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Review

Review on building energy performance improvement using phase change materials

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ABSTRACT

Confronted with the crises of the growing resource shortages and continued deterioration of the environment, building energy performance improvement using phase change materials has received much attention in recent years. This review work provides an update on recent developments, 2004 ~ 2017, in phase change materials used to optimize building envelope and equipment. Firstly, a review of building envelope optimization methods by integrating surrounding wall, roof, and floor with phase change materials, is given. This is followed by reporting articles on building equipment optimized with phase change materials to reduce regular energy consumption. Series of air cooling, heating, and ventilation systems coupled with thermal energy storage were comparatively investigated. Finally, the existing gaps in the research works on energy performance improvement with phase change materials were identified, and recommendations offered as authors' viewpoints in 5 aspects. It was also found that the phase change temperature range of PCMs used was changed from 10 ~ 39 °C for envelope to −15.4 ~ 77 °C for equipment. We believe this comprehensive review might provide an overview of the analytical tools for scholars, engineers, developers, and policy designers, and shed new light on the designing and performance optimization for PCMs used in building envelope and equipment.

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Abbreviations: A/C, air-conditioning; ASHP, air source heat pump; CFD, computational fluid dynamics; COP, coefficient of performance; FEM, finite element method; LH, latent heat; PCM, phase change material; PPD, predicted percentage dissatisfied; PV, photo-voltaic; PVT, photo-voltaic thermal; TES, thermal energy storage.

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1. Introduction

Due to the thermal characteristics of phase change materials (PCMs), they have found wide applications in different fields, such as building envelope, industry thermal energy storage (TES), battery thermal management, electric/power peak regulation, smart thermal fibers and clothing. In recent years using PCMs in buildings to improve the indoor thermal environment by balancing the environment temperature has attracted more and more attentions. As the temperature increases, the material changes its phase from solid to liquid. The reaction being endothermic, the PCM absorbs heat. Similarly, when the temperature decreases, the material changes its phase from liquid to solid. The reaction being exothermic, the PCM desorbs heat. The integration of PCM in building envelope and building service equipment, is a way to enhance the energy storage capacity of enclosures and then to rationalize the use of renewable and nonrenewable energies. Consequently, not only the building energy performance could be optimized, but also indoor thermal comfort improvement is expected because of its thermal environment regulated at the 'thermal comfort zone'. As shown in Fig. 1(a), heat transfer processions around building enclosures are complicated, consisting of three types of heat transfer processions, conduction, radiation, and convection. Although many literatures are reported, concentrating on the topic of PCMs used to improve indoor thermal comfort and decrease building energy consumption by regulating the heat and mass transfer process, the topics of building and PCMs are not comprehensively discussed and specially reported.

On the other hand, Fig. 1(b) shows the schematic diagram of a natural room temperature and the integrated degree of discomfort in winter and in summer [1]. The integrated degree of discomfort in summer, I_{sum}, is the region below the natural room temperature and above the upper limit of the comfortable region, and the integrated degree of discomfort in winter, I_{win}, is the region below the lower limit of the comfortable region and above the natural room temperature. It could be found that the temperature of indoor air changes as the ambient air temperature, and keeps little later. In addition, the maximum of indoor air temperature is little lower than that of ambient air temperature, but the minimum of indoor air temperature is much higher than that of ambient air temperature due to equipment used inside. Regulating the room temperature at the thermal comfort range could directly and effectively decrease the degree of discomfort.

Therefore, this review paper provides an update on recent developments in PCMs used in buildings, where human body exists most time in a day. The paper, broadly contained three main sections, begins with a review of building envelope optimization methods with PCMs. This is followed by reporting a review of building service equipment optimized with PCMs to reduce regular energy consumption. Finally, the existing gaps in the research works on energy performance improvement with PCMs will be identified. After suggestions for future work are listed, the conclusions are given.

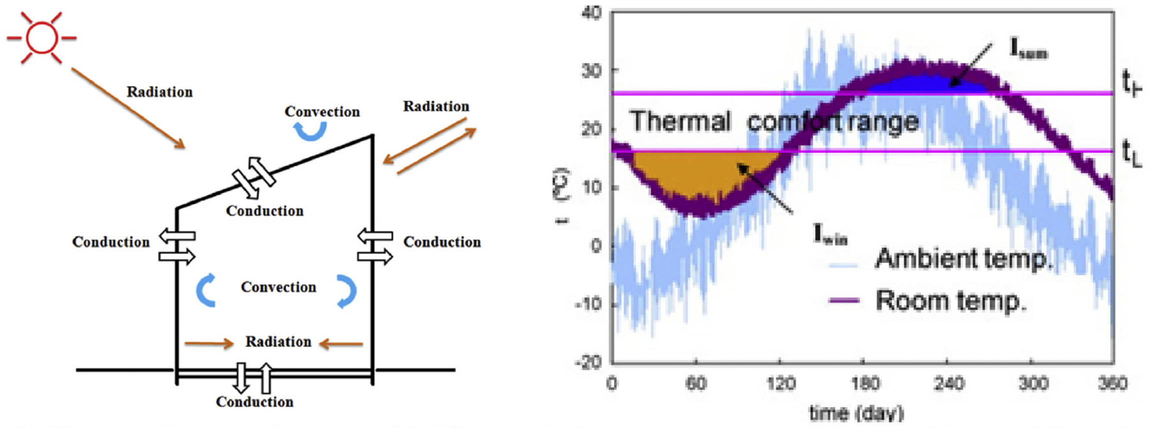
2. PCMs used in building envelope optimization

As shown in Fig. 1(a), the heat transfer procession in a building is a quite complex object submitted to internal and external solicitations. External solicitations are due to the local external weather. Internal solicitations come from solar radiative flux entering the building and internal loads. A high-energy efficiency building must have an energy efficient envelope that can ensure the thermal comfort of occupants with a minimum system energy requirement [2]. From this point of view, TES in the envelope is a key factor [3,4], which consequently promotes the applications of PCMs.

At the same time, PCMs have relatively large latent heat (LH) of fusion. Incorporating PCMs into building walls, roofs, and floors, can potentially increase the thermal mass of these enclosure components, which could not onfly decrease heat transfer rates during peak hours, but also reduce the relatively large interior temperature fluctuations. Ambient temperature fluctuation effects on building envelope are weakened by PCM-TES systems, and thus room temperature fluctuating at the thermal comfort range is expected. Therefore, more and more researchers pay their attention to building envelope optimization by using PCMs.

2.1. Surrounding wall

While space conditioning load contributes largely to the grid critical peak, shifting it partially or entirely to the off-peak period could have significant economic impact on both energy supply and demand sides. This shifting technique is accomplished by storing energy during off-peak periods in order to be utilized during peak periods. The building envelope integrated with PCMs can provide LH-TES distributed in its entire surface area



(a) Heat transfer processions around building (b) Room temperature and integrated degree of discomfort

Fig. 1. Building energy performance and indoor thermal comfort [1].

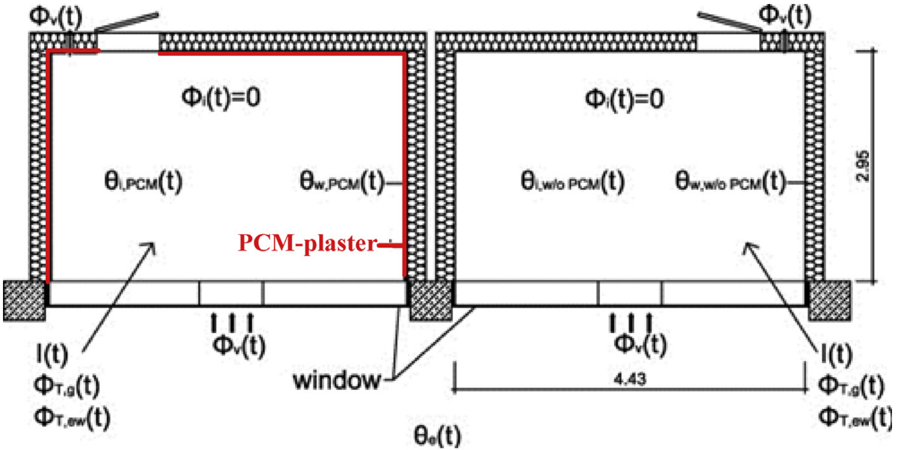
and inhibit the enhanced thermal mass in light weight buildings. And thus, building energy performance optimization could be expected.

2.1.1. PCM-gypsum plasterboard

It is easy to understand that using PCM gypsum in surrounding wall to optimize the building energy performance. Firstly, Schossig et al. [5] investigated the performance of two full-size test rooms with a lightweight construction consisting of gypsum plasterboard mounted on wooden slats with insulation as façade, with the wall coated with PCM and reference plaster respectively. Although the measured data show the potential for PCM products to reduce the cooling demand and increase the comfort in lightweight buildings, it is also necessary to ensure that the stored heat can be discharged with adequate ventilation, and thus indoor thermal comfort can be effectively improved. Then, similar experimental study on the effect of PCMs on room temperature reduction was carried out by Voelker et al. [6]. As shown in Fig. 2, two rooms are thermally separated in order to offer similar conditions, and behaved thermally equal. As concluded, the temperature reduction was up to 4 °C during peak times compared with a room without PCM. However, the functions of two rooms were not designed and fixed, which makes it is hard to evaluate the indoor thermal comfort level. With the same method, Behzadi and Farid [7] thermally examined two rooms, one reference room with interior walls and ceiling covered with commercial gypsum wallboards, while a second identical room with PCM-gypsum boards impregnated in interior walls and ceiling, using both experimental and numerical approaches. Finally, as indicated, daily indoor temperature fluctuation was reduced by up to 4 °C on a typical summer day, energy saving needed for air-conditioning (A/C) as high as 34.5%, and energy saving in winter for heating was 21% based on indoor temperature of 20 °C. That means the building energy performance was improved by using PCM-gypsum plasterboard, and thus PCM wallboard also attracts researchers' attention.

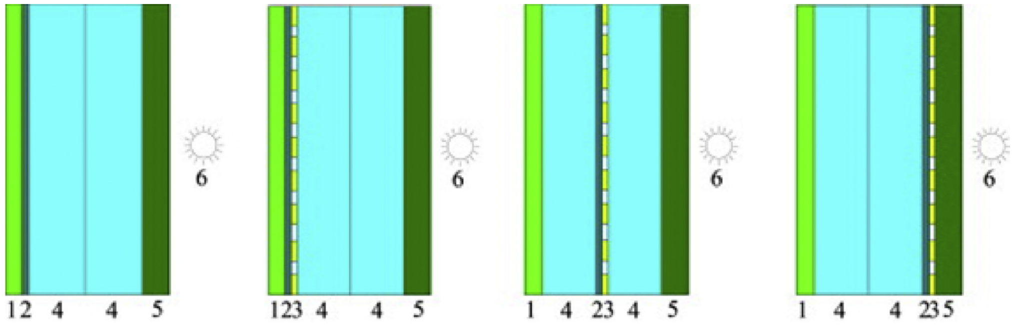
2.1.2. PCM wallboard

Similar to PCM gypsum plasterboard study, the thermal performances of a PCM copolymer composite wallboard was experimentally investigated in a full scale test room by Kuznik et al. [8]. Effects of the PCM were investigated by comparing the results obtained with and without composite wallboards for three cases: a summer day, a winter day and a mid-season day. The experimental results showed that the air temperature in the room with PCM lowers up to 4.2 °C, the comfort enhancement was more important if the surface temperatures were considered. Thermal performance of PCM wallboard was also assessed in a renovated lightweight building by Kuznik et al. [9], with two identical rooms tested: one as reference and one with PCM wallboard positioned immediately behind the plasterboard coating. As concluded, the maximum temperature of the PCM-office was much lower than the reference office and the indoor thermal comfort was enhanced. Then, a two-story typical family house outfitted with PCM walls was built by Mandilaras et al. [10], concluding the decrement factor



(a) Room with PCM plaster (b) Room without PCM plaster

Fig. 2. Test rooms with and without PCM plasterboard [6].



(a) Control wall (b) Internal side (c) At middle (d) External side

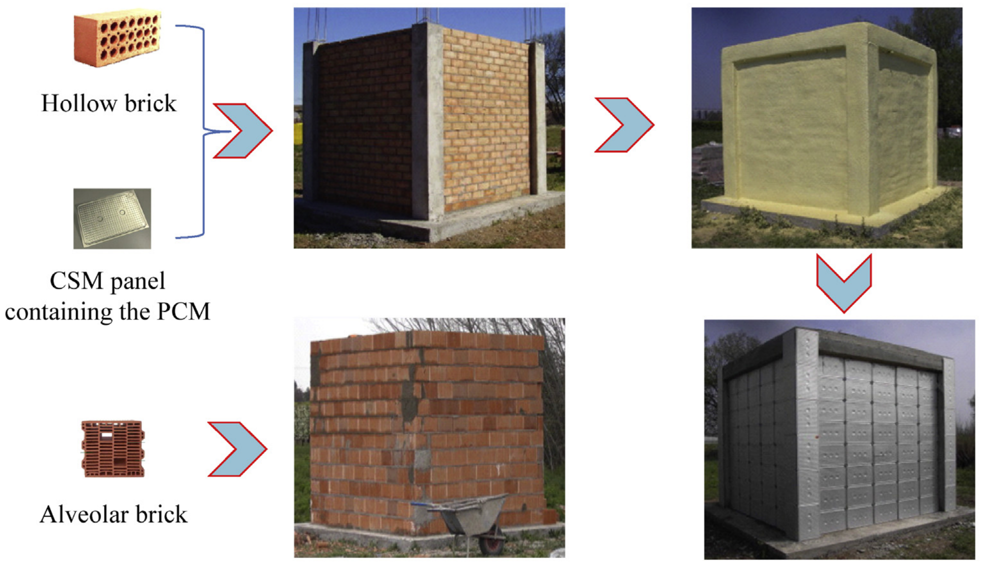
Fig. 3. Construction of the walls with PCM at different locations [11].

was reduced by 30–40% and the time lag was increased by approximately 100 min. These above studies promote the development of PCM building materials, and then PCM location within building walls was recognized to be critical for the optimum performance of the system by Jin et al. [11]. And thus, a prototype PCM thermal shield was developed and its thermal performance evaluated in three different locations, as shown in Fig. 3. As reported, compared to a wall without a PCM thermal shield, the peak heat fluxes were reduced by as much as 11% when the thermal shield placed in the inward-most location next to the internal face of the gypsum wallboard within the wall cavity. The PCM thermal shield produced only small effects on the peak heat fluxes when it was placed half way between the enclosing surfaces of the internal cavity, and placed next to the internal face of the outermost layer of the wall. However, it is demonstrated that building energy performance could be effectively improved when the envelope of bedroom is built as dynamic wall.

2.1.3. *PCM plastering mortar, concrete, brick and cubicle*

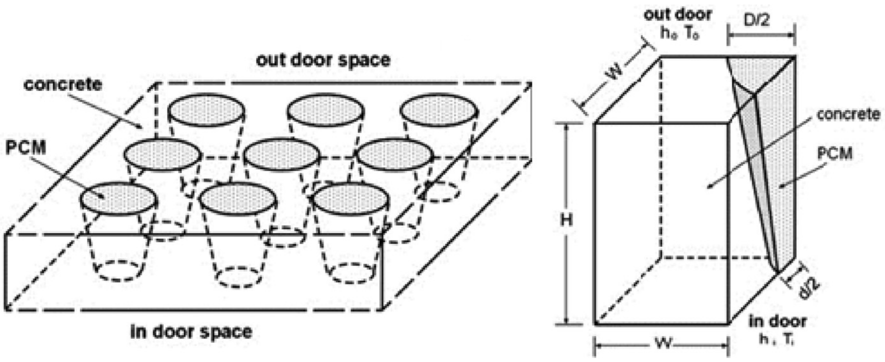
Building materials with incorporated PCMs are meant to increase heat storage capacity, enable stabilization of interior surface temperature of buildings whereby influencing the thermal comfort sensation and the stabilization of the interior ambient temperatures. A new innovative concrete with PCM on thermal aspects was investigated by Cabeza et al. [12], showing the energy storage in the walls by encapsulating PCMs and the comparison with conventional concrete without PCMs leaded to an improved thermal inertia as well as lower inner temperatures. Then, two typical construction materials, conventional and alveolar brick, were experimentally tested by Castell et al. [13]. Several cubicles were constructed and their thermal performance throughout the time was measured, as shown in Fig. 4. The free-floating experiments showed that the PCM was reduced the peak temperatures up to 1 °C and smoothed out the daily fluctuations. Moreover, the electrical energy consumption was reduced about 15% in the PCM cubicles in summer. These energy savings resulted in a reduction of the CO_2 emissions about 1–1.5 kg/year/m^2. Later, to control and shape the PCMs, a new composite construction material that embedded micro-encapsulated PCM in plastering mortar was developed and tested by Sá et al. [14], indicating the peak temperature of the indoor air was reduced by 2.6 °C after the PCM mortar used. That means, when the PCMs are used in plastering mortar, concrete, brick and cubicle, the thermal environment control performance could be improved, as well as the structure stability of buildings unaffected.

(a) Brick cubicle (b) Brick cubicle with polyurethane

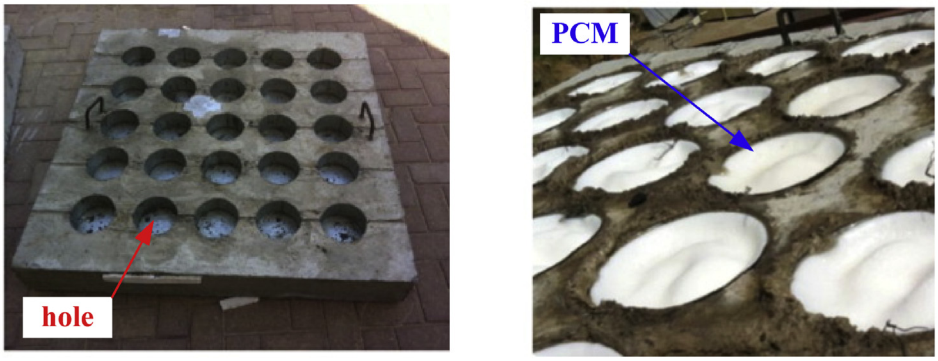


(d) Alveolar brick cubicles (c) Brick cubicle with PCM and polyurethane

Fig. 4. PCM bricks and the test cubicles [13].



(a) Schematic of the roof with PCM-holes (b) Numerical conditions



(c) Concrete roof with empty holes (d) Concrete roof with PCM-holes

Fig. 5. Numerical study conditions and photos of roof with PCM-holes [20,21].

In previous studies, the PCMs was placed at different positions close to the indoor environment, such as next to the internal face of gypsum board [5–7], close to the interior surface of the wall [8–11], or within the insulation cavity of the exterior wall [12,13]. This is because PCMs have their own melting temperature ranges and given that temperature profiles across walls differ, and PCMs experience different thermal cycles when they are placed in different locations within walls. However, none of studies have considered the PCM layer position in a function-fixed room, experimentally and numerically investigated the indoor thermal environment. Only few scholars, such as Castell et al. [13], paid attention to the economic and environmental performance after PCMs used in envelope.

2.2. Roof

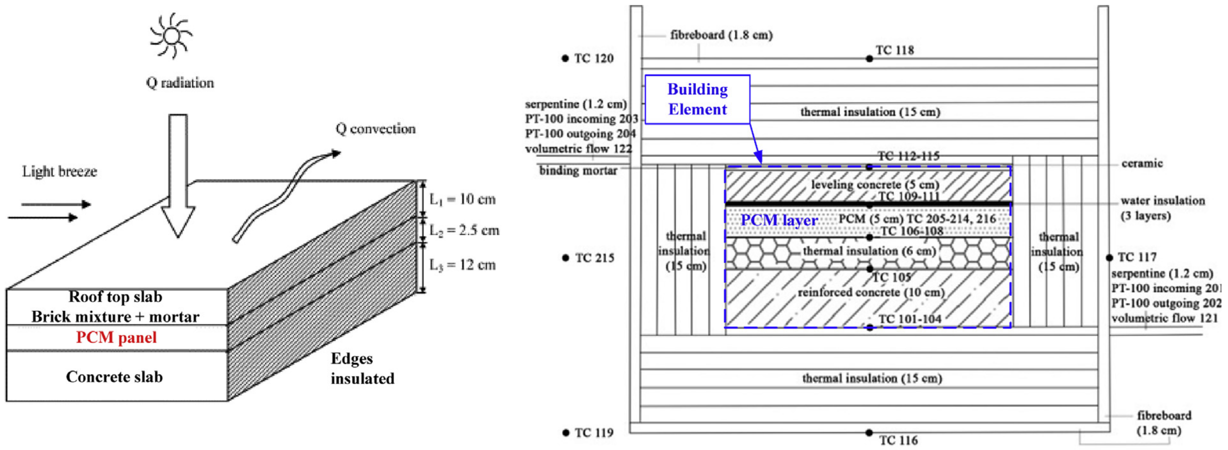
Roofs receive the most intense solar heat load among all building envelope surfaces in Equatorial-region. Solar heat gain through roof contributes to a significant portion of building heat load [15]. In tropics and sub-tropics where building cooling is needed nearly all-year-round, passive methods to reduce heat gain through roof could provide significant cooling energy-savings [16,17]. Thus, the capability of PCMs to improve indoor thermal comfort conditions and reduce cooling energy demand when included in building roof or ceiling is widely acknowledged [18]. The objective of incorporating the PCMs into the roof structure is to utilize its high LH of fusion to reduce the heat gain during the energy demanded peak hours, by absorbing the incoming energy through the melting process in the roof before it reaches the indoor space.

2.2.1. PCM embedded roof

The effectiveness of PCM integrated with gypsum board as ceiling panels in relation to building energy saving was investigated by using the explicit form of numerical method and specific heat capacity method respectively by Yahay et al. [19]. It was demonstrated that the application of PCM ceiling panels could effectively reduce the energy consumption through active cooling systems. The thermal effectiveness of a building's roof with PCM was numerically studied by Alawadhi et al. [20]. As shown in Fig. 5(a) and (b), the considered model consisted of a concrete slab with vertical cone frustum holes filled with PCM. As indicated, the heat flux at the indoor surface of the roof could be reduced up to 39% for a certain type of PCM and geometry of PCM cone frustum holes. A model was further developed and validated by them [21], with the details of concrete roof with empty holes and PCM-holes shown in Fig. 5(c) and (d). It was reported that heat gain could be reduced significantly with larger PCM holes diameter. For the examine cases in this research, the heat flux at the indoor surface of the roof was reduced between 9% and 17.26%, depending on the selected PCM, working hours, and operating month. Although the PCM embedded roof might affect the roof structure safety, but it is always designed and installed with the structure. Therefore, the integration of design and installation decrease its initial cost [22], which makes it widely used in some green buildings.

2.2.2. PCM multi-layer roof

PCM multi-layer roof also attracts researchers' attention [23]. Pasupathy et al. [24] studied the thermal performance of an inorganic eutectic PCM-TES for thermal management in a residential building, with the construction of PCM roof shown in Fig. 6(a). Two identical test rooms were constructed to study the effects of having PCM panel on the roof of the building. A flat roof element incorporated PCM as a layer was also experimentally and numerically analyzed by Tokuç, et al. [25], with scheme of the experimental setup and location of PCM layer shown in Fig. 6(b). A time-dependent simulation for summer conditions was performed



(a) Location of PCM panel in the multi-layer roof (b) Thermocouple placements in the experimental box

Fig. 6. Construction details of building roof [24,25].

using the climatic data of İstanbul. In consideration of improving building energy performance and saving first cost, a PCM thickness of 2 cm was found to be suitable for use in flat roofs in Istanbul. However, Pasupathy and Tokuc's experimental studies are in the lab, without any field testing results given in a real building.

As a matter of fact, it is hard to test the effects of PCM multi-layer roof on energy saving performance in a real building, due to difficulties of designing, installation and operation. Then, scholars start to numerically investigate it. Typically, a PCM multi-layer roof in Northeast and cold area of China was numerically investigated by Li et al. [26]. As shown in Fig. 7(a) and (b), from top to bottom, four layers were divided in the roof construction. The third layer was the function layer, whose material of common roof and PCM roof was fine stone concrete and PCM, The results showed that the PCM roofs effect on the temperature delay in the room was very strong and the delay time of temperatures peak of base layer in PCM roofs were beyond 3 h than common roof. The effect of transition temperature and LH of PCM on the thermal performance of roofs was relatively weak, compared with the roof slope, PCM layer thickness and absorption coefficients of external roof surface. Later, Roman et al. [27] reported a modeling work that evaluates and compares how cool roof and PCM based roof technologies might perform, with the construction details shown in Fig. 7(c) and (d). Different from the arrangement of Li's study [26], the PCM layer was designed at the second layer. As concluded, the maximum through roof heat gain flux was 54% lower for the PCM roof than the cool roof at a wide range of albedo, the maximum sensible heat flux 40% lower than the cool roof technology for varying albedo. However, the field testing in a real building is still in need as future work in this field.

2.2.3. PCM roof and solar heating system

Solar energy is one of clean, highly-efficient resources. It is pollution-free, renewable and not limited by regions, so it has been quickly popularized and applied in building field. The roof integrated solar heating system was designed and reported by Saman et al. [28], with PCM slabs as its TES unit shown in Fig. 8. As concluded, the effects of sensible heat were reflected in sharp increase in the outlet air temperature in the initial periods of melting and a sharp decrease in the initial periods of freezing. For heating purposes, this means a significant warming effect was perceived during the initial periods of delivering air to the living space. Obviously, this is advantageous from the indoor thermal comfort point of view.

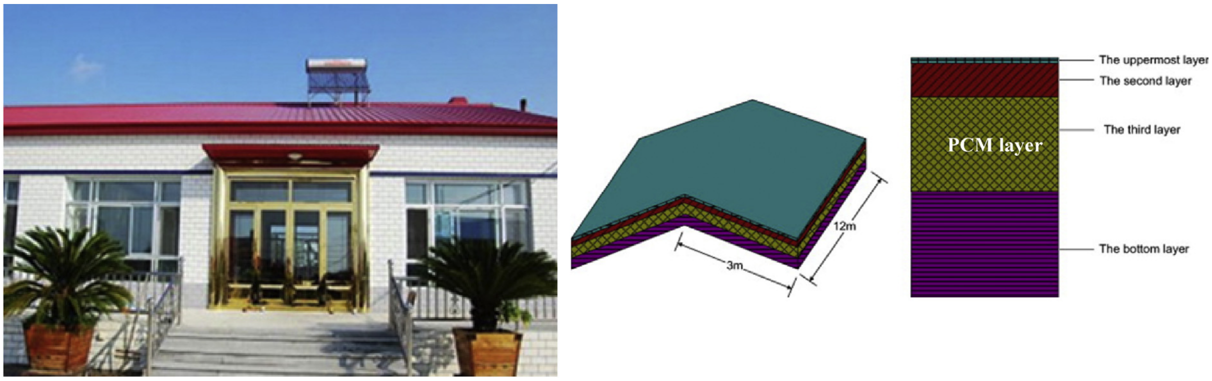
2.2.4. PV(T)-PCM roof

Another solar energy technology, coupled with PCM and used in building roof, is photo-voltaic (PV) technology. As reported by Kośny et al. [29], the roofing technology utilize amorphous silicon PV laminates integrated with thermal loads, as shown in Fig. 9(a). About 30% heating and 50% cooling load reductions were possible with the experimental roof configuration. Ceiling ventilation system integrated with solar PV thermal (PVT) collectors and PCMs were also designed [30], as shown in Fig. 9(b). In winter conditions, the proposed system could significantly improve the indoor thermal comfort of passive buildings without using A/C systems with a maximum air temperature rise of 23.1 °C. The coefficient of thermal comfort enhancement improved from almost 0 to 0.9823, while the coefficient of thermal comfort enhancement improved from 0.0060 to 0.9921. Therefore, the PV(T)-PCM roof can effectively improve building energy performance as expected.

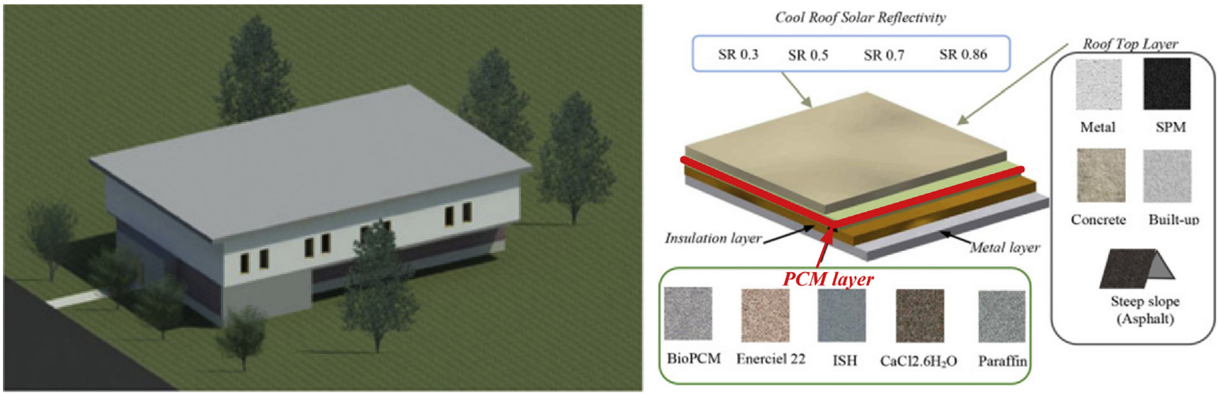
In summary, researchers carried out many studies by using PCMs on roof to save building energy consumption. The PCM embedded roof might affect the roof structure, but PCM multi-layer roof could avoid this disadvantage. PCM roof and solar heating system, PV-PCM roof system and PVT-PCM integrated ventilation system could effectively improve the building energy performance. However, it is hard to accurately control these complicated systems. The increasing initial cost will also limit its wide applications. Although many energy performance improvements studies carried out, few techno-economic analysis work were reported. Moreover, most of researchers did not take indoor thermal comfort influence into consideration in building performance improvement studies. TES systems were widely used, but the PCMs were not comparatively investigated. And thus, thermal reliability and stability of PCMs did not attract enough attention in recent years. Also, it will be a new trend to changing the numerical and/or experimental study in the lab to field testing in a real building.

2.3. Floor

Implementation of PCMs into building components allows their thermal performance to be enhanced, reducing indoor temperature fluctuations and improving the level of indoor thermal comfort. There is no solar heat gain through floor, and thus no solar energy systems coupled with floor structure designing. However, as shown in Fig. 1(a), a lot of energy would be consumed from the floor because of the heat transfer between floor and ground. Thus, it is instructive to study the thermal performance of PCM incorporated floor.

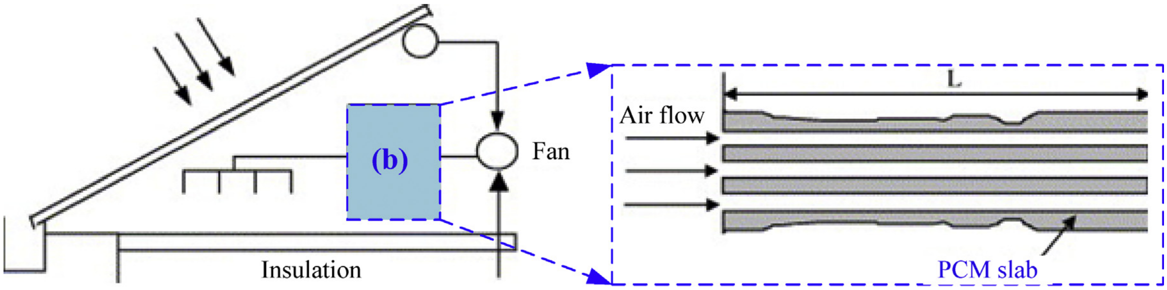


(a) Photo of modeling single residential building **(b) Construction details of the modeling roof**



(c) 3D rendering of the building (Revit) **(d) Construction details of the building roof**

Fig. 7. Prototype of modeling building and construction details of its roof [26,27].



(a) Roof integrated solar heating system **(b) Thermal storage unit with PCM slabs**

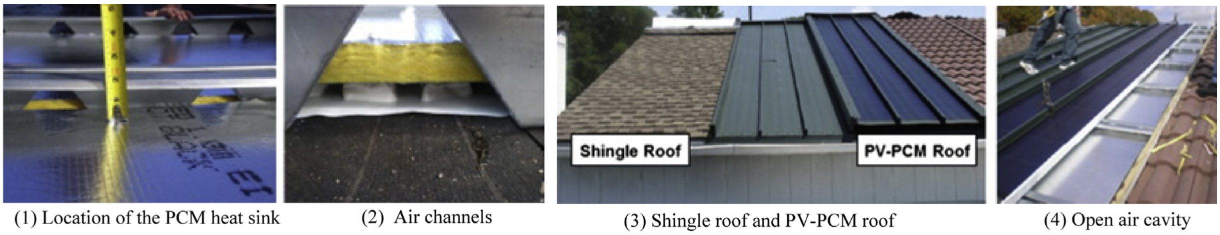
Fig. 8. Roof integrated solar heating system and TES unit [28].

2.3.1. *PCM-concrete floor*

PCM-concrete was firstly made and used in the floor [31], in which thermal energy was stored in a mix of concrete and PCMs through indoor air. When this thermal energy was being released in moderate sea climates during the evening and early night, it was aimed to reduce the need for thermal energy of conventional heating in houses. Fig. 10(a) shows the structure of the box and view on the four test boxes. As reported, the application of PCMs in concrete floors resulted in a reduction of maximum floor temperatures up to 16 ± 2% and an increase of minimum temperatures up to 7 ± 3%. Then, the lab scale was developed to practical application scale. A hollow concrete floor panel was incorporated with PCMs by Royon et al. [32,33], as shown in Fig. 11(b). Thermal response to a temperature variation was also investigated, showing a decrease of the surface wall temperature amplitude and an increase of thermal energy stored for this novel floor. Clearly, it is very convenient for this method to storage energy in the PCMs.

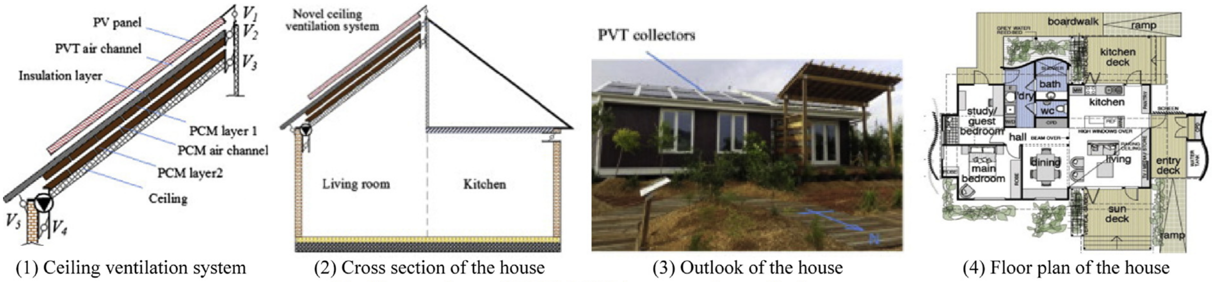
2.3.2. *PCM floor radiation heating system*

PCM concrete floor have the advantages of low cost, convenient installation, few influence on structure, and easily control in production. However, the energy source for it is still limited, due to only taking energy from high temperature indoor air. Then, PCM floor coupled with heating system and PCM floor radiation heating system were designed and investigated, where the heating sources are always electric and/or hot water. For example, Xu et al. investigated the thermal performance of an under-floor electric heating system with the PCM plates in an experimental house, as shown in Fig. 11(a) [34,35]. They found that the indoor air temperature was stable and energy of electric heating system saved with the energy storage of PCM plates. Similar results were concluded by



(1) Location of the PCM heat sink (2) Air channels (3) Shingle roof and PV-PCM roof (4) Open air cavity

(a) Photograph of the PV-PCM roof system



(1) Ceiling ventilation system (2) Cross section of the house (3) Outlook of the house (4) Floor plan of the house

(b) Illustrations of PVT-PCM integrated ventilation system

Fig. 9. PV-PCM roof and PVT-PCM integrated ventilation system [29,30].

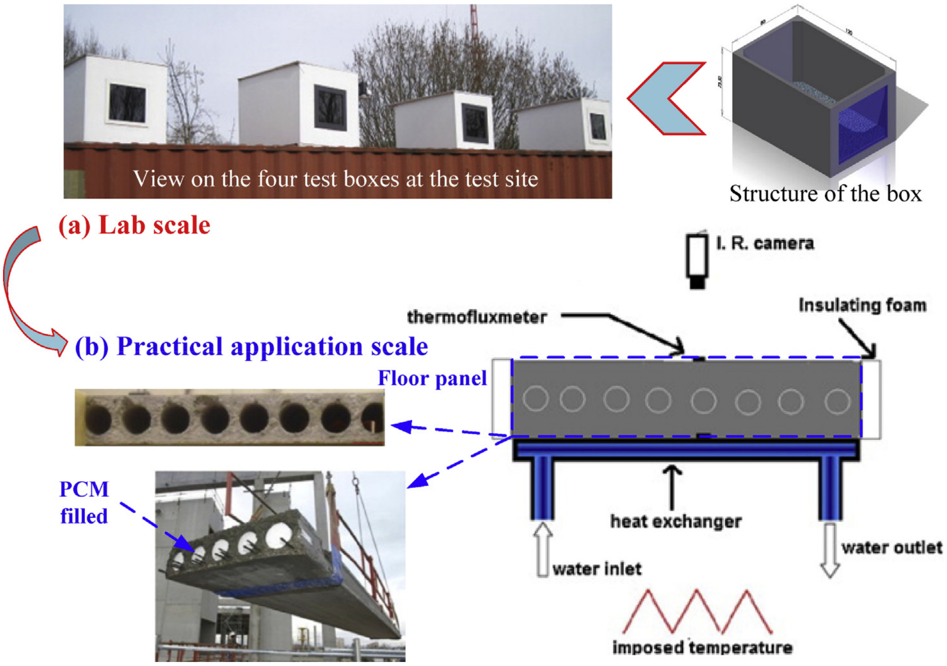
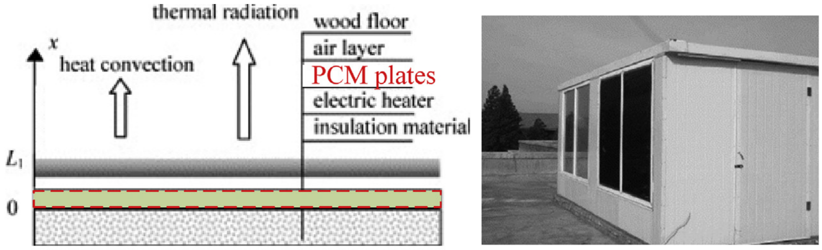


Fig. 10. Structure of the PCM-concrete floor [31,32].

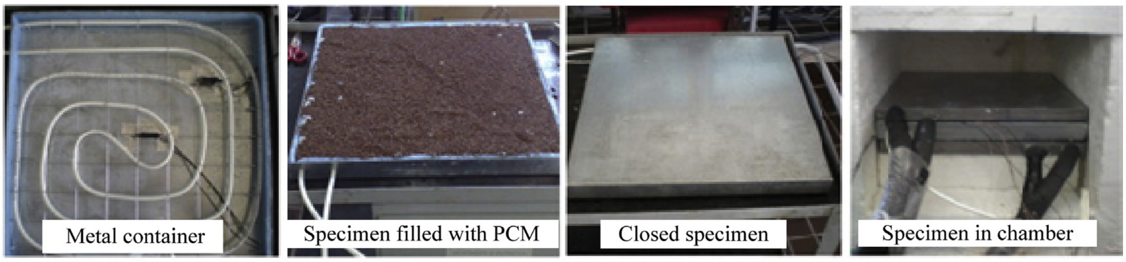
Ansuini et al. [36] using a lightweight piped radiant floor prototype with an integrated PCM layer, with their experimental floor specimen shown in Fig. 11(b). A new PCM floor was also investigated by Huang et al. [37], as shown in Fig. 11(c), revealing the new PCM floor was able to release 37,677.6 kJ heat for 16 h in the pump-off period in a room of 11.02 m^2 and that accounted for 47.7% of energy supplied by solar water. Later, the performance of a PCM floor radiation heating system was experimentally investigated by Zhou et al. [38], indicating the advantages of using PCM-capillary mat combination for low-temperature floor panel typical of solar-hot-water heating system. A two-dimensional coupled heat transfer model based on variable thermophysical parameters of PCM was established by Zhao et al. [39], concluding that the air temperature fluctuation in the cavity with PCM structure was in a smaller magnitude. A new double-layer radiant floor system with organic PCMs was proposed and tested by Xia et al. [40], showing that the double-layer radiant floor system with PCM could meet the thermal need of users under heating mode. The above research studies showed that the designed PCM floor was capable of achieving large-span intermittent heating and lower thermal conductivity for the decoration material, and helpful for adjusting the floor surface temperature in the present design.

2.3.3. *PCM embedded floor and a chilled ceiling*

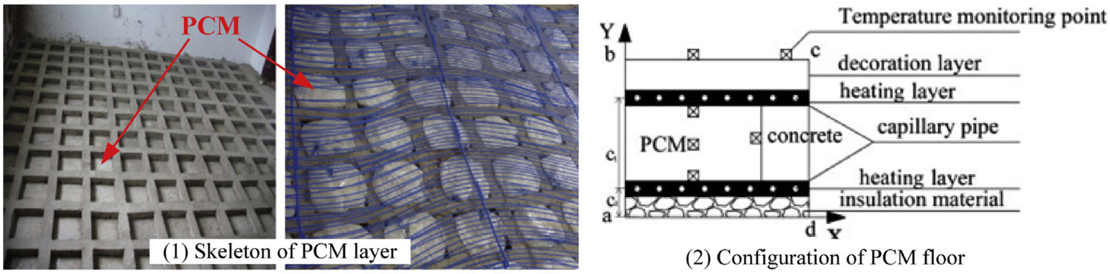
PCM embedded floor and a chilled ceiling also attracted researchers' attention. Belmonte et al. [41] reported a numerical study on PCM incorporated into the floor, and a hydronic radiant ceiling system was used as the energy discharge system. Fig. 12 shows the structure of system and the heat balance on the floor inside face. The simulation results revealed that when accompa-



(a) Under-floor Electric heating system with PCM plates and experimental house



(b) Floor specimen placed and tested inside a small adiabatic room

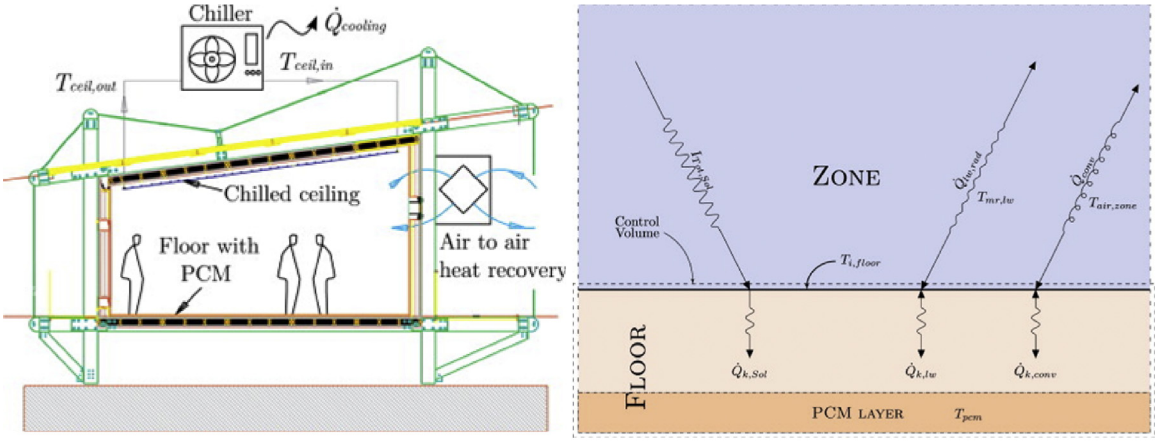


(1) Skeleton of PCM layer

(2) Configuration of PCM floor

(c) Configuration of the novel PCM floor

Fig. 11. Schematic of PCM-electric heating systems [35–37].



(a) Schematic drawing of the simulated 2nd model

(b) Heat balance on the inside face of the floor diagram

Fig. 12. Structure of system and the heat balance on the floor inside face [41].

nied by an air-to-air heat recovery system, this configuration could reduce the cooling energy demand and the energy consumption more than 50%. However, the degrees of occupant comfort will inevitably vary, for example, the predicted percentage dissatisfied (PPD) increases by 2%～5%. In the view of thermal comfort study, this system is valuable to be further investigated.

In summary, studies on PCM-floor are concentrated on two aspects, (1) integrating PCMs into floor materials or PCM slabs as a layer in the floor construction, and (2) coupling a PCM-TES with floor heating system. All researchers payed their attention on energy saving for building, while few of them take the indoor thermal comfort into consideration in their experimental and simulation studies. Although most of experimental cases on PCMs were carried out, most of them were tested in the lab. To exactly calculate the indoor thermal comfort, a true building environment should be prepared, and thus field test in real building should be conducted.

Table 1
Summary of the PCM used in building envelope.

Ref.	Type [a]	PCM used [b]	T_p [c] (°C)	LH (J/g)	Results
[8]	E	Paraffin	13.6	107.5	Air temperature in the room with PCM lowers up to 4.2 °C.
[9]	E	Paraffin	13.6	104.5	The PCM wallboards enhance the thermal comfort of occupants due to air temperature and radiative effects of the walls.
[10]	E	uk	23	175.65	Decrement factor reduced by 30%∼40% and the time lag increased by approximately 100 min.
[11]	E	Organic paraffin	28	179	PCMTS within the first insulation layer reduce peak heat fluxes greater.
[12]	E	Micronal® PCM	26	110	An improved thermal inertia as well as lower inner temperatures reached.
[13]	E	RT-27 and SP-25 A8	28/26	179/180	PCM can reduce the peak temperatures up to 1 °C and smooth out the daily fluctuations.
[29]	E	Binary organic PCM	30	185	About 30% heating and 50% cooling load reductions.
[31]	E	Paraffin	22.12	102.8	Maximum floor temperatures reduced 16 ± 2%, minimum temperatures increased 7 ± 3%.
[35]	E	Paraffin	20∼21	62∼138	For the heating system, the optimal melting temperature is about 40 °C.
[40]	E	Alcohols and Lipids	34.5	170	Thermal need of users met, and thermal layer placed above cold layer is better.
[19]	N	Lauric-stearic acid	34	50.28	Energy consumption effectively reduced through active cooling systems.
[20]	N	Paraffin	36	uk	Heat flux at the indoor surface of the roof can be reduced up to 39%.
[26]	N	uk	30∼38	138∼238	Delay time of temperatures peak in PCM roofs are beyond 3 h than common roof.
[27]	N	Paraffin and $CaCl_2{\cdot}6H_2O$	18∼30.2	152∼196	PCM roof type with a maximum through roof heat gain flux of 54%, and a maximum sensible heat flux of 40%, lower than the cool roof technology for various albedo.
[30]	N	uk	23	190	Indoor thermal comfort is effectively enhanced.
[33]	N	Paraffin	27	110	PCM activity introduced to evaluate the optimal amount of PCM.
[34]	N	Paraffin	10∼25	90∼150	Thickness of SS-PCM plates used under the floor should not be larger than 20 mm.
[39]	N	Octadecane	28.2	242	Thermal conductivity of PCM plays a central role in maintaining air temperature.
[41]	N	Organic material BioPCmat®	20.85	uk	The PCM-floor could reduce the cooling energy demand and the energy consumption more than 50%, but increased the predicted percent dissatisfied (PPD) by 2%∼5%.
[46]	N	Paraffin	23∼26	110	High energy savings are achieved in buildings with PCM-enhanced gypsum technology.
[5]	E&N	uk	25	Uk	PCM products reduce the cooling demand and increase the comfort in lightweight buildings.
[6]	E&N	Paraffin	29.6	244	Indoor peak temperature reduced up to 4 K.
[7]	E&N	Paraffin RT20	21	180	Daily indoor temperature fluctuation reduced by up to 4 °C on a typical summer day, energy saving needed for A/C as high as 34.5%, energy saving in winter for heating is 21% based on indoor temperature of 20 °C.
[14]	E&N	Paraffin	22.86	98.69	Peak temperature of the indoor air was reduced by 2.6 °C when PCM mortar used.
[21]	E&N	Paraffin	28∼39	190∼230	Heat flux at indoor space reduced by 15.93%∼17.26% depending on the operating month.
[24]	E&N	Inorganic salt hydrate	26∼28	188	Roof top surface temperature is slightly higher in the PCM room than the non-PCM room during all the months, and thus the indoor thermal comfort improved.
[25]	E&N	RT27	27	179	A PCM thickness of 2 cm was found to be suitable for use in flat roofs in Istanbul.
[28]	E&N	$CaCl_2{\cdot}6H_2O$	29	uk	For heating purposes, a significant warming effect is perceived.
[32]	E&N	Paraffin	27	110	Design guidelines to minimize the quantity and size of PCM provided.
[36]	E&N	Paraffin	26.5	uk	Radiant floor with PCM for the control of thermal comfort in summer developed.
[37]	E&N	Capric acid	29.3	162	Heat storage capacity of the floor greatly enhanced in solar water floor heating system.
[38]	E&N	Inorganic	29 ± 2	220	PCM gives less temperature variation in floor and needs longer charge time vs. sand.
[47]	E&N	$CaCl_2{\cdot}6H_2O$/expanded graphite	21.67/27.11	115.7/118.7	The optimum thickness of the PCM panels was about 8∼10 mm in this case. The performance of $CaCl_2{\cdot}6H_2O$/expanded graphite in PCM room is better than that of RT27/EG.
[48]	E&N	Paraffin	22	uk	Summer thermal comfort in lightweight buildings was improved.

[a] E: Experimental, N: Numerical.
[b] uk: unknown.
[c] T_p: Melting temperature of PCM.

2.4. Summary

PCMs used in building envelope, including wall, roof and floor, could improve the energy performance of building by regulating indoor air temperature, as well as improving indoor thermal comfort level [42,43]. The following conclusions may be drawn:

(1) In order to clearly distinguish the PCMs used in building envelope, typical studies in recent years were summarized in Table 1. Clearly, both experimental and numerical methods were used in the PCMs investigations. For building envelope thermal performance optimization, paraffin and binary organic acids [44,45] were the mainly choice for PCMs. In addition, most of researchers mentioned the indoor air temperature fluctuation, but few of them evaluated the indoor thermal comfort level.

Table 2
Software tools used in PCM integrated building envelope studies.

Ref.	Year	First author	Software tool
[46]	2017	M. Saffari	EnergyPlus and GenOpt
[47]	2017	R.D. Ye	ANSYS + FLUENT
[27]	2016	K.K. Roman	EnergyPlus
[39]	2016	M. Zhao	ANSYS + FLUENT
[25]	2015	A. Tokuç	CFD
[26]	2015	D. Li	Gambit 2.3 + FLUENT 6.3
[38]	2015	G.B. Zhou	CFD
[41]	2015	J.F. Belmonte	TRNSYS + GENOPT
[30]	2014	W.Y. Lin	TRNSYS
[33]	2014	L. Royon	COMSOL Multiphysics
[37]	2014	K.L. Huang	ANSYS
[21]	2013	H.J. Alqallaf	FEM
[32]	2013	L. Royon	COMSOL Multiphysics
[48]	2013	G. Evola	EnergyPlus 7.0
[14]	2012	A. Vaz Sá	FEM
[20]	2011	E.M. Alawadhi	FEM
[34]	2011	R. Ansuini	FEM
[7]	2010	S. Behzadi	SUNREL 1.04
[24]	2008	A. Pasupathy	Tridiagonal matrix algorithm
[5]	2005	P. Schossig	ESP-r
[28]	2005	W. Saman	Enthalpy formulation

(2) Table 2 shows the software tools used in numerical studies listed in Table 1, consisting of FEM (Finite element method), EnergyPlus, ANASYS, CFD (Computational fluid dynamics), TRNSYS, and FLUENT, etc. Some researchers used two software tools to carry out their investigations. These aforementioned works also promote the development of research tools.

(3) It is found that most of studies around PCM integrated building envelope were experiments of one part or parts of building structure in the lab, with the melting temperature at the range of 10 ~ 39 °C. This might result from the complicated conditions of real building parameters and climates for field testing. However, it is meaningful for testing a fixed function space when PCMs sued in building envelope.

(4) When the PCMs used in building materials, most scholars tested their energy performance, as shown in Table 1. However, more characteristic of PCMs or the integrated building envelope should be constantly monitored and analyzed, including their toxicity, thermal stability and durability, and influence on structure safety. In practice, the economic analysis work should be conducted during designing process.

3. PCMs used in building equipment optimization

PCM are known as an effective technology to store larger amounts of thermal energy per unit mass than conventional thermal mass building materials such as concrete and stone. They add thermal stability to lightweight constructions without adding physical mass. Therefore, integrating PCMs with building envelopes to improve indoor thermal comfort level [49] and save energy attracted so many attentions from researchers all over the world. Similar to the PCMs optimized building envelopes, PCM storage systems can also be put into air cooling, heating, and ventilation systems to store thermal energy from the evaporator or condenser, and thus improve indoor thermal level and optimize building energy performance.

3.1. Air cooling system

In order to improve indoor thermal comfort level, researchers investigated series of PCMs for different air cooling systems, such as TES coupled to an A/C system [50–52], solar cooling systems [53,54], and heat pump units [55,56], etc.

3.1.1. A/C system

It is the electricity unit price promotes the ice storage system [57] coupled to an A/C system in recent decades. The thermal behavior of such coupled system was firstly experimentally analyzed [50]. After the energy storage tank used, the cooling rate was 3.4 ~ 3.8 kW with a coefficient of performance (COP) of 2.1 ~ 2.3 within the LH storage period during the charging process, and the cooling rate was 3.5 ~ 3.0 kW in the discharging process. In a subsequent experimental study, a cold storage A/C system coupled with a spherical ice capsules packed bed [51], showing that in the charging process the COP of the system presented a peak value of 6.4 and it varied from 4.1 to 2.1 during the ice LH storage period. Clearly, the A/C system operating performance improved after combined with PCM-TES. This conclusion was also demonstrated by Parameshwaran et al. [52], with a study on improving the thermal performance and energy efficiency of chilled water based variable air volume A/C system integrated with the silver nanoparticles embedded LH-TES system. Compared to the conventional A/C system, the proposed A/C system achieved an on-peak and per day average energy savings potential of 36% ~ 58% and 24% ~ 51%, respectively, for year round operation. In total, the combined A/C system would be beneficial in terms of accomplishing good thermal comfort, acceptable indoor air quality and energy redistribution needs in buildings without sacrificing energy efficiency.

3.1.2. Solar cooling system

Solar cooling system also attracts more and more attentions, due to the clean characteristics of solar energy. Belmonte et al. [53] investigated the integration of PCMs in the heat rejection loops of absorption solar cooling systems for residential applications, indicating the alternative heat rejection loop with a PCM-TES of 1 m^3 could improve the mean overall system performance coefficient in locations with temperate and humid summers by almost one unit. Similar to Belmonte's study, Cheng et al. [54] designed and reported a packed bed cold storage unit for high temperature solar cooling application. Based on a validated model, effects of inlet heat transfer fluid temperature and flow rate on thermal performance of the unit were discussed in the cold charge process, showing that the unit is feasible in practical high temperature solar cooling application. However, solar energy has the disadvantages of low energy density, instability and unsustainable, which make the prosperous development of PCM-TES coupled with heat pump units.

3.1.3. Heat pump units

Heat pump units use renewable energy from their surroundings (ambient air, water or ground) and “high-grade” energy, e.g. electricity or gas, to raise the temperature for heating or to decrease it for cooling [58]. Combining a PCM-TES system with heat pump units is a promising technology which can lead to taking advantage of both technologies for energy savings and environmental benefits [59]. The first air source heat pump (ASHP) unit coupled to TES tanks was experimentally tested under simulated summer conditions by Moreno et al. [55]. Their experimental results pointed out that the PCM-TES tank was able to supply 14.5% more cold and to maintain the indoor temperature within comfort 20.65% longer than the water tank. However, it needed 4.55 times longer to charge the tank. Then, based on a ground source heat pump (GSHP) system integrated with PCM-TES, Zhu et al. [56] studied the optimal control method of the coupled system in an office building. Considering initial investment and operation cost, the optimal cooling storage ratio was 40% by numerical study. Compared with common GSHP hybrid cooling tower system, the annual cost of the coupled system under cooling storage ratio of 40% was reduced by 34.2%. This shows the great energy saving potential for PCM-TES applied in heat pump units.

In summary, using PCMs in equipment to improve the efficiency of air cooling system attracted many researchers' attentions in recent years. And some of achievements have been widely applied in the air cooling field. Although few researchers definitely mentioned the indoor thermal comfort improved by using PCM-TES in their studies [52,55], most of them did not report thermal comfort evaluation when the air cooling system effectively optimized. Also, it is in need to explore the best control strategy for these above coupled systems, as well as considering their economic and environmental performances.

3.2. Air heating system

PCM presents the advantage of operating within small temperature ranges and, at the same time, accumulating large amounts of heat or cold comparing to sensible storage. PCM-TES systems give the opportunity to shift the load demand from high-cost energy period to off-peak period meeting the thermal loads that occur during high-demand. The purchase of additional equipment for heating can also be deferred and the equipment sizing in new facilities can be reduced.

3.2.1. PCM-TES within the heat pump cycle

ASHP unit was firstly coupled with PCM-TES, which was proposed by Hamada and Fukai [60] when analyzing its system heating and cooling performance. As concluded, the brushes remarkably improve the thermal outputs of the thermal energy storage tanks, resulting in reduction in cost and space. Then, to evaluate the effect of the PCM storage tanks in the heat pump unit on conditions of off-peak electricity tariff, the behavior of a PCM-TES system coupled to a heat pump unit was evaluated [61], showing that only 52% of the theoretical maximum energy was available after 7 h of charging, and the average store tank size needed to cover 100% daily heating of a semidetached house was 1116 l. Similar to Hamada and Fukai [60], although Agyenim et al. [62] also concluded that an improvement on the heat transfer could lead to reduce the store size with a reduction by 30%, the economic performance or indoor thermal comfort was not discussed or evaluated. In recent decades, a solar energy assisted heat pump system was designed and tested by Qv et al. [63], demonstrating remarkable advantages of the PCM-SAHP system on correcting the mismatch between supply and demand of thermal energy and electricity. That means it saved a lot of running cost. In addition, cooling COP of the PCM-SAHP system was enhanced by 17% when the ambient temperature higher than 38 °C, and heating COP rose by 65% when outdoor air temperature was below −10 °C. These meaningful conclusions promote more heat pump systems considered to be coupled with PCM-TES, such as the aforementioned GSHP units and water source heat pump units.

3.2.2. PCM-TES as ASHP defrosting solution

Most of the studies using PCM in an A/C system are focused on solving the frosting problem by adding a storage device within the refrigeration cycle [64]. When an ASHP unit is used for space heating at a low ambient temperature in winter, PCM-TES was also in need for reverse cycle defrosting due to insufficient energy supply [65–67], although many system defrosting optimization presented, such as improving defrosting evenness values [68–70], adjusting the defrosting operating strategies [71,72], eliminating the negative effects of melting frost [73–75], etc. For example, Qu et al. [65] used the PCM-TES based defrosting method, indicating the time period when occupants would feel cold was shortened to 23.1% of previous value, and the durations of PPD value smaller than 10% were prolonged from ~16 min to ~46 min. Clearly, the indoor thermal comfort was efficiently improved. Similarly, Hu et al. [66] investigated the operating performance of PCM-TES based defrosting for another ASHP unit, showing this defrosting method shortened the defrosting time by ~3 min or 38%, and minimized the risk of shutting down the ASHP unit due to low suction pressure through increasing the compressor's suction pressure by about 200 kPa, after the PCM-TES used. In addition, the mean indoor coil surface temperature during defrosting was increased about 25 K. Similar studies were also carried out by Dong et al. [76,77]. From the views of energy saving and thermal comfort improvement, the two aforementioned studies demonstrates the benefits of PCM-TES as ASHP defrosting solution.

In conclusion, similar to using PCMs in equipment to improve the efficiency of air cooling system, more and more researchers paid their attention to air heating system with PCMs considered. Although few researchers definitely reported thermal comfort evaluations when PCM-TES systems used in their studies, there was still many system efficiency optimization studies neglecting to evaluate it or economic performance [78]. In consideration of costing nearly half a day for solar energy, its utilization with PCM-TES is important for us. For an ASHP unit, its problems of frosting and defrosting always occur at night. However, sleep human body model should be different from the awaking one [79,80]. After the PCM-TES systems used as defrosting salutation for a bedroom used ASHP unit, it should be different from the thermal comfort evaluation in Qu's study, especially when the bedroom is changed to ward in hospital or other special spaces. Therefore, the effect of PCM-TES systems as ASHP units' defrosting solution on thermal comfort should be further explored.

3.3. Ventilation system

Spaces with high occupancy density, e.g. classrooms, auditoriums and restaurants, provide challenges to ventilate at a lower energy use due to elevated temperatures. To meet occupants' thermal comfort requirements, traditional systems use a lot of energy. Alternative ventilation strategies that optimize high air movements in the occupied zone allow human activities at elevated temperatures while attaining improve occupants' perception and acceptance of the indoor climate at a low energy use. Recently, PCM-TES systems have been introduced as a good solution to eliminate the mismatch between energy supply and energy demand. PCM-TES coupled with free cooling systems have gained greater attention from the view point of global environmental problems and applications in building ventilation fields.

3.3.1. PCM-TES coupled free cooling system

To augment comfort level and decrease required ventilation power during summer, a ventilation system can be optimized by employing PCM-TES. As experimentally and numerically investigated, the PCM-TES system was able to stabilize diurnal air temperature variation and operated based on the concept of free cooling, so that charging process to PCM-TES comes up with ambient temperature lower than 26 °C and discharging process acts when room temperature passes from the pre-set value. It was proved that the system were potentially able to reduce ventilation load by up to 62.8% [81]. Similar conclusions were also reached by Zalba et al. [82] and Lazaro et al. [83,84]. To maintain a specific temperature when the cooling demand was high, the PCM phase change temperature should be lower. For very low cooling demands, the phase change temperature should be close to the required temperature level. A study on energy and exergy evaluation of PCM-TES coupled free cooling system was conducted by Mosaffa et al. [85,86], with the experimental details shown in Fig. 13(a) and (b), indicating the increase of exergy efficiency due to reducing inlet air temperature was more significant than effect from increasing air flow rate during charging. Later, in order to obtain the best balance between the exergy destruction cost rate and the capital cost rate, the PCM-TES unit was also used for air

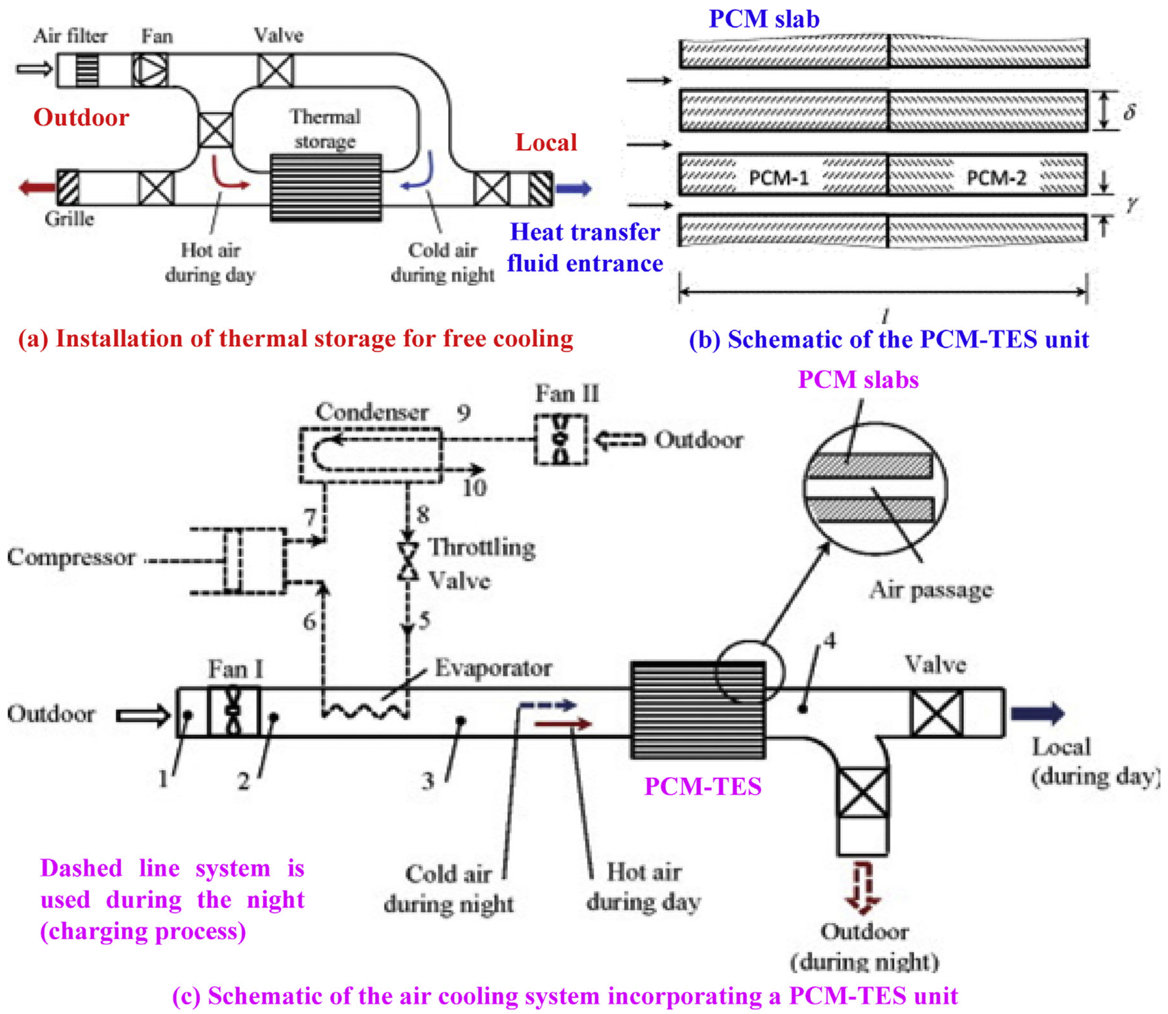


Fig. 13. Schematic of PCM-TES coupled free cooling system [85,87].

cooling [87], as shown in Fig. 13(c). These conclusions make contributions to the designing optimization for free cooling system.

3.3.2. PCM window-based cooling unit

Based on PCM-TES and free cooling system, PCM window-based cooling unit was developed, which was firstly carried out by Xiang et al. [88]. At night, outdoor coolness was stored in the unit by natural ventilation and it was actively released to indoor environment during daytime. The simulation results showed that the PCM slabs with optimum thickness of 5 mm could freeze completely within 7 h from 21:00 to 4:00. Additionally, the inlet air velocity at daytime should be controlled to satisfy the effective draft temperature stipulated for thermal comfort. The cooling unit could save about 1.9 kW h, which economized 0.95 RMB within 1 h, compared with a traditional air conditioner with the same capacity. The proposed cooling unit had the advantages of convenient installation for existing buildings and energy saving potential particularly applying natural ventilation at night time. On the other hand, for improving summer comfort in domestic residence, a PCM stock was coupled with summer ventilation system [89]. The behavior of such a system in a retrofitted house with the climate of 4 different French cities was numerically investigated, with the ventilation modes diagram shown in Fig. 14. As reported, the energy performance in the house with the PCM system coupled to an over-ventilation was significantly improved in the 4 climates. However, in this study, this unit worked in an office building for day work, not in the bedroom for sleeping. For some cold climate regions, PCM window-based unit might be used to save thermal energy at day and used them in the bedroom at night, and thus the sleep thermal comfort could be improved.

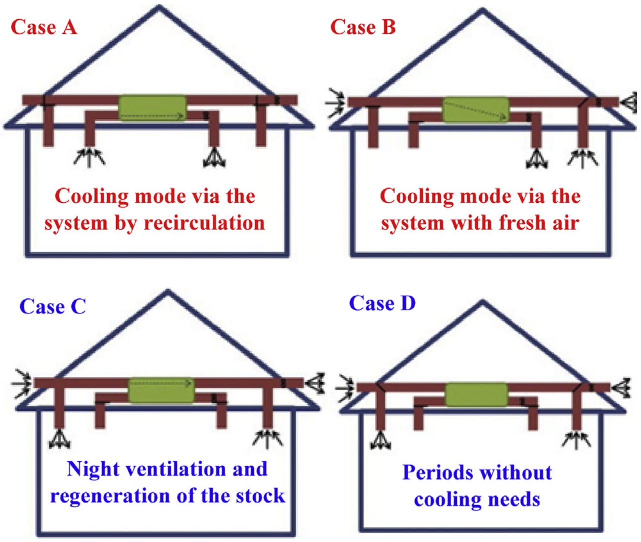
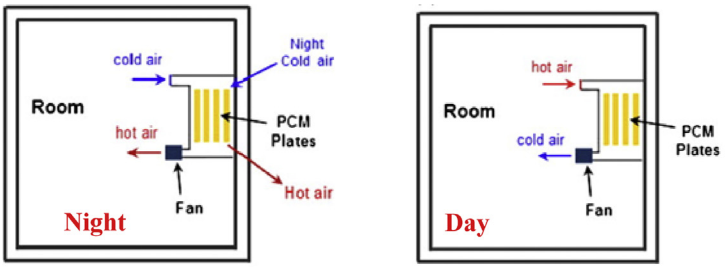
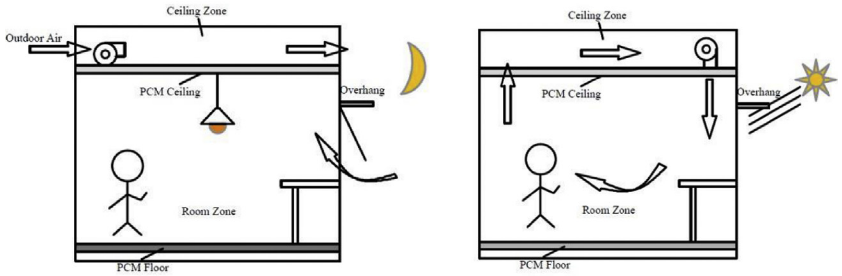


Fig. 14. Diagrams of PCM window-based cooling unit [89].



(a) Night time and day time



(a) Night mode and day mode

Fig. 15. Principal function of cooling system and two simulation modes [90,91].

3.3.3. *PCM board coupled night ventilation system*

Night purge ventilation is a well-known passive technique for conserving cooling energy by storing night cool energy in the thermal mass of the building fabric. Darzi et al. [90] developed a numerical study to simulate and to find out the optimum design for plate type storage filled with PCM which was used in night ventilation systems. Principal function of PCM ventilation system is shown in Fig. 15(a). The results showed that cooling power could be increased by increasing the mass flow rate. The thickness of the PCM plates played an important role in the thermal performance of the unit and had a linear relation with the melting process duration of PCM. A similar passive cooling system combining the PCMs and night ventilation for residential buildings was modelled [91], with two modes studied showing in Fig. 15(b). By simulating the main parameters such as property of PCMs coupled ventilation rate that affects the system design, an initial scheme was given out and the feasibility was proved with a little sacrifice of the comfortable level of the indoor environment. It is worth mentioning that the indoor air temperature was simulated to fluctuate below 28 °C for most of the days, which was the upper level for human body comfort.

Later, two PCM board and night ventilation systems were separately investigated by Solgi et al. [92] and Barzin et al. [93], indicating cooling load was reduced and a weekly electricity saved 73%, respectively. Jaworski et al. presented a new structure of PCM board and night ventilation system, which is built in the ceiling [94].When a melting point of PCM is properly chosen it is possible that the temperature of air flowing into the building reach a level corresponding to thermal comfort conditions, regardless the temperature at the intake. Warm air during a day release the heat basically to PCM causing its melting. During night time cool ambient air is heated up while it takes back heat accumulated in PCM. Needless to say, it is a study on improving sleep thermal comfort at night for bedroom, as well as saving energy consumption.

In conclusion, although most attentions were paid to system energy performance [81–93], indoor thermal comfort were still considered and mentioned in some previous experimental studies [88,94] and numerical ones [88–91], as well as system economic analysis [87,88]. However, none of researchers specially investigated the sleep thermal comfort for the bedroom, even for the night worked air heating ventilation system. This may be a new research point in this field. Additionally, using PCM-TES integrated ventilation system to improve the human sleep thermal comfort in the bedroom [95] is strongly suggested.

3.4. *Summary*

PCMs used in building equipment could improve indoor thermal comfort by regulating air temperature, and effectively increase the energy efficiency of air cooling, heating, and ventilation systems. The following conclusions may be drawn:

(1) Table 3 lists the summary of the PCMs used in equipment studies to improve thermal comfort in this article. The same as previous studies on building envelope, both experimental and numerical methods were considered in the building equipment optimization studies. Differently, most of them were used to model the equipment, but not the environment and building itself. Therefore, as shown in Table 4, the software tools used in numerical studies consist of CFD, COMSOL Multiphysics, DOE-2, EnergyPlus, Matlab, and TRNSYS, but without the FLUENT, FEM, and SUNREL etc.

(2) Comparted to the building envelopment, experiments about building equipment are much easier to be carried out. Only the system itself need to be considered, with the conditions of building and ambient climate neglected. In addition, phase change temperature of PCMs applied in building inner envelopes should be near the human body comfort level, below 28 °C [91], but the phase change temperature range of PCMs becomes much wider for equipment TES applications, at −15.4 ~ 77 °C. For example, the melting temperature of ice (water) is 0 °C in A/C system [50,60], and 46 °C for salt hydrates in PCM-TES integrated heat pump units [55]. Therefore, much more kinds of PCMs could be considered in the engineering applications, such as hydrated salts and binary fatty acids.

(3) For air cooling systems, most researchers payed their attention to energy saving, with the indoor thermal comfort neglected. But in air heating systems, such as in ASHP units defrosting

Table 3
Summary of the PCMs used in building equipment studies.

Ref.	Type [a]	PCM used [b]	T_p [c] (°C)	LH (J/g)	Results
[50]	E	Ice (water)	0	335	The ice storage A/C system with separate helical heat pipe can stably work.
[51]	E	Ethylene glycol solution	−1.8	uk	The cool storage A/C system with spherical capsules packed bed can stably work.
[52]	E	Silver nanoparticles	uk	uk	Appreciable energy savings in the range of 7.5–58% is achieved by this system.
[54]	E	Salt hydrates	10	155	14.5% more cold supplied and indoor temperature within comfort 20.65% longer kept.
[62]	E	RT58	62∼77	uk	Store heat pump size can be reduced by up to 30%.
[63]	E	RT5HC	5∼6	245	Cooling COP of the hybrid system enhanced by 17%; heating COP rose by 65%.
[65]	E	$CaCl_2\cdot 6H_2O$	29	190.8	Shorter defrosting process, higher indoor air temperature, and indoor TC improved.
[67]	E	$CaCl_2\cdot 6H_2O$	29	190.8	Shorter defrosting time and good system reliability.
[92]	E	uk	29	uk	An almost 47% reduction in cooling energy of air conditioning system.
[93]	E	PT20	20	180	A weekly electricity saving of 73% was achieved.
[94]	E	Micronal DS-5008X	23.5	102.6	Inlet air temperature reaches a level corresponding to thermal comfort conditions.
[96]	E	NH_4Cl	−15.4	281.82	Energy consumption during a defrosting cycle decreased by 8%.
[53]	N	Hydrated salts	30	190	The system improved the mean overall system performance coefficient, but the mean chiller's performance coefficient and the total cooling energy produced in the evaporator reduced 7%∼13% and 21%∼38%, respectively.
[56]	N	$Na_2SO_4\cdot 10H_2O$ and NH_4Cl/KCl	8.3	95.4	Annual cost of new system under cooling storage ratio of 40% was reduced by 34.2%.
[85]	N	$CaCl_2\cdot 6H_2O$	29	216	LHTS unit is optimized with energy effectiveness method, and system optimized.
[86]	N	$CaCl_2\cdot 6H_2O$ and RT25	29/26.6	190.8/232	Optimization is performed based on the energy and exergy efficiencies.
[87]	N	RT27/S27/SP25	27/27/25	179/183/180	Operation is analyzed from exergoeconomic and environmental points of view.
[89]	N	PCM like real paraffin	23	170	The thermal comfort in the house is significantly improved in the 4 climates.
[90]	N	SP22A17	22∼24	150	Using a PCM with higher latent heat increases the performance of heat exchanger. Full melting of PCM had a linear relation with PCM thickness.
[91]	N	uk	27	uk	Passive cooling system was optimized. The indoor air temperature was simulated to fluctuate below 28 °C, the upper level for human body comfort.
[54]	E&N	Capric and lauric acid	12.6	93	The unit is feasible in practical high temperature solar cooling application.
[73]	E&N	Ice (water)	0	355	Carbon fiber brushes improve the heat transfer rates in the PCM tank.
[81]	E&N	Paraffinic hydrocarbon	23.5∼24.9	41.9	System were potentially able to reduce ventilation load up to 62.8%.
[83]	E&N	uk	18.7∼21.8	uk	A novel method to choose PCM is given, and T_m should be close to the required level.
[84]	E&N	An inorganic PCM	uk	uk	A heat exchanger using a PCM can be applied for free cooling.
[82]	E&N	RT25	20∼25	164	Technically feasible and economically advantageous to existing cooling systems.
[88]	E&N	Paraffin	22∼24	189	Indoor temperature decreased by 3.3 °C, electric energy efficiency ratio reached 8.7.
[97]	E&N	Paraffin	22	170	A specific function describing the variations of heat transfer coefficient along the channel was determined and validated by experimental results.
[98]	E&N	uk	18∼24	70	Heat was stored and released up to 6∼8 h after solar irradiation. Yearly heating requirements were reduced by 17% in a cold climate.
[99]	E&N	BioPCM	5∼15	219	In a shell-and-tube PCM heat exchanger, the larger number of tube rows and shorter cycle time resulted in the higher thermal efficiency.

[a] E: Experimental, N: Numerical.
[b] uk: unknown.
[c] T_p: Melting temperature of PCM.

applications, it was detailed calculated and discussed [65,66]. Defrosting operation of an ASHP unit mainly occurs at night, they always service for the bedroom. Therefore, the thermal comfort evaluation equations may be different due to occupants' sleeping status, because the model of human at sleep status is different from the ordinary model [80]. As to ventilation systems, most of them work at day time for office with the cool capacity saved at night time. Consequently, heating indoor air at server cold regions with the thermal energy saved from exhaust air at day time is strongly suggested.

Table 4
Software tools used in PCM integrated building equipment studies.

Ref.	Year	First author	Software tool
[97]	2017	Ł. Wardziak	CFD
[98]	2017	F. Guarino	EnergyPlus
[99]	2017	P. Promoppatum	COMSOL
[87]	2016	A.H. Mosaffa	COMSOL Multiphysics
[56]	2015	N. Zhu	DOE-2
[88]	2015	J. Borderon	TRNSYS + Matlab
[91]	2015	F.F. Jiao	EnergyPlus
[53]	2014	J.F. Belmonte	TRNSYS
[86]	2014	A.H. Mosaffa	COMSOL Multiphysics
[85]	2013	A.H. Mosaffa	COMSOL Multiphysics
[90]	2013	A.A. Rabienataj Darzi	CFD

4. Outlook for future research

Extensive related studies on using PCMs in the buildings to save energy consumption have been undertaken. Both experimental and numerical approaches were adopted in these studies to investigate the effects of PCMs on building envelope and equipment. The following future research areas are thus suggested.

a) More attention should be payed to the location of PCM plates in a fixed function space when their effects on indoor thermal environment investigated, for example, hanging PCM plates on the ceiling, or upside of the bed in the bedroom. PCMs can also be used in the furniture, such as Kang used in rural northeast of China [100].

b) The indoor thermal comfort evaluation standards in a ward should be adjusted based on the traditional one, due to the physical conditions of patients are different from the normal [101]. Models suitable to children and the old people should be further developed, when the space function is changed to kindergarten or nursing home.

c) It is still a problem for PCMs that their slow heat transferring rates in a tank, at both discharging and releasing processes, although various methods have been undertaken to optimize the heat storage and extraction rates. It is also a hot topic that the declination reason and recover methods of PCMs' thermal properties after melting/solidification cycle repeated more than 1000 times [102].

d) As energy materials, form-stable PCMs microcapsule with good latent thermal capacities and stabilities, and phase change nanofluid with good dispersion stability, should be experimentally investigated, especially applied in the refrigerant of A/C or heat pump units.

e) After PCM-TES systems used, it is valuable to design alternative control strategies [71], such as for ASHP units' defrosting optimization. Life cycle assessment on economic feasibility and environmental benefits of all building equipment coupled PCM-TES systems should be evaluated.

5. Conclusions

To regulate the indoor thermal environment with phase change materials thermal energy storage system, as well as optimize building energy performance, various measures reported in 2004 ~ 2017 were analyzed and reviewed in this paper. Experimental and numerical investigations on incorporating phase change materials into building walls, roofs, and floors are classified and summarized. Paraffin and binary organic acids are the mainly phase change materials used in envelopes. ANASYS, CFD, EnergyPlus, FEM, FLUENT, and TRNSYS all find their applications in this field. Potentially increasing the thermal mass of these enclosure components, phase change materials not only decrease heat transfer rates during peak hours, but also reduce the relatively large interior temperature fluctuations. Consequently, building energy saving and indoor thermal comfort improvement are both expected.

In addition, air cooling, heating, and ventilation systems coupled phase change materials thermal energy storage system are presented, such as storing the cold for cooling system, supplying thermal needs for defrosting in air source heat pump units, and saving solar thermal at noon for night using, etc. Differently, the software tools widely used in building equipment are changed to CFD, COMSOL Multiphysics, DOE-2, EnergyPlus, Matlab, and TRNSYS. Phase change temperature range of PCMs used is changed from $10 \sim 39\,^{\circ}\mathrm{C}$ for envelope to $-15.4 \sim 77\,^{\circ}\mathrm{C}$ for equipment. Phase change material tank was economically analyzed, as well as the thermal comfort evaluated. Finally, the existing gaps in the research works on phase change materials used in building are identified, and recommendations are offered as per the viewpoint of the present authors.

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