Building heating applications with phase change material: a comprehensive review

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ABSTRACT

Energy crisis and environmental problems motive a variety of research strategies to increase energy efficiency, decrease stress on energy infrastructure, and consequently reduce CO_2 emissions. Improving efficiency of building heating applications by advanced techniques such as solar collectors and heat pumps, is considered as one research strategy. Utilization of phase change material (PCM) with the virtue of high energy storage density is another research strategy. However, a comprehensive review for intergrating these two research strategies, namely building heating applications with PCM, is still lacking. This study presents a comprehensive review of research works for these applications including PCM roofs, ceilings, and walls, PCM windows, PCM floors, solar chimneys with PCM, solar heating applications with PCM, heat pump applications with PCM, and electrical heaters with PCM. Research development for these passive and active applications including key findings, is sufficiently presented. Summaries and discussions are conducted to identify research gaps for each application. To better utilize the PCM, PCM types, encapsulation forms of PCM, and types of PCM units in these applications are analyzed and discussion. Research methods used in these review literatures are summarized and discussed to further determine research possibilities and limitations. Important conclusions and future recommendations for the research of these applications are given to guide scholars to perform further advances in research.

Keywords: Phase change material; Heating; Solar energy; Building; Heat pump

Contents

Nomenclature

Abbreviations

ASHP	air-source heat pump
ASHPP	air-source heat pump with PCM
EHP	electrical heater with PCM
EPCM	eutectic PCM
GA	genetic algorithm
GDP	Gross Domestic Product
GSHP	ground-source heat pump
GSHPP	ground-source heat pump with PCM
HPP	heat pump application with PCM
HTE	heat transfer effect
HTF	heat transfer fluid
IPCM	inorganic PCM
PCM	phase change material
PV	photovoltaic
PTP	PV thermal collector with PCM
SAHSP	solar air heating system with PCM
SBAP	solar building air heating system with PCM
SDP	solar desalination system with PCM

c_p	specific heat of the PCM (kJ/(kg·K))
c_s	specific heat of the solid (kJ/(kg·K))
H	enthalpy (kJ/kg)
H_p	enthalpy of the PCM (kJ/kg)
H_r	enthalpy of the PCM at the reference temperature (kJ/kg)
h_{sl}	volumetric heat transfer coefficient between the liquid and solid (W/(m^3·K))
h_{wl}	volumetric heat transfer coefficient between the wall and liquid (W/(m^3·K))
k	thermal conductivity (W/(m·K))
k_l	thermal conductivity of the liquid (W/(m·K))
k_p	thermal conductivity of the PCM (W/(m·K))
k_s	thermal conductivity of the solid (W/(m·K))
L_p	latent heat of the PCM (kJ/kg)
r	radius (m)
T	temperature (°C)
T_l	temperature of the liquid (°C)
T_p	temperature of the PCM (°C)
T_r	reference temperature (°C)
T_s	temperature of the solid (°C)
T_w	temperature of the wall (°C)
t	time (s)
u	velocity (m/s)

SDHP	solar domestic hot water heating system with PCM	u_l	velocity of the liquid (m/s)
SDSP	solar drying system with PCM	x	distance (m)
SHP	solar heating application with PCM		
SGP	solar greenhouse heating system with PCM	*Greek symbols*	
SWHSP	solar water heating system with PCM	β	liquid fraction (-)
OPCM	organic PCM	ε	porosity (-)
ONPCM	organic/non-paraffin PCM	ρ	density (kg/m^3)
OPPCM	organic/paraffin PCM	ρ_l	density of the liquid (kg/m^3)
		ρ_p	density of the PCM (kg/m^3)
Symbols		ρ_s	density of the solid (kg/m^3)
c_l	specific heat of the liquid (kJ/(kg·K))		

1. Introduction

Energy crisis is still a big concern in current societies due to huge population growth and high energy use increase [1]. The use of fossil fuels dominates in the global energy maket and it will continue to provide 70% to 80% primary energy for the world by 2030 [2]. Thereupon, environmental problems including global warming, frequent disasters and melting icebergs, caused by fossil fuels will become much more serious [3]. A variety of research stratigies are motivated for handling current energy and environmental problems.

One research strategy is to reduce the energy use of the building heating applications. 40% of the entire world’s energy are used by buildings [4]. Many contries have proposed related policies for enhancing energy efficiency and reduce CO_2 emissions in buildings. “Clean Growth Strategy” in UK states that by 2030 the energy efficiency of the businesses and industries will be enhanced by 25% [5]. “13th Five-Year Plan” in China states that during the period of this plan, the per unit Gross Domestic Product (GDP) energy use will be fallen by 15% [6]. “2030 Energy Strategy” in EU states that by 2030 the energy efficiency will be improved by at least 32.5% [7]. Energy use in buildings mainly results from heating, cooling, lighting, and ventilation. Reduction of energy use caused by spacing heating and hot water use in buildings is a matter of concern, requiring advanced techniques, such as passive [8] and active measures [9].

Another research strategy is to well use thermal energy storage with phase change material (PCM). Thermal energy storage is a good means to improve the use of renewable energy source [10], overcome the unpreidictable energy output from renewable energy systems [11], and enhance the energy efficiency of energy systems [12]. Thermal energy storage methods mainly include sensible, latent, and thermochemical storage [13]. Compared with other heat storage materials, PCM possesses the advantages of simplicity, high reliability, high energy storage density [14], low power use, and nearly isothermal temperature during the phase transition process [15]. Hence, it is widely applied in lots of fields for improving the energy efficiency, such as free cooling [16], thermal management [17], defrosting [18], and air-conditioning [19].

Intergating the two above-mentioned strategies, i.e. enhancing energy efficiency of building heating applications with PCM, is a new and relevant trend to overcome the problems of energy crisis and environmental pollution. In the last decade, researchers have summarized many review literatures related to each strategy. For the first strategy, Su et al. [20] reviewed the heating soluations including air-source heat pumps (ASHPs), ground-source heat pumps (GSHPs), and gas boiler water heaters for building applications in China. Spatial data analysis method is highly recommended to identify viable solutions for heating purpose in different Chinese regions. Wang et al. [21] summarized the development of solar-assisted heat pumps for building domestic hot water use. Benli [22] reviewd the current application situation of solar water heaters in Turkey. Solar water heaters were suggested to be installed in the Northern and Eastern districts in Turkey. For the second strategy, Chandel and Agarwal [23] reviewed the photovoltaic power applications with PCM that was used to cool photovoltaic panels for enhancing the system efficiency. Further investigations of improving economic benefits of using the PCM are suggested [23]. Saffari et al. [24] summarized the building cooling techniques with PCM. Abdulateef et al. [25] summarized the techiniques to use fins to increase the heat transfer effect (HTE) between the PCM and the heat transfer fluids (HTFs). However, to the authors’ knowledge, few research works conducted the comprehensive review of both strategies, i.e. building heating applications with PCM.

This study therefore presents a comprehensive review of building applications with PCM for heating purpose, which contributes to addresses the following research problems:

- What is the current research development state of different buildings heating applications with PCM? What are the current key findings in each application?
- What are the research gaps for each building heating application with PCM?
- What kinds of PCM are adopted in the building heating applications with PCM? How is the PCM adopted?
- What are the limitations of research methods for studies of buildings heating applications with PCM?

- What are the important conclusions and future recommendations after reviewing the current research findings and applications?

To well remedy these knowledge gaps, this review summarized the literatures related to building heating applications with PCM. These applications are classified into passive and active application, shown in Fig. 1. Current research developments of passive applications and relevant key findings are presented in Section 2. Current research developments of active applications and relevant key findings are presented in Section 3. In Section 2 and Section 3, the summaries and discussions of the research gaps for each kind of application are also given. Section 4 conducts the discussion of PCM types, encapsulation forms of PCM, types of PCM units. Discussions on research methods for studies of the reviewed applications are given in Section 5. Section 6 summarized the important conclusions and future recommendations for these applications.

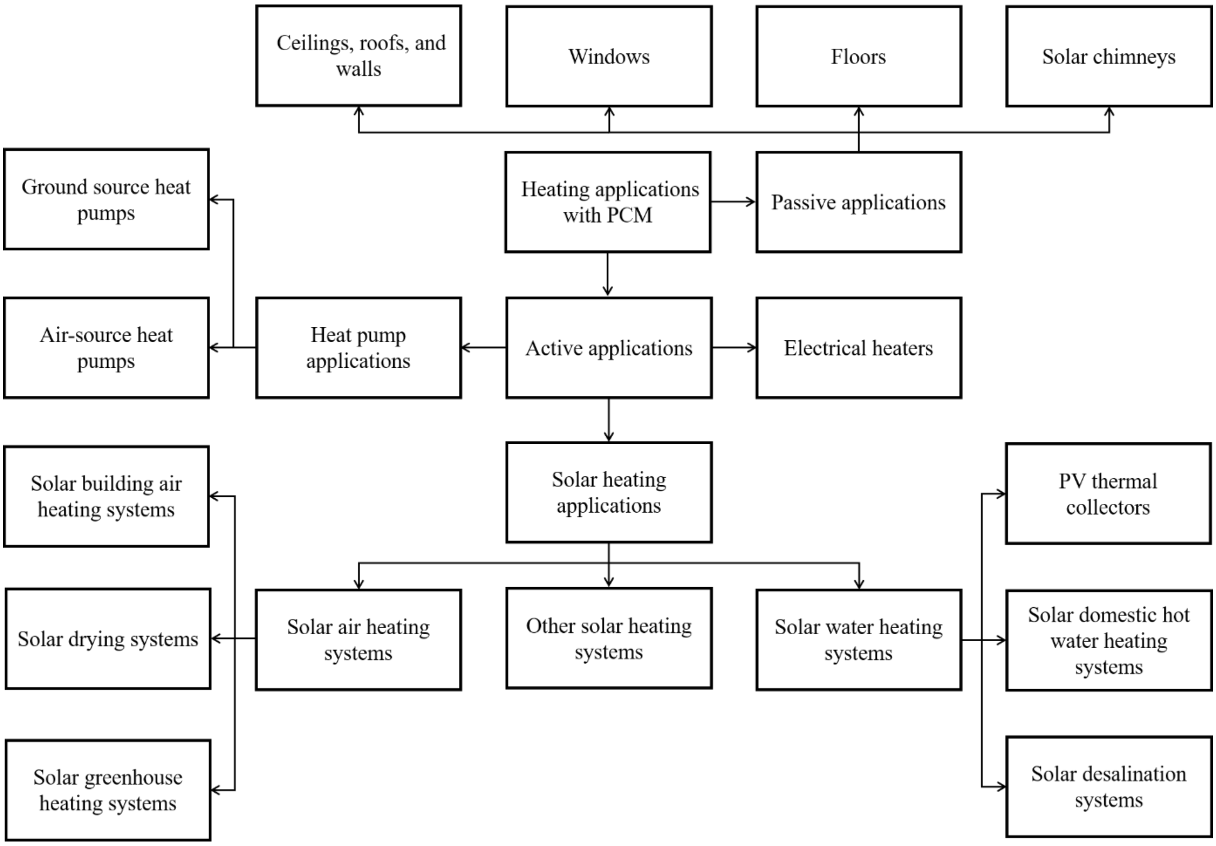

Fig. 1. Classification of building applications with PCM for heating purpose.

2. Research development on passive applications with PCM

The passive utilizations of PCM are mainly adopted at various components of the building envelope including roof, ceiling, wallboard, window, floor, and solar chimney, as shown in Fig. 2. PCM helps in increasing thermal mass of the building envelope key parts, leading to the reduction of HTE between the outdoor environment and buildings, especially during peak periods. This contributes to decreasing the peak heating or cooling load of a building. In addition, PCM impairs the influence of the fluctuations of the ambient environment temperature on these key components of the building envelope, resulting in smaller indoor room temperature variations [26]. Thus, it is an efficient method to maintain the room temperature within occupants' thermal comfort range.

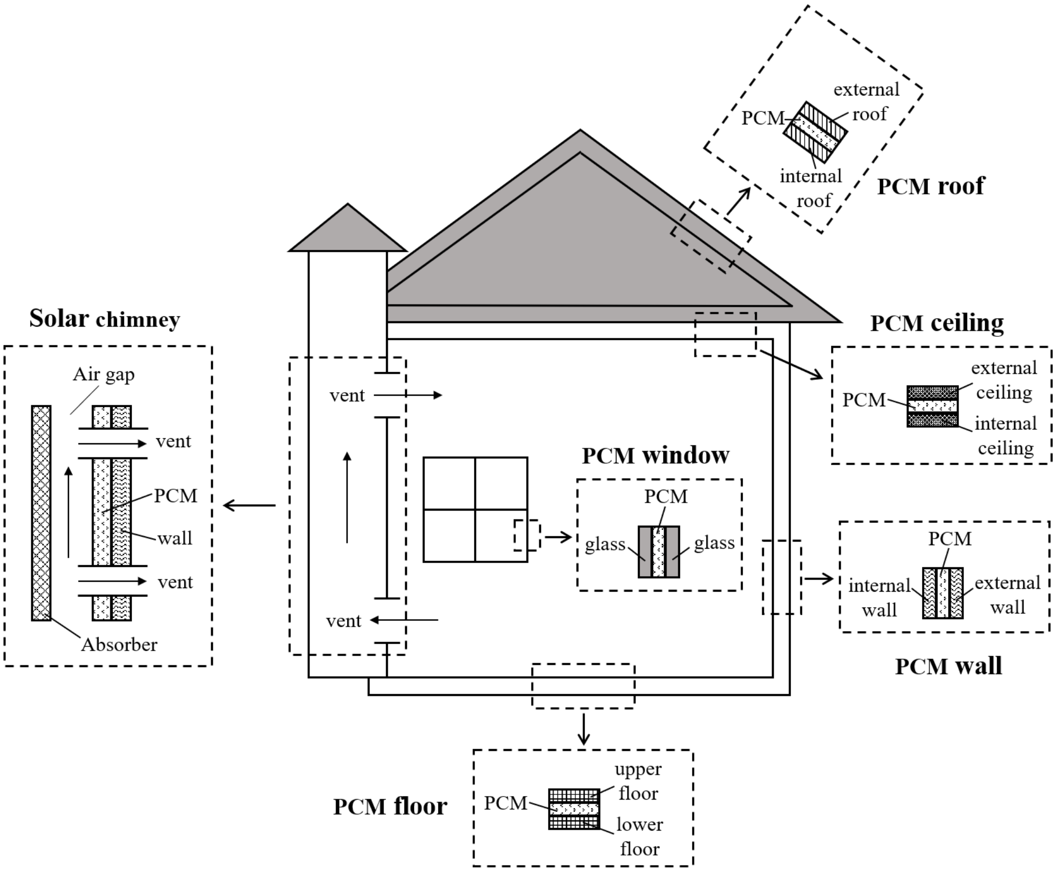

Fig. 2. Passive applications with PCM.

Akeiber et al. [27] have reviewed the passive cooling applications with PCM in different components of the building envelopes. However, in cold climates, the required energy for meeting heating demand is higher than that for meeting cooling demand. Especially in some severe cold climatic regions, no energy is required to meet the cooling demand. In these climatic regions, integrating PCM in building envelopes will play the role in reducing heating energy demand. Scholars have conducted different studies on the passive applications with PCM for heating purpose. According to different functions of the PCM in the building envelope, these applications can be classified into: (1) PCM roofs, ceilings, and walls; (2) PCM windows; (3) PCM floors; and (4) solar chimneys with PCM. The recent development on these applications are presented below. For each of the passive applications with PCM, the discussion includes the merits, deeper investigation, and performance optimization. It is not possible to find the same amount and quality of the research work for each application. However, the form of the presentation is kept similar, so that the further research can be developed in the similar manner.

2.1. PCM roofs, ceilings, and walls

Scholars have explored the applications of PCM roofs, ceilings, and walls for building heating applications, and discovered their merits including heating demand reduction potential, enhancement of thermal comfort, and better utilization of solar energy. These applications were widely explored in different climate regions in different countries, including China, Austrilia, Iraq, Canada, Japan, France, and Greece. The investigations and findings related to merits of these applications are summarized in Table 1.

Table 1 Investigations and findings related to merits of PCM roofs, ceilings, and walls

Authors and references	Year	Application locations	Investigations	Key findings
Kheradmand et al. [28]	2016	-	Thermal behavior analysis of the PCM plasterboard in a prototype	PCM plasterboard might effectively reduce the heating demand of the building in comparison with the conventional plaster wallboard.
Meng et al.	2017	China	Thermal performance	During the heating season, the indoor air

[29]			comparision between a composite PCM room and an ordinary room	temperature in the PCM room was 6.93K to 9.48K higher than that in the ordinary room at night.
Mi et al. [30]	2016	China	Energy and economic performance evaluation of the PCM wallboard in office buildings for five climate regions	PCM could effectively increase the thermal storage ability of the wall.
Wang et al. [31]	2016	China	Experimental evaluation of the PCM wallboard application	In winter, the heating demand of the room with PCM wallboard was 10%-30% lower than that with conventional wallboard.
Jamil et al. [32]	2016	Australia	Retrofitting study of using PCM in a real house	Installing the PCM in the ceilings of the building could effectively reduce the thermal discomfort hours.
Marin et al. [33]	2016	Worldwide	Energy saving analysis of using the PCM wallboard in typical cities with different climates	Energy performance of buildings might be improved in arid and warm temperate climate areas when PCM-enhanced gypsum boards were applied.
Akeiber et al. [34]	2017	Iraq	Experimental comparison of the energy performance of buildings with and without PCM	Buildings with PCM might have considerable energy saving potential and good indoor thermal comfort in comparison with those without PCM.
Fateh et al. [35]	2017	-	Numerical and experimental analysis of PCM wallboard in buildings	Peak heating load of buildings was reduced by nearly 15% when PCM was used.
Guarino et al. [36]	2017	Canada	Performance investigation of a room with the PCM	PCM wallboard might effectively increase the ultilization of solar energy

			wallboard that opposed a window	in buildings, and decrease more than 17% annual heating demand.
Kusama and Ishidoya [37]	2017	Japan	Experimental investigation of PCM ceiling and wall	Buildings with PCM plaster wallboards might better utilize solar energy, obtaining better thermal comfort effect, and higher energy saving potential than that with conventional plaster wallboards.
Berthou et al. [38]	2015	France	A novel translucent solar wallboard combining silica aerogels with PCM brick	This type of wallboard could effectively prevent heat loss and increase heat gain.
Plytaria et al. [39]	2018	Greece	Simulated investigation of PCM wall in a building	Heating load of the building was reduced by nearly 1.54% when PCM was used in north and south walls.

It could be concluded from Table 1 that PCM roofs, ceilings, and walls have sufficient merits for being used in buildings for heating purpose, and these merits have been supported by different investigations from scholars in different contries. Based on the merits of PCM roofs, ceilings, and walls, deeper investigations have been conducted. The investigations and findings related to these applications are summarized in Table 2.

Table 2 Investigations and findings related to investigations of PCM roofs, ceilings, and walls

Authors and references	Year	Investigations	Key findings
Dong et al. [40]	2015	Numerical analysis of influence of PCM latent heat, solar irradiation, PCM layer thickness, roof slope, and external surface absorption coefficients on thermal performance of the PCM roof	PCM layer thickness and external surface absorption coefficients had a greater influence on the system performance than other factors.

Thiele et al. [41]	2015	Numerical analysis of thermal behavior of the microencapsulated PCM wallboard applied in building envelopes	Enabling the melting temperature of PCM close to set indoor temperature could reduce thermal energy flux.
Soares et al. [42]	2016	Experimental study of the thermal performance of the PCM wallboard for building applications considering both natural convection and subcooling phenomena	Adding fins could well enhance the discharging process by conduction.
Biswas and Abhari [43]	2014	Numerical and experimental study of the wallboard with a type of low-cost PCM	From the economic aspect, using the PCM in only inner section of the wall was more advategeous than that in the entire wall.
Kant et al. [44]	2017	Numerical analysis for the thermal performance of the building wallboard with different kinds of PCM	Capric acid was more effective to reduce the heat flux than paraffin, leading to lower heating demand during the heating season.
Lachheb et al. [45]	2017	Numerical analysis of the wallboard thickness and mass fraction of PCM in composite plasters	Building thermal comfort could be enhanced by increasing of the wallboard thickness, and the heat flux amplitude might be reduced by the increase of the PCM mass fraction in the plaster.
Saffari et al. [46]	2016	Numerical study on the effect of occupants clothing behavior on the energy use of the building envelope with PCM wallboards	Occupants clothing behavior of wearing slightly warmer clothes contributed to enhance the system energy saving potential.
Barzin et al. [47]	2016	Experimental study of the passive building heating system with the PCM by combining the weather forecast and the price-based	Energy saving potential could reach up to 14% when the price-based control method was used. In addition, energy

	control method	saving ratio of 31% could be obtained when the weather forecast was considered.

It could be concluded from Table 2 that deeper investigations of PCM roofs, ceilings, and walls has been sufficiently conducted from both numerical and experimental aspect. By conducting parametric studies, suitable factors and methods for enhancing the system performance have been found. Findings from the above-explained invesigations of these applications advocate the optimization for enhancing the system performance. Typically, performance optimization comprises decision variables, optimization objectives, implementation methods, and results. Table 3 summarizes these information for the performance optimization of the PCM roofs, ceilings, and walls.

Table 3 Performance optimization of PCM roofs, ceilings, and walls

Authors and references	Decision variables	Optimization objectives	Implementation methods	Results
Saffari et al. [48]	Melting temperature	Maximizing energy benefits of a building with PCM wallboards	EnergyPlus and GenOpt	PCM melting temperature of 20ºC was the optimal value for acquiring the highest annual energy benefits.
Soares et al. [49]	PCM thermal properties, solar absorptance in inner surface, PCM layer thickness, and PCM layer location in the wallbord	Maximizing energy saving potential of the system	EnergyPlus and GenOpt	Energy use during the heating season could be reduced by 33% to 38% when PCM wallboard was used in cities like Milan, Paris, and Bucharest.
Tokuc et al. [50]	PCM thickness	Better energy benefits of	CFD analysis	2 cm was a suitable PCM thickness when PCM was

		buildings with PCM		applied in the building roof in Istanbul, Turkey.
Jin et al. [51]	Position of PCM layer in the wallboard	Maximizing peak heat flux reduction	Numerical analysis	The optimal position of the PCM layer is influenced by paremeters of PCM and environmental conditions

2.2. PCM windows

In addition to the advantage of reducing heating demand of buildings, PCM has good optical properties that allows it to be used as the transparent substance. Goia et al. [52] experimentally compared the performance of the building windows with and without PCM. In their work, it was observed that during heating seasons, heat losses from buildings were suitably reduced, but the heat gains from the solar were significantly decreased. Thus, the PCM window might not be effecient for thermal insulation in winter.

Li et al. [53] analyzed the influence of the optical parameters including refractive index and extinction coefficient of the PCM on the performance of doule-glazing windows with the PCM. It was found that the effect of the PCM refractive index on the system performance was weak, while that of the PCM extinction coefficient was strong. Further, they suggested that suitable adjustement of PCM position in the glass windows was necessary for enhancing the thermal performance of this application in winter [54].

Few studies about PCM windows were conducted. The reason for this phenomenon might be that scholars thought the economic performance of this application was not satisfactory, as presented in the study of Goia et al. [52]. Building owners and government might be confused by the effects of this application and thereby only a few research fundings has been investigated.

2.3. PCM floors

PCM floors can significantly enhance the performance of underfloor heating systems in winter. To verify this, different research activities are conducted. Plytaria et al. [55] conducted the investigation of a solar assisted heat pump used in a building with the PCM floor area of 100 m^2. The schematic diagram of the used PCM floor is shown in Fig. 3. The floor was composed of the mortar, concrete, pipes, PCM, insulation, and beton, respectively. It was concluded that the heating load of the building was reduced by nearly 40% when the PCM floor was used [56]. In addition, the authors found that the indoor temperature could be increased by approximately 0.8 K in some winter days [57], and 2 K in some winter days [58], when the PCM floor was used. The performance estimation of the underfloor heating system, where the PCM wallboards with higher melting temperature were placed between the floor and heater, was conducted in [59]. The results demonstrated that the energy and cost saving ratio of the heating system with PCM were respectively 32% and 42% when compared with that without PCM. Kim et al. [60] presented an experimental study of PCM floors adopted in the Chiba Prefecture, Japan. In their study, three almost identical experimental rooms with : 1) the convential wallboard, 2) four layers of PCM sheets in the floor, and 3) one layer of PCM sheet in the floor, wall and ceiling, were established. They found that the heating energy use of the second and third rooms were respectively reduced by 9.2% and 18.4% when compared with the convetional room [60]. A numerical study of thermal behavior of the PCM floors, concluded that the PCM floors contributed to the indoor temperature fluctuation with smaller amplitude in comparison with the conventional floors [61]. Further, Lu et al. [62] found that the temperature in the room with the PCM floors and walls was 7.15 K higher than that in the traditional room.

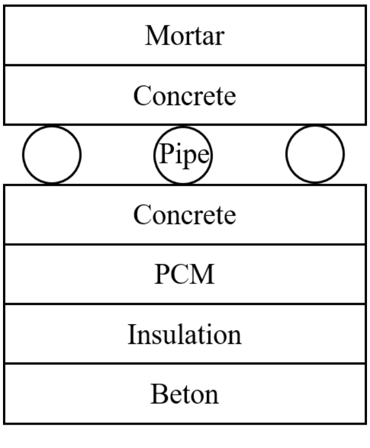

Fig. 3. PCM floor in the study of Plytaria et al. [55].

Optimizing the performance of the buildings with the PCM floors is another research hotspot. Royon et al. [63] conducted the design optimization of the PCM floor used in the building. The new evaluation index, i.e. PCM activity, which represented the availability of the PCM, was proposed for optimizing the amount of the PCM used in the floor. In their case study, 50% was selected as the optimal PCM activity.

2.4. Solar chimneys with PCM

As presented in the study of Li et al. [64], the solar chimney systems with PCM has two modes: close mode and open mode. During the close mode, the PCM is utilized to store the solar heat, while during the open mode, the stored heat is released to the air in the heated space. They not only proposed the concepts of this application, but also conducted deeper investigations including numerical solutions of the heat transfer models [64], experimental validation of models [65], parametric studies considering thermal properties of the PCM [65], initial temperature of the PCM [65], and different geometries [66]. One important conclusion was that the structure and distribution of the fins in the PCM container has an important influence on the HTE improvement [66].

2.5. Summary and discussion on passive applications with PCM

From the above-metioned research studies, it could be summarized that a number of investigations related to PCM roofs, ceilings, and walls has been conducted. The reserach on merits, deeper investigations, and performance optimization has been sufficiently presented for the PCM roofs, ceilings, and walls. However, the research on development of PCM windows, PCM floors, and solar chimneys with PCM were slow. Although a few studies on PCM windows have been performed, the achieved results are not satisfactory. The research on the merits of the PCM floors has been widely presented, while more deeper investigations and performance optimization should be conducted. Regarding the solar chimneys with PCM, there were many studies on its merits. However, performance optimization for this application was still needed.

In conclusion, PCM roofs, ceilings, and walls, and PCM floors have been paid many attentions by scholars. However, the investigations of PCM windows should be further conducted, because current research results indicated that this application might be not economically feasible. The scholars in this field should learn to develop some novel designs to improve the system performance, such as the novel designs used in solar chimneys with PCM, shown in Table 4.

Table 4 Summaries of novel designs and their effects in solar chimneys with PCM

Authors and references	Year	Novel designs	Effects
Kara [67]	2016	Addition of novel triple glass	Solar energy gained into the building was increased. In addition, daily overall efficiency could reach up to 17%-20% during the heating period.
Zhou and Pang [68]	2015	Utilization of longitudinal vortex generators	The performance of the system was effectively enhanced.
Luo et al. [69]	2017	Utilizaiton of novel solar PCM wallboard	Better heating effect could be obtained in comparion with convetional wallboard.

It could be concluded from Table 4 that the solar energy could be better utilized when the proposed novel designs were used in the solar chimneys with PCM.

3. Research development on active applications with PCM

Renewable energies including solar, ambient air, and geothermal energy, have the flaw of unstable outputs, which means that they might not provide required energy when buildings have high energy demand. One key techinque to overcome this issue is to use themal energy storage devices (e.g. PCM), which can store the renewable energy when it is sufficient, and release it when it is insufficient while building energy demand exists. For heating purpose, solar heating applications are usually combined with the PCM to achieve this function. In addition, heat pump applications and electrical heaters are integrated with the PCM to enhance the economic performance. Hence, active applications with PCM are classified into: 1) solar heating applications with PCM (SHPs); 2) heat pump applications with PCM (HPPs); and 3) electrical heaters with PCM (EHPs). The recent development on these applications are presented below. Like the presented form for the passive applications with PCM, the active applications with PCM are analyzed by demonstrating the merits, deeper investigations, and performance optimization.

3.1. Solar heating applications with PCM

According to the kind of the working fluid in the solar heating applications, SHPs are classified into: 1) solar water heating systems with PCM (SWHSPs), 2) solar air heating system with PCM (SAHSPs), and 3) other solar heating systems with PCM.

3.1.1. Solar water heating systems with PCM

SWHSPs cover the following applications: 1) solar desalination systems with PCM (SDPs), 2) solar domestic hot water heating systems with PCM (SDHPs), and 3) photovoltaic (PV) thermal collectors with PCM (PTPs). The details of each applications are introduced below.

- **Solar desalination systems with PCM**

A classical SDP in Jordan that includes solar collector, water basin and PCM tubes was proposed in the study of Al-harahsheh et al. [70]. The schematic diagram of the SDP is shown in Fig. 4. During the day, the heat collected from the solar collector and double glass was used to distill the brackish water. The latent heat was stored in PCM tubes when the temperature reached the melting temperature. During the night, the heat stored in PCM tubes was released to continue the desalination of brackish water.

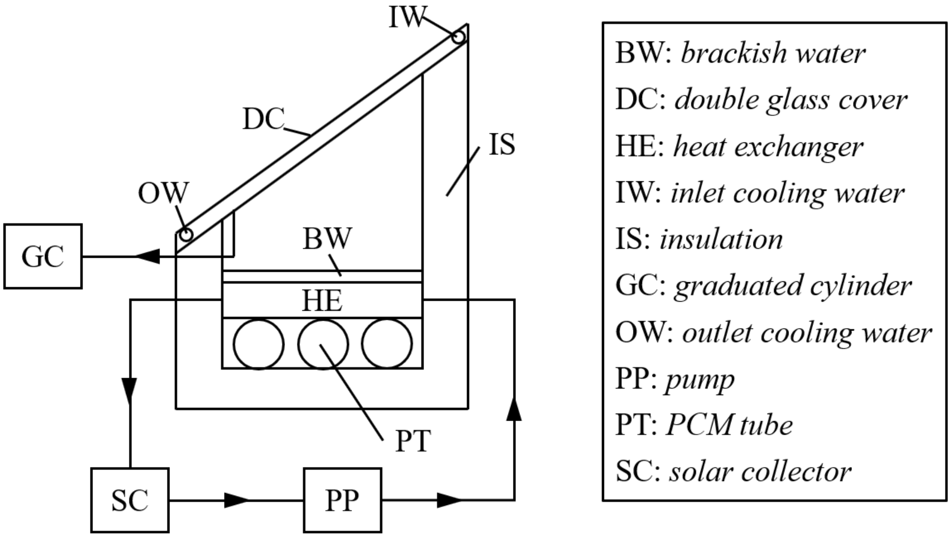

Fig. 4. A SDP in the study of Al-harahsheh et al. [70].

One merit of the SDPs is higher freshwater yield. Kabeel et al. [71] compared freshwater yield of a SDP that consisted of parabolic solar concentrator and PCM plate, with covntional system, and found that in summer and winter, the freshwater yield of the former system was 55%-65% and 35%-45% higher than the latter one, respectively.

Another merit of the SDPs is higher energy and exergy efficiency. Experimental results in the study of Sarhaddi et al. [72], indicated that in semi-cloudy days, the energy and exergy efficiency of the SDP that were respectively 74.35% and 8.59%, were higher than those of the conventional system. However, one worthy concern was that in sunny days, the energy and exergy efficiency of the SDP were lower than those of the conventional system.

Changing water flow rate is regarded as an effective means to improve the performance of the SDPs. Al-harahsheh et al. [70] found that the freshwater yield could be improved by increasing hot water flow rate from 2 ml/s to 30 ml/s, and increasing cold water flow rate from 6 ml/s to 10ml/s. However, experimental results in the study of Arunkumar et al. [73], indicated that in a SDP with a parabolic solar concentrator and PCM balls, increasing the cold water flow rate was not economically beneficial.

Using composite PCM with higher thermal conductivity is regarded as another effective means to improve the performance of the SDP. Elfasakhany [74] concluded that the freshwater yield of the SDP with the copper/parrafin composite was 6% higher than that of the SDP with the pure parrafin.

- **Solar domestic hot water heating systems with PCM**

Fig. 5 shows the schematic diagram of a typical SDHP. The thermal energy collected by the solar collector will be stored in the PCM storage tank, and the stored thermal energy will be released for the domestic hot water use. A number of merits for SDHPs including more hot water supply, more heat loss reduction, and shifting peak power demand, have been discovered and documented by scholars. The relevant investigations and key findings are presented in Table 5.

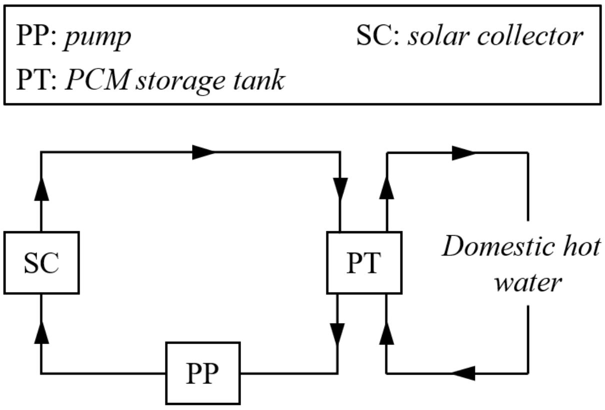

Fig. 5. Schematic of a typical SDHP.

Table 5 Investigations and key findings related to merits of solar hot water heating systems with PCM

Authors and references	Year	Investigations	Key findings
Khalifa et al. [75]	2013	Experimental study of a SDHP	Water could be heated after sunset when PCM was used.
Bouadila et al. [76]	2014	Experimental and numerical studies of thermal performance of a SDHP	PCM could effectively enhance the performance of the SDHP during the night.
Chaabane et al. [77]	2014	Comparison between a SDHP and a conventional system	More heat loss could be reduced when PCM was used.

Nkwetta et al. [78]	2014	Studies on the effect of amount of PCM use and control stratigies on the performance of a SDHP	There was a considerable potential to shift the peak power demand and to save energy when PCM was used.
Felinski and Sekret [79]	2017	A new SDHP where PCM was placed inside the evacuated tube collector	The SDHP could obtain more solar energy used to heat the water than the conventional system.
Fazilati and Alemrajabi [80]	2013	Energy and exergy analysis of a SDHP in different solar radiation intensity	Energy and exergy efficiency of the SDHP were respectivley increased by 39% and 16%, when PCM was used.

Parameteric studies of SDHPs are conducted to investigate the effect of water flow rate, PCM thickness, and solar collector area, on heat transfer rate, energy efficiency, and exergy efficiency. The relevant investigations and key findings are summarized in Table 6.

Table 6 Parametric studies of solar hot water heating systems with PCM

Authors and references	Year	Parameters	Performance index	Key findings
Prieto et al. [81]	2017	PCM thickness, inlet temperature, and water flow rate	Heat transfer rate	Reducing PCM thickness of contributed to increasing the heat transfer rate.
Murray and Groulx [82]	2014	Water flow rate	Heat transfer rate	Increasing water flow rate could effectively shorten the charing time, while it had a weak effect on the rate of solidification during the discharging process.
Wang et al. [83]	2017	Water flow rate and solar collector area	Heat storage efficiency and exergy efficiency	Water flow rate had little influence on thermal performance, while solar collector area had strong influence on that.

Kanimozhi et al. [84]	2017	Factor time	Heat improvement	Factor time played a significant role on the charging and discharging processes of the PCM
Mahfuz et al. [85]	2014	Water flow rate	Energy efficiency and exergy efficiency	Energy and exergy efficiency of the SDHP were respectively 63.88% and 9.58% when the mass flow rate was 0.033kg/min.

A number of novel designs for the SDHPs is proposed, such as slurry PCM, liquid-flow window with PCM storage unit, and multi-type PCM packed bed. The detailed information of these novel designs are presented in Table 7.

Table 7 Novel designs of solar hot water heating systems with PCM

Authors and references	Year	Novel designs	Effects
Serale et al. [86]	2016	Slurry PCM	Using slurry PCM could increase the utilization of solar energy in SDHPs.
Serale et al. [87]	2015	Slurry PCM	Increasing the micro-encapusulated PCM concentration contributed to improving the performance of the SDHP.
Chow and Lyu [88]	2017	Liquid-flow window with PCM storage unit	The new SDHP could generate 31.4% and 11.4% more hot water than the conventional system.
Yang et al. [89]	2014	Multi-type PCM packed bed	The collector efficiency of the SDHP with multiple-type PCM packed bed was higher than that with single-type PCM packed bed.

Composite PCMs are extensively adopted in the SDHPs for enhancing the system performance. In order to demonstrate the advantages of composit PCMs in comparison with pure PCMs, different studies are conducted as listed in Table 8.

Table 8 Advantages of using composite PCM in SDHPs

Authors and references	Year	Composite PCMs	Advantages
Sobhansarbandi et al. [90]	2017	Carbon nanotube sheet with paraffin	During the night, the SDHP could generate more hot water when the composite PCM was applied.
Lin and Al-Kayeim [91]	2014	Copper with paraffin	Energy efficiency of the SDHP was improved by 1.7% when the composite PCM was applied.
Nabavitabatabayi et al. [92]	2014	Copper with paraffin	The SDHP using the composite PCM could shift the peak power demand for a longer period than that using the pure PCM.

Optimization is also conducted for enhancing the performance of SDHPs. Genetic algorithm (GA) was used to optimize the configuration of a SDHP for minimizing the system electricity use in [93]. The PCM storage unit volume, water tank volume, and PCM melting temperature were selected as optimization variables. Padovan et al. [94] conducted the multi-objective optimization of a SDHP, where minimizing the annual primary energy use was selected as one opimization objective, and minimizing the PCM storage tank volume was selected as another opimization objective. The optimal configuration of the PCM storage tank were identified.

- **PV thermal collectors with PCM**

The aim of adopting PCM in PV thermal collectors, shown in Fig. 6, is not only to store the heat collected from PV modules, but also to reduce the temperature of PV modules, and thereby improve its energy efficiency [95]. In the study of Gaur et al. [95], the PTP was used for converting thermal energy into electricity and providing heat for water in Lyon, France. It was concluded that a optimal mass of PCM used in the PTP could contribute to higher electricity efficiency and higher outlet water temperature.

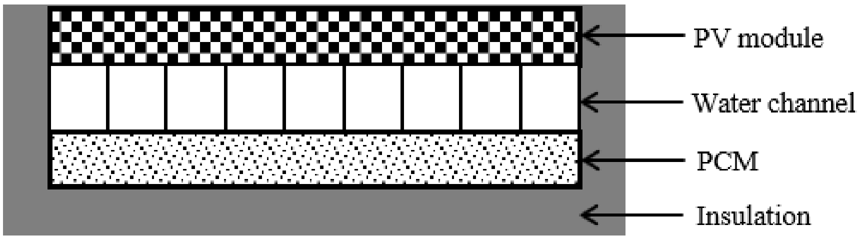

Fig. 6. A PTP in the study of Gaur et al. [95].

Gaur et al. [95] found that increasing the mass of the PCM in the PTPs contributed to increasing the system efficiency during the day and increasing the hot water temperature during the night. Browne et al. [96] conducted the experimental comparison of the larger-scale PV thermal collector system with and without PCM. They and found that the hot water temperature of the system with PCM was nearly 5.5 K higher than that of the system without PCM. Imam et al. [97] found that the rate of water temperature increase could be reduced when the PCM was adopted in a PV thermal collector with compound parabolic concentrator. In addition, experimental results in the study of Sardarabadi et al. [98], indicated that the energy and exergy efficiency of a PTP were 42% and 23% higher than those of the conventional system, respectively.

In addition to be applied in SDHPs, slurry PCM can also be used in PTPs for enhancing their thermal and energy performance. Liu et al. [99] compared the peformance of a type of slurry PCM with latent heat of 226.26 kJ/(kg·K) and water, which were regared as HTF in a PTP. The authors showed that the maximum thermal and electrical efficiency of the PTP were enhanced by 9.24% and 1.8% when the PCM slurry was used, respectively [99]. Further, they evaluated the performance of another slurry PCM with latent heat of 175 kJ/(kg·K), and found that the overall net efficiency of the PTP that utilized this type of slurry PCM could reach up to 80.57% [100].

Performance optimization is also conducted for a PTP in the study of Su et al. [101]. PCM layer thickness and PCM melting temperature are selected as decision variables. The results indicated that the maximum thermal energy could be gained when the PCM layer thickness and PCM melting temperature were 3.4 cm and 40°C, respectively.

3.1.2. Solar air heating systems with PCM

SAHPs cover the following applications: 1) solar building air heating systems with PCM (SBAPs), 2) solar drying systems with PCM (SDSPs), and 3) solar greenhouse heating systems with PCM (SGPs). These applications are presented as follows.

- **Solar building air heating systems with PCM**

PCM in SBAPs can release heat stored for the buildings when solar energy is not available. Fig. 7 shows a SBAP in the studies of Kabeel et al. [102]. The air flowed through the gap between the glass cover and absorber plate, and the PCM bed was placed below the absorber plate. During the charging mode, the hot air leaving solar collector was used to charge the PCM; while during the discharging mode, the cold air from the room was heated by solidification of the PCM.

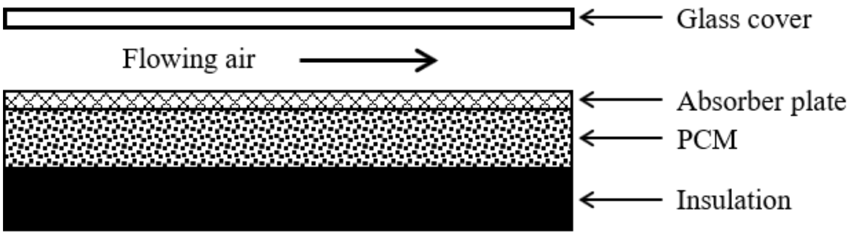

Fig. 7. A SBAP in the study of Kabeel et al. [102].

Experimental studies of the SBAPs in different locations including Tanta, Tunis, Brno, and Puigverd de Lleida, are conducted to explore the merits of adopting PCM in SBAPs. The mertis of these applications are depicted in Table 9.

Table 9 Experimental studies in different locations for exploring merits of SBAPs

Authors and references	Year	Locations	Investigations	Merits
Kabeel et al. [102]	2016	Tanta, Egypt	Performance comparison of the flate	Daily efficiency of the SBAP was higher than the conventional system. In addition, daily

			and v-corrugated plate SBAPs	efficiency of the v-corrugated plate SBAP was higher than that of the flate plate SBAP.
Khadraoui et al. [103]	2016	Tunis, Tunisia	Peformance comparison between a SBAP and a conventional system	The SBAP could generate higher outlet air temperature than the conventional system. In addition, daily energy efficiency of the SBAP was higher than that of the conventional system.
Charvát et al. [104]	2014	Brno, Czech Republic	Thermal analysis of a SBAP	Latent heat storage method was more advantageous than sensible storage method
Navarro et al. [105]	2015	Puigverd de Lleida, Spain	Experimental evaluation of a SBAP	The charing and discharging efficiencies of the SBAP could reach to approximately 70%.
Navarro et al. [106]	2016	Puigverd de Lleida, Spain	Experimental evaluation of a SBAP	The SBAP could effectively reduce the energy use when compared with the convential system.

Simulation studies are also conducted for illustrating the merit of SBAPs. Osterman and U. Stritih [107] simulated the heat transfer process in a SBAP. The results indicated that the annual energy use was reduced for nearly 142 kWh, when the system was applied a builidng with the size of 4 m×3 m×2.8 m in Ljubljan, Slovenia. Further, Lin et al. [108] conducted the simulation of a SBAP with a PV thermal collector, and found that using this SBAP could effectively improve the indoor thermal comfort of buildings by well maintaining the room temperature within thermal comfort ranges.

PCM packed bed that has the advange of higher HTE between PCM and HTF [109], is extenstively applied in SBAPs. Karthikeyan et al. [110] analyzed the thermal performance of a SBAP. The study on the influence of the PCM ball size, thermal conductivity of PCM, inlet temperature, and mass flow rate of HTF on the thermal performance of the SBAP, concluded that reducing PCM ball size, increasing inlet temperature of HTF, and mass flow rate of HTF, could enhance the HTE during the charging process. Belmonte et al. [111] simulated the

SBAP with PCM packed bed in different locations. They concluded that the SBAP could successfully satisfy a big proportion of heating requirements in buildings in different climatic regions. Further, double PCM packed beds were adopted in a SBAP [112]. The experimental results from Research and Technology Center of Energy, Tunisia, indicated that the daily energy efficiency of the SBAP reached up to approximately 47% [112].

Performance optimization of SBAPs was performed in the studies of Su et al. [113] and Arkar et al.[114]. In the studies of Su et al. [113], the dynamic simulation of a SBAP with a PV thermal collector was conducted, and it was found that proper position of PCM layer could well enhance the performance of the SBAP [113]. In the study of Arkar et al. [114], the SBAP was used in a lightweight building in Ljubljana, Slovenia, which had the heated floor area of 125 m^2. The results on the performance optimization of the SBAP that was conducted by thermal analysis, showed that the optimal air mass flow rate and mass of PCM were 40 m^3/h and 150-200 kg per square meter of the collector area, respectively [115].

- **Solar drying systems with PCM**

SDSPs are mainly designed to dry foods and drugs. Shalaby and Bek [116] designed a SDSP, comprising solar air heaters, trays, fan, and PCM unit. The schematic diagram of the SDSP is shown in Fig. 8. The The hot air that was heated by the heat collected from solar heaters, was adopted to dry medicines, and stored heat into PCM unit. The heat stored in PCM unit would be release to continue to dry medicines when solar heaters were not available.

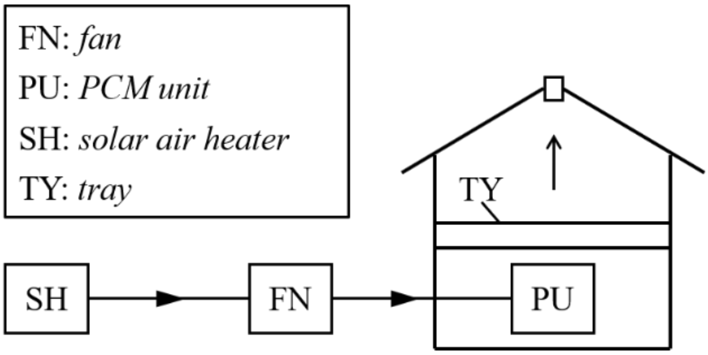

Fig. 8. A SDSP in the study of Shalaby and Bek [116].

Merits of SDSPs have been discovered, including good drying effect, higher moisture content removal, drying time reduction, and shorter payback period. The detailed information of the studies on explorations of the SDSPs merits is given in Table 10.

Table 10 Studies on explorations of merits of SDSPs

Authors and references	Year	Investigations	Merits
Shalaby and Bek [116]	2014	Experimental comparison between a SDSP and a conventional system for drying drugs	During the night, the air temperature could be 2.5-7.5ºC higher than the ambient environment temperature for at least 5 hours when the PCM was used.
Ndukwu et al. [117]	2017	Experimental comparision between a SDSP and a conventional system for dring red chilli	The moisture content removal was 72.27% when PCM was used, while it was 10.3% when PCM was not used.
Rabha et al. [118]	2017	A SDSP with forced convenction for dring red chilli	Drying time of the SDSP was reduced by 122.8% when compared with the open solar drying system.
Reyes et al. [119]	2014	Performance analysis of a SDSP for drying mushrooms	The thermal efficiency of the SDSP was significantly improved when PCM was used.
Jain and Tewari [120]	2015	Thermal and economic analysis of a SDSP for drying hebs in Jodhpur, India	The simple payback period of the SDSP was 1.57 years.
Baniasadi et al. [121]	2017	Experimental study of a SDSP for drying apricot slices	During the night the drying period could be effectively extended when the SDSP was used, and the overall effeciency of the SDSP is approximately 11%.

- **Solar greenhouse heating systems with PCM**

Fig. 9 shows the schematic diagram of a typical SGP in the in the study of Llorach-Massana et al. [122]. PCM in these applications is used for storing the excess of heat of the greenhouse during the day; while during the nighttime the stored heat is released to warm the root zone of the plant to promote their growth.

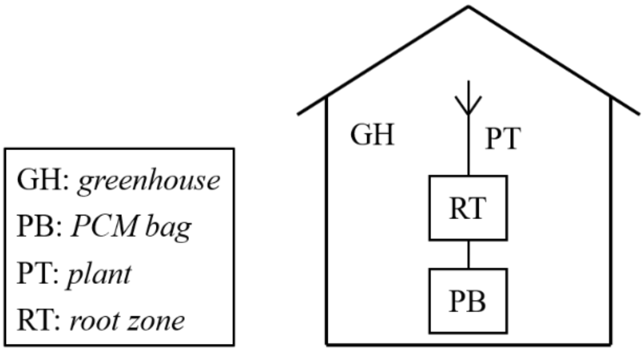

Fig. 9. A SGP in the study of Llorach-Massana et al. [122].

Merits of SGPs were presented in the studies of Bouadila et al. [123] and Llorach-Massana et al. [122]. In the first study, an experimental study of a SGP was conducted, and it was found that during the night, the released heat by PCM could satify nearly 30% of the total heating requirements of the greenhouse [123]. In the second study, the evironmental and economic analysis of a SGP was conducted, and it was concluded that the SGP could effectively reduce the environmental impacts of crops and increase the benefits of farmers [122].

Further, Zhou et al. [124] solved the heat transfer model of the SGP, the reliablity of which was validated by real data. In addition, the analysis on the effect of the nocturnal shutter on the thermal performance of the SGP, concluded that during the night the temperature of the greenhouse with nocturnal shutter was 2 K higher than that withhout nocturnal shutter [125]. Performance optimization of the SGP was conducted by Ziapour et al. [126]. GA was adopted to identify the optimal collector pipe radius, aiming to obtain better energy and economic performance.

3.1.3. Other solar heating systems with PCM

In addition to water and air that are selected as HTF, other fluids are adopted in SAHPs, like biomass fluid. Lu et al. [127] designed the solar biogas fermentation system with PCM, in which the biomass fluid was considered as HTF. The PCM was used to provide heat for the biomass fluid when solar irradiation was not available. The analysis results demonstrated that this system had a promising application future in the cold rural regions of China.

3.2. Heat pump applications with PCM

This section covers two types of HPPs: air-source heat pumps with PCM (ASHPPs) and ground-source heat pumps with PCM (GSHPPs). The merits, investigation methods, performance optimization of these applications are presented as follows.

3.2.1. Air-source heat pumps with PCM

One merit of using the ASHPPs is to shift the energy use during the on-peak to off-peak period, leading to the enhancement of the economic performance. Li et al. [128] proposed a heating system with ASHPPs, as shown in Fig. 10. The system was adopted in an outdoor swimming pool in Hong Kong. The results indicated that the proposed system could bring a considerable economic benefit [128]. In addition, Vadiee et al. [129] presented the feasiblity analysis of adopting PCM to shave the peak load in the greenhouse heating system with the ASHPs. They found that the payback period of this application might be within seven years on the basis of saving fossil fuel cost. Although adopting the PCM to shift electricity use significantly increased the economic performance, Kelly et al. [130] emphasized that more effective control strategies should be considered for enhancing the energy and environmental performance.

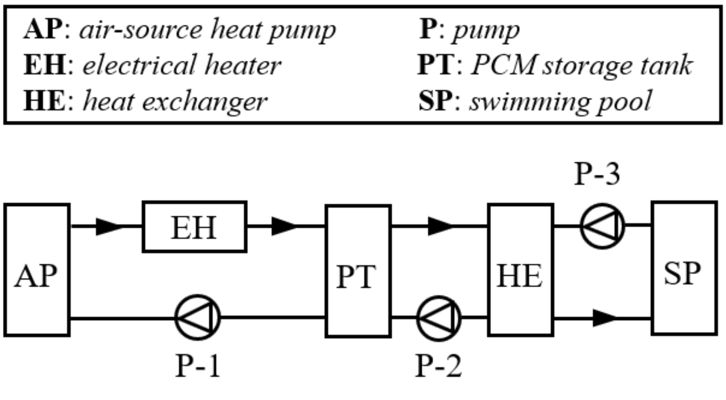

Fig. 10. A heating system with ASHPP in the study of Li et al. [128].

Another merit of using the ASHPPs is to enhance the heat storage capactiy of the water tank in the heating system. As presented in the study of Zou et al. [131], the PCM storage tank was used in a heating system instead of the water tank, and it was found that the COP of the system was increased, and the required heating time was shortened.

Performance optimization was conducted in a heating system integrating an ASHP and a PCM storage tank, which shaved the peak load [132]. The optimal type of the PCM and exchange surfaces were determined by analyzing variations of dimensionless number, while ensuring that the specific requiments can be satisfied.

3.2.2. Ground-source heat pumps with PCM

Kong et al. [133] and Qi et al. [134] explored merits of the GSHPPs. Kong et al. [133] adopted slurry PCM as HTF in a GSHP system, and it was found that the COP of the system using slurry PCM was 4.9% higher than that of the system using water. Qi et al. [134] adopted PCM as backfill material in a GSHP system, and it was concluded that better thermal performane could be gained when PCM was used instead of traditional soil.

Few studies about GSHPPs were conducted. The reason might be that the initial investment of the GSHP was high, and it could play a good role in storing heat into the ground. Hence, scholars might think other storage devices for storing heat from renewable energy sources were not needed.

3.3. Electrical heaters with PCM

Stathopoulos et al. [135] stated that in France, EHPs had the merit of peak shaving. They designed an air-PCM heat exchanger with fins, which were combined with EHPs. These fins were adopted to improve the HTE between the air and PCM plates.

Two optimization methods were proposed to identify the optimal configurations of the PCM storage unit and types of the PCM in the study of Mankibi et al. [136]. In the first method, three design scenarios were considered, including heating load shifting, charing performance during the nighttime, and thermal comfort requirement. Three different configurations of the PCM storage unit were compared by thermal analysis. In the second method, the optimization objective was proposed, i.e. to adopt the shortest time to fully charge PCM.

3.4. Summary and discussion on active applications with PCM

From the abovemetioned recent research studies, it could be summarized that investigations of SDHPs and SBAPs were sufficiently conducted, including explorations of merits, deeper investigations, and performance optimization. For the SDHPs, parametric studies, novel designs, and composite PCMs were conducted in many studies. For the SBAPs, PCM packed bed was considered as a popular means to be investigated. Few studies on explorations of merits, deeper investigations, and performance optimization of the PTPs and the SGPs were conducted, and thus more attentions should be paid on these two applicaitons. For the SDPs, performance optimization was needed. Current investigations about the SDSPs mainly focused on the merits of using PCM. Deeper investigations and performance optimization were needed, such as which factors could influence the drying effect of SDSPs and how to use minimum energy to dry maximum amounts of products. More kinds of HTF should be condisered in the SHPs. For example, PCM slurry was proved to have a good HTE, and it might be used in the SHPs for further improving the system performance. Deeper investigations of ASHPPs, GSHPPs, and EHPs were lacking. One common function of ASHPPs and EHPs was to use PCM to shift the electricity use from the on-peak to off-peak period. The reason why this function worked was that there was a electric price difference between the on-peak and off-peak period. However, in some countries the government might still not enact this policy. This might restrict the investigations of ASHPPs and EHPs. GSHP was mainly used to store heat into the ground. The initial investment of GSHP was high, and scholars might think the effect of storing heat was good enough and no other storage devices (e.g. PCM) were needed in this system.

4. Discussion on PCM utilizations

This section introduced how the PCM was utilized in building heating applications. Three aspects were presented, including PCM types, encapsulation forms of PCM, and types of PCM units.

4.1. PCM types

PCM is mainly classified into organic PCM (OPCM), inorganic PCM (IPCM), and eutectic PCM (EPCM) [137]. The advantages of OPCMs include non-corrosives and low undercooling, while the disadvantages of OPCMs include high price, inflammability, and low thermal conductivity [138]. OPCMs are the most commonly used PCMs in the heating applications, which contain organic/paraffin PCMs (OPPCMs) and organic/non-paraffin PCMs (ONPCMs). IPCMs have the advantage of higher latent heat, while they have disadvantages of subcooling, corrosion, phase separation, and low thermal stability [139]. Furthermore, merits of EPCMs include no subcooling or phase segregation, high density and high thermal conductivity, while it has the fault of low latent heat and low specific heat [140]. After analyzing the reviewd literatures, it could be found that in the reviewed literatures OPPCMs were the most popular PCMs; IPCMs and EPCMs were the second popular PCMs; and ONPCMs were the most unpopular PCMs. It should be noted that how to select the suitable PCM in different applications is summarized in the study of Sharma et al. [141] and is given in Table 11. The core point is that comprehensive thermal properties, reliability, corrosiveness, and cost should be considered. More attention should be paid in the eutectic PCM, contributing to more expected properties of PCM by adjusting proportions of different material in the eutectics. The melting temperature and latent heat of the PCM in the reviewed literatures are summarized in Table 12.

Table 11 Basic selection principles of PCM [141]

Thermal demands	Physical demands	Kinetic demands	Chemical demands	Economic demands
1. Desired phase transition	1. Favorable phase equilibrium	1. No supercooling 2. Adequate	1. Long-term chemical stability	1. Sufficient 2. Available

temperature 2. High latent heat of transition 3. Good HTE	2. High density 3. Small volume change 4. Low vapor pressure	crystallization rate	2. Compatibility with construction materials 3. No toxicity 4. No fire hazard	3. Cost effective

Table 12 Summary of the melting temperature and latent heat of the used PCM

Names of PCM	Authors and references	Melting temperature (ºC)	Latent heat (kJ/kg)
RT10	Kheradmand et al. [28]	10	150
MC24	Kheradmand et al. [28]	24	162.4
BSF26	Kheradmand et al. [28]	26	110
MC28	Kheradmand et al. [28]	28	170.1
SP29	Meng et al. [29]	28 - 30	190
RT18	Meng et al. [29]	17 - 19	225
PCM27	Mi et al. [30]	27	-
GH-20	Wang et al. [31]	20 - 25.4	33.25
Q25 BioPCM™	Jamil et al. [32]	27	-
Micronal® PCM	Marin et al. [33]	25	-
40% Oil + 60% wax	Akeiber et al. [34]	40 - 44	232
Energain® PCM	Fateh et al. [35]	-	-
-	Guarino et al. [36]	-	70
-	Kusama and Ishidoya [37]	25	170
Fatty acids eutectic	Berthou et al. [38]	21.3	152
BioPCM	Plytaria et al. [39]	25	175
PCM303	Dong et al. [40]	30	138
PCM307	Dong et al. [40]	34	188
PCM311	Dong et al. [40]	38	238
PureTemp 20	Thiele et al. [41]	10 - 28	100 - 400

Micronal® DS5001X	Soares et al. [42]	25.67 ± 0.07	111.3 ± 1.4
Rubitherm® RT 28 HC	Soares et al. [42]	27.55 ± 0.19	258.1 ± 5.1
PCM-HDPE pellets	Biswas and Abhari [43]	16.5 - 26.5	116.7
Paraffin wax	Kant and Sharma [44]	28.2	245
Capric acid	Kant and Sharma [44]	32	152.7
RT-25	Kant and Sharma [44]	26.6	232
Micronal® DS5001X	Lachheb et al. [45]	26	110
RUBITHERM®RT organic PCM	Saffari et al. [46]	23	-
RUBITHERM®RT organic PCM	Saffari et al. [46]	25	-
RUBITHERM®RT organic PCM	Saffari et al. [46]	27	-
PT 20	Barzin et al. [47]	20	180
Paraffin wax	Saffari et al. [48]	18 - 27	110
DuPont™ Energain® PCM	Soares et al. [49]	18 - 26	70
RT27	Tokuc et al. [50]	25 - 28	179
RT27	Jin et al. [51]	27	179
Paraffin wax	Goia et al. [52]	35	170
-	Li et al. [53]	27 - 29	205
$Na_2SO_4 \cdot 10H_2O$	Li et al. [54]	30 - 32	241
BioPCM Q29/M91	Plytaria et al. [55]	29	180
BioPCM Q29/M91	Plytaria et al. [56]	29	180
BioPCM Q29/M91	Plytaria et al. [57]	29	175
BioPCM Q29/M91	Plytaria et al. [58]	29	210
Paraffin wax	Devaux and Farid [59]	27 - 29	120
Paraffin wax	Devaux and Farid [59]	21.7	-
Paraffin mixed with polypropy-lene and elastomer	Kim et al. [60]	19 - 26	62.24
Octadecane	Zhao et al. [61]	28.2	242
Paraffin wax	Royon et al. [63]	27	110
RT 42	Li et al. [64]	38 - 43	174

RT 42	Li et al. [65]	38 - 43	174
RT 42	Li et al. [66]	38 - 43	174
Rubitherm® GR41	Kara [67]	45	-
Rubitherm® GR35	Kara [67]	29	-
$CaCl_2 \cdot 6H_2O$	Zhou and Pang [68]	26 ± 1	180
-	Luo et al. [69]	25 - 27	160
Sodium thiosulfate pentahydrate	Al-harahsheh et al. [70]	48.5	208.5
Paraffin wax	Kabeel et al. [71]	57	226
Paraffin wax	Sarhaddi et al. [72]	56	226
Paraffin wax	Arunkumar et al. [73]	58 - 60	226
Paraffin wax	Elfasakhany [74]	60.5	166.7
Cu-paraffin wax	Elfasakhany [74]	59.6	160.3
Paraffin wax	Khalifa et al. [75]	46.7	-
Paraffin wax	Bouadila et al. [76]	56.3	189
Myristic acid	Chaabane et al. [77]	54	189
RT42-graphite	Chaabane et al. [77]	43	139.7
Sodium acetate trihydrate + 10% graphite	Nkwetta et al. [78]	58	-
Hydrotreated technical grade paraffin	Felinski and Sekret [79]	58	217.6
Paraffin wax	Fazilati and Alemrajabi [80]	55	187
-	Prieto et al. [81]	53 - 61	123.506
Dodecanoic acid	Murray and Groulx [82]	42.5 ± 0.5	182 ± 5%
RT54HC	Wang et al. [83]	52	168
Paraffin wax	Kanimozhi et al. [84]	54	203
Honey wax	Kanimozhi et al. [84]	58	217
Paraffin wax	Mahfuz et al. [85]	56.06	200.74
N-eicosane	Serale et al. [86]	36 - 38	195
N-eicosane	Serale et al. [87]	36 - 38	195

RT35HC	Chow and Lyu [88]	34 - 36	240
PCM-1	Yang et al. [89]	60 - 62	209
PCM-2	Yang et al. [89]	50 - 52	200
PCM-3	Yang et al. [89]	42 - 44	168
Octadecane	Sobhansarbandi et al. [90]	28.1	244
Paraffin wax	Lin and Al-Kayiem [91]	60.42	184.2
0.5% Nano Cu-PCM	Lin and Al-Kayiem [91]	59.57	172.2
1.0% Nano Cu-PCM	Lin and Al-Kayiem [91]	58.97	166.7
1.5% Nano Cu-PCM	Lin and Al-Kayiem [91]	58.15	160.3
2.0% Nano Cu-PCM	Lin and Al-Kayiem [91]	57.81	157.3
-	Nabavitabatabayi et al. [92]	57 - 61	185
Composite based on compressed expanded graphite	Haillot et al. [93]	58	190
Graphite-PCM compound	Padovan and Manzan [94]	25 - 60	-
OM 37	Gaur et al. [95]	37	211
75% Capric acid + 25% palmitic acid	Browne et al. [96]	17.7 - 22.8	189 - 191
Paraffin wax	Imam et al. [97]	56	256
Paraffin wax	Sardarabadi et al. [98]	42 - 72	200 - 220
Octadecane mixed with silica	Liu et al. [99]	28.47	226.26
-	Liu et al. [100]	28	175
-	Su et al. [101]	22.8	210
Paraffin wax	Kabeel et al. [102]	54	190
Paraffin wax	Khadraoui et al. [103]	56 - 60	214.4
Rubitherm RT42	Charvat et al. [104]	38 - 43	174 ± 7.5%
RT-21	Navarro et al. [105]	21	134
RT-21	Navarro et al. [106]	21-22	134
RT22HC	Osterman et al. [107]	-	181 ± 9
SP24E	Lin et al. [108]	21 - 25	190

Paraffin wax	Karthikeyan et al. [110]	55.5 - 66.5	-
Granular PCM including paraffin wax	Belmonte et al. [111]	27	44
AC27	Arfaoui et al. [112]	27	192.6
-	Su et al. [113]	28	210
Rubitherm PX-21	Arkar and Medved [114]	19.6	86
Rubitherm PX-21	Arkar et al. [115]	19.6	86
Paraffin wax	Shalaby and Bek [116]	49	-
$Na_2SO_4 \cdot 10H_2O$	Ndukwu et al. [117]	32	252
Paraffin wax	Rabha and Muthukumar [118]	58 - 60	-
Paraffin wax	Reyes et al. [119]	56 - 58	200 - 220
Paraffin wax	Jain and Tewari [120]	-	-
Paraffin wax	Baniasadi et al. [121]	70	-
Rubitherm RT18HC	Massana et al. [122]	17 - 19	250
AC27	Bouadila et al. [123]	27	192.6
-	Zhou et al. [124]	42	140
AC27	Kooli et al. [125]	27	192.6
Paraffin wax	Ziapour and Hashtroudi [126]	53	188
RT54	Lu et al. [127]	55	179
38% Urea+62% acetamide	Li et al. [128]	53	224
Sodium acetate trihydrate	Li et al. [128]	58	266
Palmitic acid	Li et al. [128]	61	222
S19	Vadiee and Martin [129]	19	160
-	Kelly et al. [130]	48	210
RT44HC	Zou et al. [131]	43	255
-	Kuznik et al. [132]	30 - 45	100 - 300

CT00	Kong et al. [133]	39.5	132
CT01	Kong et al. [133]	38.4	190
CT02	Kong et al. [133]	36.9	169
CT03	Kong et al. [133]	41.7	139
RT27	Qi et al. [134]	28 - 30	179
66% capric acid + 34% lauric acid	Qi et al. [134]	20.4	138.8
Enhanced acid	Qi et al. [134]	20.4	138.8
Mikrotek 37D paraffin	Stathopoulos et al. [135]	37	226.8 - 230

4.2. Encapsulation forms of PCM

The encapsulation forms of PCM in these applications are mainly classified into direct incorporation, macro-encapsulation, micro-encapsulation, immersion [41]. Direct incorporation is the approach of directly mixing PCM and building materials, such as plaster and cement mortar. Macro-encapsulation is the approach of encapsulating PCM into the container, such as tube, panel and slab. Micro-encapsulation is the approach of encapsulating PCM using the microscopic support material, including high-density polyethylene and styrene-butadiene-styrene. Immersion is the approach of dipping the porous building material into melting PCM. After analyzing the reviewd literatures, it could be found that macro-encapsulation was the most popular way to investigate the applications of PCM for heating purpose. This phenomenon might be caused by that the research background of scholars was engineering. They mainly solve the problem of the encapsulation in an engineering method, i.e. macro-encapsulation. The second popular way was using micro-encapsulation. The microscopic support material might prevent the leakage of PCM, contributing to better exerting the fucntions of PCM. A popular way was to firstly complete the micro-encapsulation of PCM, and then mix it with building materials. This means should be advocated. However, this encapsulation form was not easy to use in a large-scale practical application. The reason was that the mass fraction of PCM in this encapsulation form is low, leading to low latent heat. Direct incorporation and immersion were the most unpopular way. Although they could realize the encapsulation of PCM in a simple and economic method, they might cause the leakage of PCM, reducing its working life in building applications. Scholars might focus on the investigation of more practical and efficient ways to encapsulate the PCM.

4.3. Types of PCM units

In this review analysis, the typical types of PCM unit are classified into plate PCM container, PCM plasterboard, PCM storage tank, shell and tube PCM, PCM ball, and PCM packed bed. After analyzing the reviewd literatures, it could be found that in the reviewed literatures plate PCM container was the most popular type; shell and tube PCM was the second popular type; PCM storage tank was the third popular type; PCM plasterboard was the fourth popular type; PCM packed bed was the fifth popular type; and PCM ball was the most unpopular type. In the passive applications with PCM, plate PCM container and PCM plasterboard were used; while in the active applications with PCM, plate PCM container, PCM storage tank, shell and tube PCM, PCM ball, and PCM packed bed were used. More research works might be conducted to use PCM ball, in which the volume of the ball was evidently larger than that in PCM packed bed. However, PCM packed bed could better enhance the HTE between PCM and HTF. This might be the reason why the PCM packed bed was more popular than PCM ball.

5. Discussion on research methods

The research methods used in the reviewed litertures are classified into: modelling and simulation studies, experimental studies, and performance studies. After analyzing the reviewd literatures, it could be found that the number of literatures conducting the performance study was most; and the number of literatures conducting the modelling and simulation study and experimental study were almost same.

For modelling and simulation studies, mostly used simulation tools and software were: MATLAB, TRNSYS, CFD, EnergyPlus, COMSOL Multiphysics, FORTRAN, and ESP-r. It could be found TRNSYS was the most popular software; MATLAB and FLUENT were the second popular software; EnergyPlus was the third popular software; COMSOL Multiphysics was the fourth popular software; FORTRAN was the fifith popular software; and ESP-r was the most unpopular software. It should be noted that in some simulation studies the calculation formulas were presented, but the used simulation tools or software were not mentioned. The formulas presented in these studies could be used to model the heat transfer process occurring at the investigated system. FLUENT and COMSOL Multiphysics was the popular software to simulate the heat transfer process of thermal energy storage systems, especially for specified PCM units. The scholars could use the existed model in the FLUENT and COMSOL Multiphysics to complete the simulation process. However, meshing high-quality grids might confuse some scholars. In addition, it was hard to use the FLUENT and COMSOL Multiphysics to model a thermal energy storage system which included multiple components and complicated control strategies. To realize the dynamic simulation of a thermal energy storage system, TRNSYS including comprehensive libraries with a variety of components could play an important role. It could connect with other software including MATLAB and FLUENT, which could better realize the simulation of a system. EnergyPlus could be used to establish the model of the buildings, and thus it was usually used to analyze the energy performance of the buildings with PCM walls, roofs, ceilings, and floors. MATLAB and FORTRAN could be used to simulate the heat transfer process of PCM units by the means of codes. Thus, strong knowledge of heat transfer and coding were required for well using these two tools. ESP-r was usually used to simulate the energy performance of buildings integrated with different components. Although few studies in the reviewed literatures used the ESP-r, it was still possible to use the ESP-r to conduct the simulation of a thermal energy storage system.

Experimental studies are classified into: short-term and long-term experimental studies. The literature is regarded as a long-term experimental study when the tested period exceeded 15 days, otherwise the literature is regared as a short-term experimental study. It was found that the number of the long-term experimental study was evidently less than that of the short-term experimental study, which suggested that the long-term experimental study should be performed more. The cost of conducting long-term experimental study might be high, and thus long-term study based on the real implementation of applications might be used to obtain same effects with long-term experimental study.

Performance studies are classified into: thermal performance analysis, energy performance analysis, economic performance analysis, exergy performance analysis, environmental performance analysis, comparative study between with and without PCM, and performance optimization. It was found that the vast majority of literatures conducted the thermal performance analysis. The second most popular research method was the comparative study that compares the performance of the system with and without PCM, which verify the advantage of using PCM. The third popular research method was the energy analysis, which demonstrated that using PCM in building heating applications could improve the energy efficiency. However, the number of economic analysis, exergy analysis, environmental analysis, and performance optimization were evidently lower. Peformance optimization of these applications was strongly suggested due to effectively enhance the efficiency of the systems.

6. Mathematical models of PCM units

The mathematical models of PCM units are related to the used types of PCM units. As described in Section 4.3, the main used types of PCM units included plate PCM container, PCM plasterboard, PCM storage tank, shell and tube PCM, PCM ball, and PCM packed bed. Since the heat transfer mechanism of the plate PCM container was similar with PCM plasterboard, the plate PCM model was used to denote the models of plate PCM container and PCM plasterboard. In addition, the heat transfer mechanism of the PCM ball was similar with PCM packed bed, and thus the PCM packed bed model was used to denote the models of PCM ball and PCM packed bed. Hence, this section presented four heat transfer models of PCM units, which included plate PCM, PCM storage tank, shell and tube PCM, and PCM packed bed models. The detailed descriptions of these models were shown as follows.

6.1. Plate PCM model

Jin et al. [51] presented a one-dimension plate PCM model, which ignored the effect of the convection on the molten PCM. The effective heat capacity method was used to describe the heat transfer process of the plate PCM unit. The governing equation was shown as Eqn. (1):

$$\rho_p \cdot c_p \cdot \frac{\partial T_p}{\partial t} = k_p \cdot \frac{\partial^2 T_p}{\partial x^2} \tag{1}$$

where ρ_p, c_p, k_p, and T_p are the density, specific heat, thermal conductivity, and temperature of the PCM, respectively. t and x are the time and distance, respectively. Further, Jin et al. [142] presented another one-dimension plate PCM model, in which the enthalpy method was used to describe the heat transfer process of the plate PCM unit. The governing equation was shown as Eqn. (2):

$$\rho_p \cdot \frac{\partial H_p}{\partial t} = k_p \cdot \frac{\partial^2 T_p}{\partial x^2} \tag{2}$$

where H_p is the enthalpy of the PCM. In the first study of Jin et al. [51], the numerical results of the model using effective heat capacity method were compared with the experimental results. Although the detailed error between the numerical and experimental results was not mentioned, it could be found that the numerical results could well fit the experimental results. In the second study of Jin et al. [142], the numerical results of these two models were compared with the analytical results. Although the detailed error between the numerical and analytical results was not mentioned, it could be found that the numerical results could well fit the analytical results.

6.2. PCM storage tank model

Gracia et al. [143] presented a PCM storage tank model. The schematic diagram of the PCM storage tank was shown in Fig. 11, in which the PCM tubes were placed inside the storage tank and surrounded by the HTF. A fully implicit finite volume method was used to describe the heat transfer process between the HTF and PCM. The two-dimension energy governing equation for the PCM was shown as Eqn. (3):

$$\rho \cdot \frac{\partial H}{\partial t} + \rho \cdot u \cdot \frac{\partial H}{\partial x} = k \cdot (\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial r^2}) \tag{3}$$

where ρ, H, u, k, r, and T are the density, enthalpy, velocity, thermal conductivity, radius, and temperature, respectively. In the study of Gracia et al. [143], the numerical results of this model were compared with the experimental results in other literature. Although the detailed error between the numerical and experimental results was not mentioned, it could be found that the numerical results could well match the experimental results.

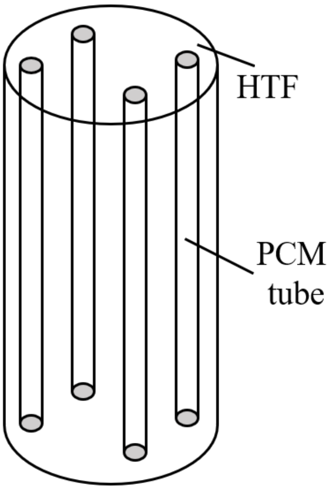

Fig. 11. Schematic diagram of PCM storage tank [92].

6.3. Shell and tube PCM model

Parsazadeh and Duan [144] presented a shell and tube PCM model. The schematic diagram of the investigated shell and tube PCM unit was shown in Fig. 12, in which the HTF flowed through the center of the PCM unit. The volume of fluid method was used to simulate the heat transfer process between the PCM and HTF. The energy governing equation was shown as Eqn. (4):

$$\frac{\partial}{\partial t}(\rho \cdot H) + \frac{\partial}{\partial x}(\rho \cdot u \cdot H) = \frac{\partial}{\partial x}\left(k \cdot \frac{\partial T}{\partial x}\right) \tag{4}$$

The enthalpy porosity method was used to describe the phase change process. The H_p could be determined by Eqn. (5):

$$H_p = H_r + \int_{T_r}^{T_p} c_p \cdot dT_p + \beta \cdot L_p \tag{5}$$

where T_r is the reference temperature; H_r is the enthalpy of the PCM at the reference temperature; β is the liquid fraction; and L_p is the latent heat of the PCM. In the study of Parsazadeh and Duan [144], the numerical results of this model were compared with the numerical and experimental results in other literatures. It was found that the average deviations of this model were 7.8% and 1.8%, respectively.

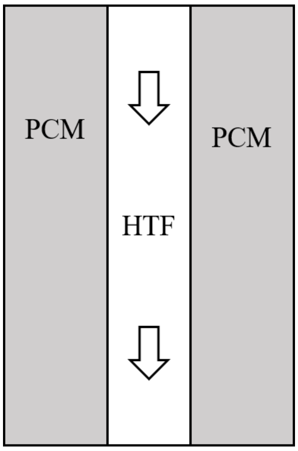

Fig. 12. Schematic diagram of shell and tube PCM unit [144].

6.4. PCM packed bed model

Peng et al. [145] presented a PCM packed model. The schematic diagram of the PCM packed bed was shown in Fig. 13, where the PCM was encapsulated into the capsules that were surrounded by the HTF. The energy equations were presented in the form of liquid and solid phase. The solid-phase equation was shown as Eqn. (6):

$$(1-\varepsilon)\cdot\rho_s\cdot c_s\cdot\frac{\partial T_s}{\partial t}=(1-\varepsilon)\cdot k_s\cdot\frac{\partial^2 T_s}{\partial x^2}+h_{sl}\cdot(T_l-T_s) \tag{6}$$

where ε is the porosity; h_{sl} is the volumetric heat transfer coefficient between the liquid and solid; T_l is the temperature of the liquid; and ρ_s, c_s, T_s, and k_s are the density, specific heat, temperature, and thermal conductivity of the solid, respectively. The liquid-phase equation was shown as Eqn. (7):

$$\varepsilon\cdot\rho_l\cdot c_l\cdot\frac{\partial T_l}{\partial t}+\varepsilon\cdot u_l\cdot\rho_l\cdot c_l\cdot\frac{\partial T_l}{\partial x}=\varepsilon\cdot k_l\cdot\frac{\partial^2 T_l}{\partial x^2}+h_{sl}\cdot(T_s-T_l)+h_{wl}\cdot(T_w-T_l) \tag{7}$$

where u_l is the velocity of the liquid; h_{wl} is the volumetric heat transfer coefficient between the wall and liquid; T_w is the temperature of the wall; and ρ_l, c_l, and k_l are the density, specific heat, and thermal conductivity of the liquid, respectively. In the study of Peng et al. [145], the numerical results of this model were compared with the experimental results in other literature. It could be concluded that the average deviations of this model were 4.32% and 5.18%, respectively.

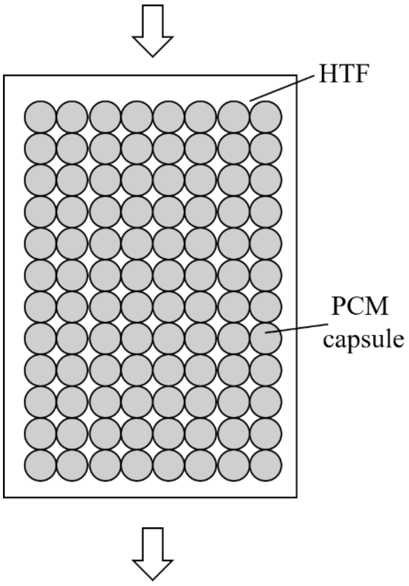

Fig. 13. Schematic diagram of PCM packed bed [145].

7. Conclusions and future recommendations

A comprehensive review of building heating applications with the PCM was presented in this study. Research development of passive and active applications was summarized with the key findings. The summarized passive applications included the PCM roofs, ceilings, and walls, PCM windows, PCM floors, and solar chimneys with PCM; and the summarized active applications included the SHPs, HPPs, and EHPs. Discussions on the PCM utilization and research methods in the reviewed literatures were presented. The important conclusions are depicted as follows:

1. PCM roofs, ceilings, and walls have the merits of heating demand reduction, enhancement of thermal comfort, and better utilization of solar energy. Numerical and experimental studies are performed to deeply investigate the performance of this application. EnergyPlus and CFD are adopted to perform the performance optimization of this application.
2. Further investigations of the PCM windows are needed to be conducted for checking its effectiveness in cold seasons, because current research results show that this application might be not economically feasible.
3. PCM floors have the merits of energy saving pential, improvement of indoor thermal comfort, and high room temperature in cold season. A new performance indicator “PCM

activity" is proposed in the performance optimization of this application. Deeper investigations of this application are needed, such as how to arrange the pipes and PCM could result in better system performance.

4. Novel designs including novel triple glass, utilization of longitudinal vortex generators, and novel solar PCM wallboard, are adopted in solar chimneys with PCM for enhancing its performance. Performance optimization of this application are needed, such as what the optimal configurations of this application are.
5. SDPs have the merits of higher freshwater yield, higher energy and exergy efficiency. Changing water flow rate and using the composite PCMs with higher thermal conductivity, are considered as two effective means to improve the performance of this application. Performance optimization of this application are needed, such as what the optimal water flow rate and types of PCMs that can cause the maximum energy efficiency are.
6. SDHPs have the merits of more hot water supply, more heat loss reduction, and shifting peak power demand. A number of parametric studies are performed to investigate the performance of this application. Nove designs including slurry PCM, liquid-flow window, multi-type PCM packed bed, and composite PCMs are adopted in this application. Single-objective and multi-objectives optimization of this application are conducted for optimizing the system performance.
7. PTPs have the merits of higher hot water temperature, higher energy and exergy efficiency. Slurry PCM is adopted in this application for improving the system performance. To obtain maximum thermal energy, performance optimization of this application is conducted.
8. SBAPs have the merits of higher energy efficiency, energy use reduction, and higher outlet air temperature. PCM packed bed is adopted in this application for enhancing the HTE. Performance optimization is conducted to identify the optimal position of PCM layer, air flow rate, and mass of PCM in this application.
9. SDSPs have the merits of good drying effect, higher moisture content removal, drying time reduction, and shorter payback period. Deeper investigations and performance optimization of this application are needed, such as how to use minimum energy for

drying products.

10. SGPs have the merits of more heat supply, and environmental impacts reduction. More concern should be paid on deeper investigations and performance optimization of this application, such as how to utilize less energy for producing more foods.
11. ASHPPs have the merits of enhancement of economic benefits, and increasing thermal capacity. Performance optimization is conducted to identify the optimal type of PCM and exchanger surfaces.
12. Slurry PCM and adopting PCM as backfill material are main applications in GSHPPs. Deeper investigations are needed, because slurry PCM could improve the HTE while its preparation might be hard; and too many amounts of PCM filled in the soil might cause high initial investment.
13. EHPs have the merits of peak shaving, and two optimization methods are proposed and compared in this applicaton.

In addition, future possible research opportunities are proposed to guide scholars in the aspects of building heating applications with PCM, depicted as follows:

1. Composite PCMs, especially eutectics with paraffin, with more comprehensive thermal properties, should be encouraged to be used in building applications.
2. PCM slurry, fins, and PCM packed bed, which can effectively improve HTE, is highly suggested in building applications.
3. Long-term experimental study, economic analysis, exergy analysis, environmental analysis, and performance optimization, of building heating applications with PCM should be further conducted, especially for real applications to follow up the real implementation
4. Investigations of SDSPs are mainly based on experimental studies. Necessary simulation and performance optimization are needed.
5. In addition to water and air considered as HTF in solar heating applications, other kinds of HTF should be considered for exploring their application prospect.
6. Practical and efficient control strategies for building heating applications with the PCM should be proposed for further enhancing the performance of the systems.

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