manufacturer	PCM	Type	Phase change Temperature_°C		Latent heat kJ/kg	Specific heat kJ/kg-K	Thermal Conductivity W/m-K	Density kg/m³
			Melting point	Freezing point	ΔHl/ΔHs	Cps/Cpl	Ks/Kl	ρs/ρl
	T27		27	……	175	……	……	1500
	T29		29	……	175			1500
PCM Products Ltd. www.pcmproducts.net	S18	Salt Hydrates	18	……	145	1.9	0.43	1520
	S19		19	……	175	1.9	0.43	1520
	S20		20	……	195	2.2	0.54	1530
	S21		21	……	220	2.2	0.54	1530
	S22		22	……	215	2.2	0.54	1530
	S23		23	……	200	2.2	0.54	1530
	S24		24	……	180	2.2	0.54	1530
	S25		25	……	175	2.2	0.54	1530
	S27		27	……	185	2.2	0.54	1530
	A18	Organic	18	……	155	2.18	0.22	765
	A19		19	……	150	2.18	0.22	765
	A20		20	……	160	2.2	0.22	770
	A21		21	……	160	2.2	0.22	770
	A22		22	……	160	2.2	0.18	785
	A23		23	……	155	2.2	0.18	785
	A24		24	……	155	2.22	0.18	790
	A25		25	……	150	2.22	0.18	785
	A26		26	……	230	2.22	0.21	790
	A27		27	……	250	2.22	0.22	768
	A28		28	……	265	2.22	0.21	789
	A29		29	……	225	2.22	0.18	810
Microtek Laboratories.inc www.microteklabs.com	Nextek 18D	Micro encapsulated/ organic	18	……	190	……	……	……
	Nextek 24D		24	……	170	……	……	……
	Nextek 28D		28	……	155	……	……	……
	Micronal 24D		24	……	105	……	……	……
	Micronal 28D		28	……	150	……	……	……
	MPCM 18D		18	……	180	……	……	……
	MPCM 24D		24	……	155	……	……	……
	MPCM 28D		28	……	175	……	……	……
	PCM18	Organic	18	……	205–215	……	……	……
	PCM24		24	……	165–175	……	……	……
	PCM28		28	……	195–205	……	……	……
SavENRG www.rgees.com	OM18P	Organic	18.7–19.26	18.8	233	1.8/2.2	……	780/750
	HS22P	Inorganic	23	22	185	2.2/3.04	1.13/0.56	1840/ 1540
PureTemp www.puretemp.com	PureTemp 18	Organic	18	……	192	1.47/1.74	0.25/0.15	950/860
	PureTemp 20		20	……	171	2.07/2.15	0.23/0.14	950/860
	PureTemp 23		23	……	201	1.84/1.99	0.25/0.15	910/830
	PureTemp 25		25	……	187	1.99/2.29	0.25/0.15	950/860
	PureTemp 27		27	……	202	2.46/2.63	0.25/0.15	950/860
	PureTemp 28		28	……	190	2.34/2.54	0.25/0.15	950/860
	PureTemp 29		29	……	202	1.77/1.94	0.25/0.15	940/850
CrodaTherm www.crodatherm.com	CrodaTherm19	Organic	19.3	17.9	175/176	2.5/1.8	0.23/0.16	911/850
	CrodaTherm21		21	19	190	2.3/1.9	0.18/0.15	891/850
	CrodaTherm24		24.1	20.1	183	2.4/1.7	0.29/0.16	949/842
	CrodaTherm24W		23.8	22.4	184	3.7/2.2	0.22/0.16	906/843
	CrodaTherm29		29	26	207	2.3/1.4	0.22/0.25	917/851
	CrodaThermME29D		28.8	23.5	183/179	……	……	980
	CrodaThermME29P		28.8	23.5	183/180	……	……	337

Table A.2
List of commercial PCM for domestic hot water application.

Manufacturer	PCM	Type	Phase change Temperature _°C		Latent heat kJ/kg	Specific heat kJ/kg-K	Thermal Conductivity W/m-K	Density kg/m³
			Melting point	Freezing point	ΔHl/ΔHs	Cps/Cpl	Ks/Kl	ρs/ρl
Rubitherm Tech GmbH www.rubitherm.com	RT54HC	Organic/Paraffin	53-54	54–53	200	2	0.2	850/800
	RT55		51–57	57–56	170	2	0.2	880/770
	RT60		55–61	61–55	160	2	0.2	880/770
	RT62HC		62–63	62	230	2	0.2	850/840
	RT64HC		63–65	64–61	250	2	0.2	880/780
	RT65		58–65	65–58	150	2	0.2	880/780
	RT69HC		68–70	69–67	230	2	0.2	940/840
	SP58		56–59	56–54	250	2	0.6	1400/1300

(*continued on next page*)

Table A.2 (*continued*)

Manufacturer	PCM	Type	Phase change Temperature _°C		Latent heat kJ/kg	Specific heat kJ/kg-K	Thermal Conductivity W/m-K	Density kg/m^3
			Melting point	Freezing point	ΔHl/ΔHs	Cps/Cpl	Ks/Kl	ρs/ρl
		Inorganic/Salt hydrates						
Climator www.climator.com	Climsel C58	Inorganic/Salt hydrates	55–58	–	260	–	0.57/0.47	1400
PCM Energy pvt Ltd. www.pcmenergy.com	TM 58	Inorganic/Salt hydrates	58	–	220	–	–	1400
	TM 68		68	–	220	–	–	1800
	TM 70		70	–	230	–	–	1800
PCM Products Ltd. www.pcmproducts.net	S50	Inorganic/Salt hydrates	50	–	125	1.59	0.43	1601
	S58		58	–	145	2.55	0.69	1505
	S70		70	–	100	2.1	0.57	1680
	A50	Organic	50	–	190	2.15	0.18	810
	A52		52	–	220	2.15	0.18	810
	A53		52	–	155	2.22	0.22	910
	A58		58	–	215	2.22	0.22	910
	A58H		58	–	240	2.85	0.18	820
	A62		62	–	205	2.2	0.22	910
	A70		70	–	225	2.2	0.23	890
	X55	Solid to Solid	55	–	115	1.62	0.36	1060
	X70		70	–	160	1.57	0.36	1085
Microtek Laboratories.inc www.microteklabs.com	PCM 57	Organic	57	–	180–200	–	–	–
PureTemp www.puretemp.com	PureTemp53	Organic	53	–	225	2.36/2.60	0.25/0.15	920/840
	PureTemp58		58	–	225	2.47/2.71	0.25/0.15	890/810
	PureTemp60		60	–	220	2.04/2.38	0.25/0.15	960/870
	PureTemp63		63	–	206	1.99/2.16	0.25/0.15	920/840
	PureTemp68		68	–	213	1.85/1.91	0.25/0.15	960/870
CrodaTherm www.crodatherm.com	Croda 53	Organic	53	51	226/225	1.9/2.2	0.28/0.16	904/829
	Croda 60		59.8	58.4	217/212	2.3/1.4	0.29/0.17	922/824

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