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Application of latent heat thermal energy storage in buildings: State-of-the-art and outlook

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Abstract

Latent heat thermal energy storage (LHTES) is becoming more and more attractive for space heating and cooling of buildings. The application of LHTES in buildings has the following advantages: (1) the ability to narrow the gap between the peak and off-peak loads of electricity demand; (2) the ability to save operative fees by shifting the electrical consumption from peak periods to off-peak periods since the cost of electricity at night is 1/3–1/5 of that during the day; (3) the ability to utilize solar energy continuously, storing solar energy during the day, and releasing it at night, particularly for space heating in winter by reducing diurnal temperature fluctuation thus improving the degree of thermal comfort; (4) the ability to store the natural cooling by ventilation at night in summer and to release it to decrease the room temperature during the day, thus reducing the cooling load of air conditioning. This paper investigates previous work on thermal energy storage by incorporating phase change materials (PCMs) in the building envelope. The basic principle, candidate PCMs and their thermophysical properties, incorporation methods, thermal analyses of the use of PCMs in walls, floor, ceiling and window etc. and heat transfer enhancement are discussed. We show that with suitable PCMs and a suitable incorporation method with building material, LHTES can be economically efficient for heating and cooling buildings. However, several problems need to be tackled before LHTES can reliably and practically be applied. We conclude with some suggestions for future work.

Keywords: PCM; Latent heat; Thermal energy storage; Building envelope; Heat transfer

1. Introduction

Thermal energy storage for space heating and cooling of buildings is becoming increasingly important due to the rising cost of fossil fuels and environmental concerns. Particularly, in extremely cold/hot areas, electrical energy consumption varies greatly during the day and the night partly due to domestic space heating/cooling. Such variation leads to a peak load period and an off-peak period (usually between midnight and early morning). In order to level the electrical load, a differential pricing policy has been implemented in many cities in China. For example, in many Chinese regions, the electricity tariff at night tends to be 1/3–1/5 of that during the day [1]. If the thermal energy of heat or coolness is provided and stored during the night and then released to the indoor ambient during the day, part or all peak loads can be shifted to off-peak period. Thus, effective energy management and economic benefit is achieved.

Solar energy has an enormous potential for space heating of buildings in winter. However, solar radiation is a time-dependent energy source with an intermittent and variable character with the peak solar radiation occurring near noon. These problems can be addressed by storing thermal energy, i.e. solar energy can be collected and stored during the day and released to indoor air when the room temperature falls at night [2]. Also, cool can be collected and stored from ambient air by natural (or forced) convection during night in summer, and then released to the indoor ambient during the hottest hours of the day. These thermal energy storage mechanisms can decrease indoor air temperature swings and improve the indoor thermal comfort level [3].

The thermal energy storage may be in the form of sensible heat, latent heat etc. For sensible heat storage,

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Nomenclature

ACH	air change per hour (h^{-1})
A_{sa}	temperature wave amplitude of outdoor
$A_{x=0}$	temperature wave amplitude of inner surface of wall
c_p	specific heat ($J\,kg^{-1}\,°C^{-1}$)
H_m	heat of fusion ($J\,kg^{-1}$)
I	integrated discomfort degree for indoor temperature
k	thermal conductivity ($W\,m^{-1}\,°C^{-1}$)
t	temperature (°C)
t_H	the higher limit temperature in the thermal comfort range (°C)
t_L	the lower limit temperature in the thermal comfort range (°C)
ϕ	time lag
f	decrement factor
τ	time (s)
ρ	density ($kg\,m^{-3}$)

Subscripts

in	indoor
out	outdoor
sum	summer
win	winter

heavy material mass is needed. By comparison, latent heat storage is preferred due to the large energy storage density and nearly isothermal nature of the storage process during which the storage material, phase change material (PCM), undergoes a change in phase. The earlier application of PCMs described in the literature, was their use for heating and cooling in buildings, by Telkes in 1975 [4], and Lane in 1986 [5]. Over the past decades, extensive research work on the incorporation of PCMs into building envelopes (walls, ceiling and floor etc.) to achieve latent heat storage has been done, and can be found in the literature. However, there are still some difficulties for effective, reliable and practical applications of this technology. The aims of this paper are: (1) to analyze operative principles of applying PCM in building envelopes; (2) to provide an overview of recent studies on PCMs and their applications in building envelopes; (3) to discuss the developing trends in this subject.

2. Operative principles of applying PCMs in buildings

2.1. PCM building envelope

2.1.1. Factors influencing indoor air temperature

As we know, many factors influence the indoor air temperature of a building. These include climate conditions (outdoor temperature, wind velocity, solar radiation, etc.), building structure and the building material's thermophysical properties (wall thickness, area ratio of window to wall, thermal conductivity and specific heat of wall material, etc.), indoor heat source, air change rate per hour (ACH) and auxiliary heating/cooling installations etc. Fig. 1 indicates that the difference between the indoor temperature and the comfort range determines the heating and cooling load when there is no space heating and cooling. Therefore, the heating and cooling load will decrease with decreasing this temperature difference.

For a given building located in a specific region, the building structure parameters such as wall thickness, area ratio of window to wall, cubage of the room etc., are known. The outdoor temperature t_{out} and solar energy $q_{r,out}$ change with the different hour and day during the entire year, and can be calculated by a commercial software package Medpha (Meteorological Data Producer for HVAC Analysis) [6]. Then, with a certain interior heat source, the natural room temperature t_{in} (i.e., the room temperature without any active cooling or heating) depends on the material thermophysical properties (i.e., the thermal conductivity, k, and the product of specific heat and density, ρc_p). In other words, the relationship between t_{in} and the aforementioned parameters can be expressed as follows (for a more detailed description of the model, see Ref. [6]):

$$t_{in} = f_1(\mathrm{ACH}, k, \rho c_p). \quad (1)$$

From Eq. (1), we have,

$$k = f_2(\mathrm{ACH}, t_{in}, \rho c_p) \quad (2)$$

or

$$\rho c_p = f_3(\mathrm{ACH}, t_{in}, k). \quad (3)$$

From Eqs. (2) and (3), the desired k and ρc_p values can be determined for a given ACH, by keeping the t_{in} value in

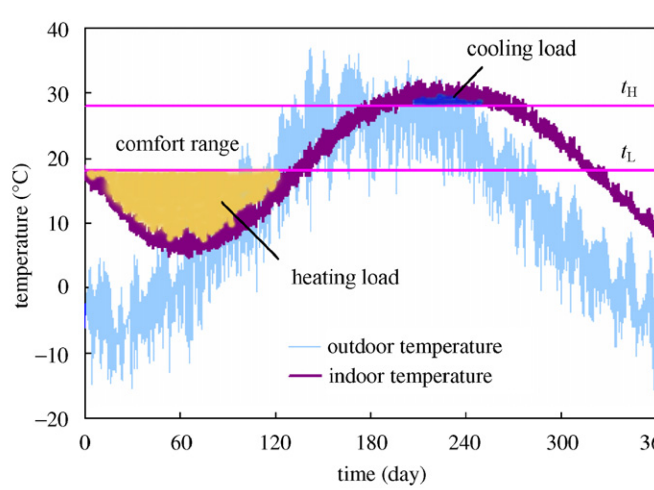

Fig. 1. The indoor/outdoor air temperature and heating/cooling load [6].

the thermal comfort region (e.g., the lower limit t_L and upper limit t_H may be 18 and 28 °C, respectively). For convenience, two parameters, I_{win} and I_{sum}, were defined to study the influences of different material's thermophysical properties on the indoor thermal comfort degree [6]. That is

$$I_{sum} = \int_{year} (t_{in} - t_H)\,d\tau \quad \text{when} \quad t_{in} > t_H. \tag{4}$$

$$I_{win} = \int_{year} (t_L - t_{in})\,d\tau \quad \text{when} \quad t_{in} < t_L. \tag{5}$$

The two parameters describe the indoor discomfort level of the building in winter and in summer and are called integrated discomfort level for indoor temperature in summer (I_{sum}) and integrated discomfort level for indoor temperature in winter (I_{win}), respectively.

If there are certain building materials whose ρc_p and k values can make the given room meet the condition $I_{win} = I_{sum} \approx 0$, we call these materials ideal building materials. This means that the indoor temperature will be in the comfort range all year round without auxiliary heating or cooling. As an example, Fig. 2 shows the comparison between the ideal material and concrete buildings [6]. k_1 is the thermal conductivity for the external wall, and k_2 is the thermal conductivity for the internal wall. It is seen that for a given room located in Beijing, the ideal ρc_p value is 100 MJ/(m^3 °C) or higher and k_1 is 0.05 W/(m °C) or lower.

In reality, it is very difficult to find any material with such a high ρc_p value. PCMs can provide high latent heat thermal energy storage density over the narrow range of temperatures typically encountered in buildings. Therefore, they are taken into account for application.

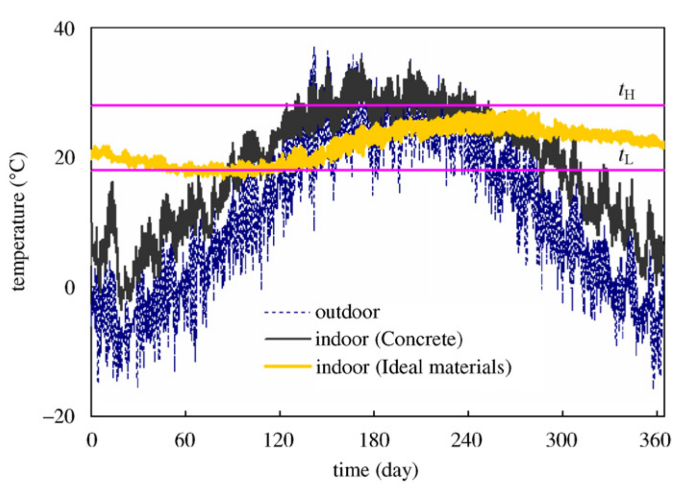

Fig. 2. Indoor temperatures of a room applying concrete and ideal building materials [6] (ideal material: $k_1 = 0.05$ W/(m °C), $k_2 = 0.5$ W/(m °C), $\rho c_p = 100$ MJ/(m^3 °C); concrete: $k_1 = k_2 = 0.5$ W/(m °C), $\rho c_p = 1.4$ MJ/(m^3 °C).

2.1.2. Non-linear properties of the PCM wall

Asan and Sancaktar investigated the effects of a common wall's thermophysical properties on 'time lag' ϕ and 'decrement factor' f (see Fig. 3) [7]. ϕ and f describe the change of wavelength and amplitude for heat waves propagating from outside to the inner surface of the wall. The combined effects of heat capacity and thermal conductivity on ϕ and f were calculated for different building materials. For wall materials with constant thermophysical properties, the change of the inner surface temperature is similar to the outdoor temperature with linear properties, due to that the heat transfer and boundary conditions are linear equations. While for PCMs, the change of inner surface temperature shows non-linear characteristics. Fig. 4 shows the temperature of a PCM wall's inner surface with a different heat of fusion H_m and melting temperature t_m. The outdoor temperature is assumed as a sinusoidal curve from 15 to 25 °C, and the indoor temperature is kept at 22 °C. The thickness of the wall is 2 cm, and the thermal conductivity is 0.2 W/(m °C). It can be seen from the figure that H_m and t_m can maintain the inner surface temperature at some desired value (nearly the PCM melting temperature) for some period, which was defined as 'PCM lag' in Ref. [8]. This is contributed to the fact that the heat transfer equations are nonlinear since PCMs' thermal capacity changes with temperature. For a certain building and in certain climates, the PCM lag is affected by the thermophysical properties of the PCM wall. If the PCM lag is long enough with proper melting temperature, the indoor air temperature can be kept in the comfort range.

2.2. Under-floor electric heating combined with PCMs

Radiant heating has a number of advantages over convective air heating systems. It saves living and working space since it is integrated into the building envelope. Also, thermal mass integrated into a floor heating system can be

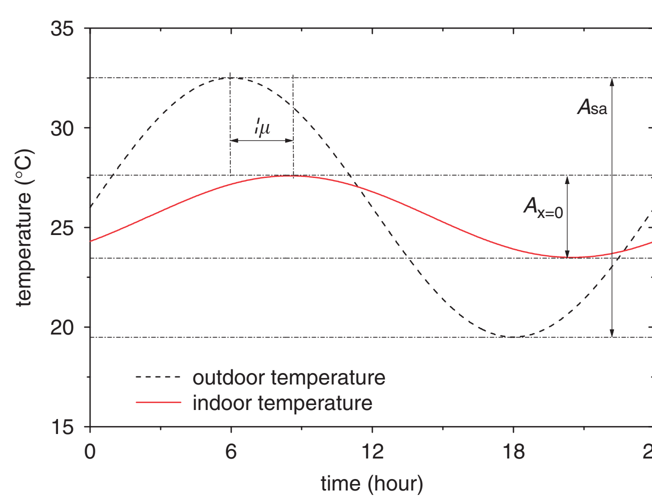

Fig. 3. The schematic representation of time lag ϕ and decrement factor f ($f = A_{x=0}/A_{sa}$).

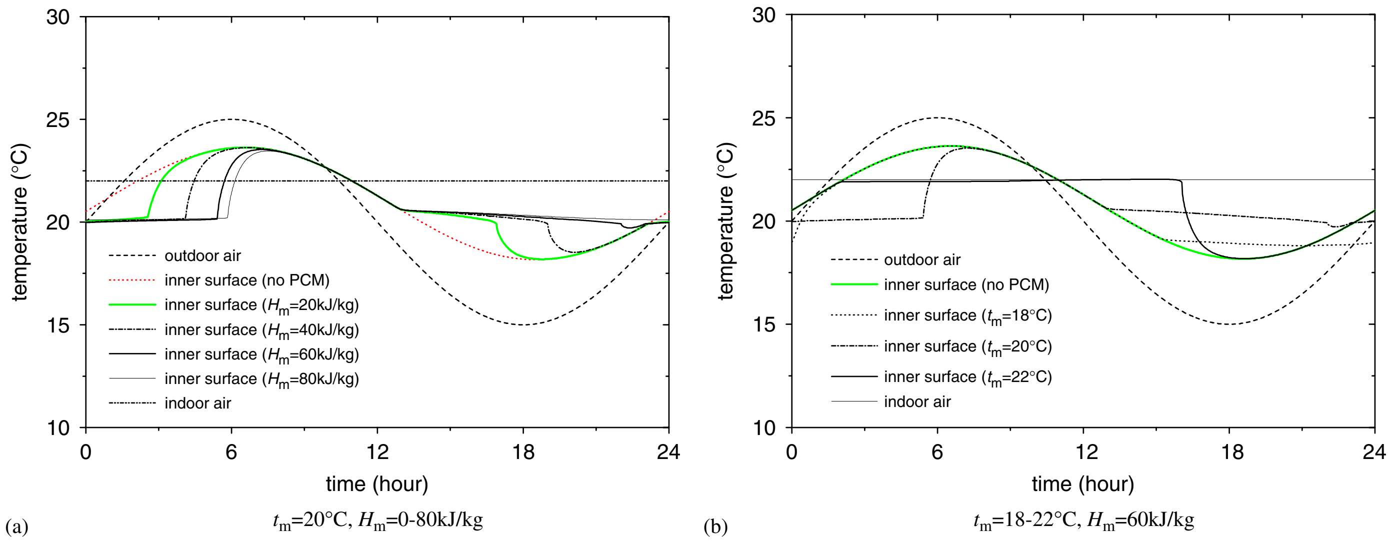

Fig. 4. Temperature of PCM wall's inner surface with different heat of fusion and melting temperature [8].

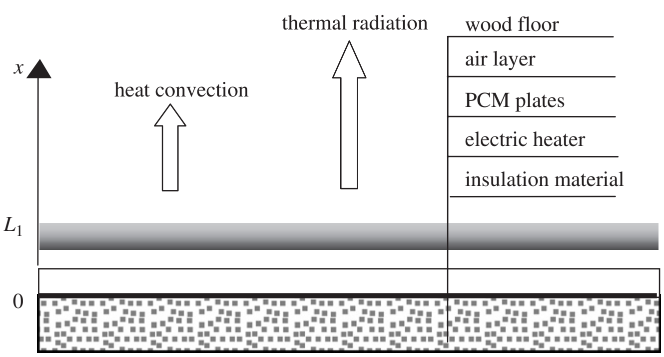

Fig. 5. Schematic of under-floor electric heating system with shape-stabilized PCM plates [10].

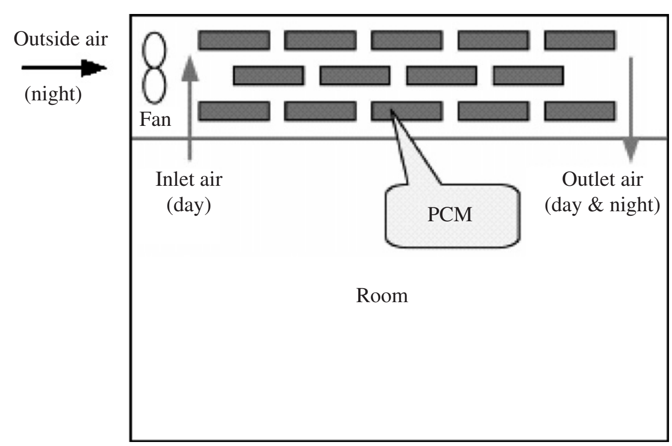

Fig. 6. Schematic of NVP system [11].

used for off-peak storage of thermal energy. Thus, peak loads may be reduced and shifted to nighttime when electricity costs are lower [9]. From an application point of view, dense materials such as concrete may cause larger fluctuations of indoor temperature, while PCMs can provide large latent heat storage over the narrow range of temperatures typically encountered in buildings, thus they can improve the thermal comfort level. Fig. 5 shows the schematic of an under-floor electric heating system with shape-stabilized PCM plates which include polystyrene insulation, electric heaters, PCM, air layer and wood floor [10]. Electric heaters heat and melt the PCM layer by using cheaper nighttime electricity and the system stores heat. During the day the electric heaters are switched off and the PCM layer solidifies, discharging the heat stored. In many cities in China, the electricity tariff at night is 1/3–1/5 of that during the day. Therefore, the shift of electrical consumption from peak periods to off-peak periods will provide significant economic benefit. Moreover, it is of importance to power plants by leveling the electrical load.

2.3. Cool storage by night ventilation with PCM

Night ventilation is a useful and low-cost way to improve thermal comfort in summer, whether it relies on window openings, ceiling fans or any other methods. Ventilating the building during the night in summer can cool down its structural elements. The cooled fabric then releases cool the following day and provides comfort by reducing both the indoor air and wall temperature. However, the traditional night ventilation effect is not satisfactory enough due to the lower thermal capacity of the building envelope, a smaller heat transfer area or a lower air flow rate. An innovative latent heat thermal energy storage (LHTES) system–Night ventilation with a PCM packed bed storage (NVP) system is developed, as shown in Fig. 6 [11]. The most important component includes PCM package bed and the air duct among the PCM capsules. At night, the outdoor cool air is blown through the LHTES system to charge cool to the PCM. In the day, air cycles between the LHTES system and the room, and the cool stored by the PCM at night is discharged to the room.

3. PCMs and thermophysical properties

Many PCMs including organic, inorganic and their eutectic or non-eutectic mixtures were reviewed in detail in Refs. [2,3,12]. However, for successful applications of PCMs in buildings, there are some conditions limiting the selections of PCMs, such as heat of fusion, melting temperature, compatibility with building materials, flammability etc.

3.1. Heat of fusion (H_m) and melting temperature (t_m)

From Fig. 4 and the above discussion, it is known that to keep the indoor air temperature in the comfort range for long time (even the whole year) without heating and cooling load, the heat of fusion of a PCM, H_m, should be high enough so as to keep the wall's inner surface at the melting temperature for a whole day or even a whole year. Another very important criterion for selecting the PCM is the melting temperature, t_m, which should be in the comfort temperature range. For a given climate condition and given buildings, if the melting temperature is too high, the quantity of solar radiation heat stored by the PCM will be too low in the daytime; if the melting temperature is too low, it is difficult to maintain the indoor air temperature at a comfortable level during the night. The exact value of t_m should be selected according to the different conditions such as buildings and climates. Peippo et al.'s [13] analysis of a PCM wall in a passive solar house indicates that the optimal diurnal heat storage occurs with a melting temperature of 1–3 °C above the average room temperature. Neeper [14] examined the thermal dynamics of a gypsum wallboard impregnated by fatty acids and paraffin waxes and concluded that the maximum diurnal energy storage occurs at a PCM melting point temperature that is close to the average comfort room temperature in most circumstances. For wallboard installed on the building envelope (external wall), the optimal value of the melt temperature also depends on the outdoor temperature and the thermal resistance of the wall. Heim and Clarke's [15] numerical analysis on the PCM-gypsum composites during the heating season showed that the optimal PCM solidification temperature was 22 °C, which is 2 °C higher than the heating set point for the room. Similar conclusions can be found in Refs, [16–18].

3.2. Candidate PCMs

For a comprehensive understanding of the potential PCMs that can be applied in buildings, the suitable PCMs investigated in the literature are listed in Table 1. Most of their melting points fall between 18 and 28 °C, just the human comfort temperature range.

Table 1
PCMs investigated in the literature for building applications

PCM	Transition point/range (°C)	Heat of fusion (kJ/kg)	References
$CaCl_2 \cdot 6H_2O$	24–29	192	[17]
$Na_2S_2O_3 \cdot 5H_2O$	40	210	[19]
$CaCl_2 \cdot 6H_2O$ + Nucleator + $MgCl_2 \cdot 6H_2O$ (2:1)	23	—	[20]
Hexadecane	18	236	[21]
	18	205	[22–25]
Heptadecane	22	214	[21]
Octadecane	28	244	[21]
Black paraffin	25–30	150	[21]
Emerest2325 (butyl stearate + butyl palmitate 49/48)	17–21	138–140	[26,27]
Emerest2326 (butyl stearate + butyl Palmitate 50/48)	18–22	140	[28,29]
Butyl stearate	19	140	[30]
1-dodecanol	26	200	[30]
Capric-lauric 45/55	21	143	[30]
Capric-lauric 82/18	19.1–20.4	147	[31]
Capric-lauric 61.5/38.5	19.1	132	[13,32]
Capric-myrstic 73.5/26.5	21.4	152	[13,32]
Capric-palmitate 75.2/24.8	22.1	153	[13,32]
Capric-stearate 86.6/13.4	26.8	160	[13,32]
Peg1000 + Peg600	23–26	150.5	[33]
Propyl palmitate	19	186	[30]
RT25	25	147	[34]

As is well known, inorganic PCMs, typically hydrated salts, have some attractive properties such as a higher energy storage density, a higher thermal conductivity, being non-flammable, being inexpensive and readily available etc. However, they also have some obvious disadvantages such as being corrosive, being incompatible with some building materials and needing supporting containers. In particular, they experience supercooling and phase segregation during transition and their application requires the use of some nucleating and thickening agents. In recent years, some organic PCMs are getting more and more attention due to the avoidance of the problems inherent with inorganic PCMs. They have little supercooling and segregation, and are compatible with and suitable for absorption in various building materials [30]. However, they are flammable and have volume changes and low heat conductivity, which are concerns in many recent studies. Eutectic or non-eutectic mixtures of organic or inorganic PCMs could be used to deliver the desired melting point required.

In recent years, shape-stabilized PCMs are attracting the most attention and are being applied in building envelopes due to their good thermal performance over a long period, and form stability during heat melting and solidification, which remarkably distinguishes them from common organic PCMs. Also, shape-stabilized PCMs can be easily compounded with common building materials for their shape stability and then can be manufactured into various composite building materials.

3.3. Long-term stability and fire characteristics

As mentioned by Zalba et al. [2], poor stability of inorganic PCMs involves two aspects: poor stability of material properties during repeated thermal cyclings and corrosion between the PCM and its surrounding containers. Organic PCM mixtures have been verified to have excellent thermal stability [26,35]. Hadjieva et al. [19] investigated the structural stability of the PCM ($Na_2S_2O_3 \cdot 5H_2O$) impregnated in concrete and concluded that the large absorption area of an autoclaved porous concrete serves as a good supporting matrix of an incongruently melting $Na_2S_2O_3 \cdot 5H_2O$ and improves its structure stability during thermal cycling. Corrosion tests mainly focused on salt hydrates. Cabeza et al. [20] performed a long-term immersion corrosion test on metal–PCM pairs in the 24–29 °C temperature range. The PCM was a commercial one, with a chemical composition of $CaCl_2 \cdot 6H_2O$ and an unknown nucleator, which was then mixed with $MgCl_2 \cdot 6H_2O$ (2:1 wt%) to obtain a new PCM with a melting temperature of around 23 °C. They concluded that aluminum and steel should not be used in combination with these PCMs, but brass, copper and stainless steel have shown no problems.

Studies were already underway to assess one of the organic PCMs' fatal drawbacks-flammability. Salyer and Sircar [36] presented a report on the reaction to fire and pointed out the possible fire-retardant additives (organic halogen compounds) that improve the response to fire of the material. Banu et al. [37] performed flammability tests on gypsum wallboard impregnated with about 24% organic PCM, which evaluated the surface-burning characteristics: flame spread and smoke development classifications determined in a horizontal tunnel with a movable roof (Steiner tunnel), as well as heat and smoke release rates determined by a cone calorimeter (a fire test instrument based on the principle of oxygen consumption calorimetry). The tests showed that the energy-storing wallboard does not meet all requirements of their building code regarding fire characteristics for building materials. Their results indicated the possibility of reducing the flammability of energy-storing wallboard by the incorporation of a flame retardant. Koschenz and Lehmann [21] developed a thermally activated ceiling panel incorporating paraffin and indicated that the micro-encapsulation of the PCM, its bedding in gypsum and encasement in a sheet steel tray ensure a certain level of fire resistance.

3.4. Test of thermophysical properties

Differential scanning calorimeter (DSC) analysis is commonly used to evaluate the thermal characteristics of PCM as well as composites with building materials such as gypsum board [18,27,29]. With a volume expansion meter, a water-calorimeter, a DSC and a hot wire method, Inaba [38] measured the density, specific heat, latent heat and effective thermal conductivity of shape-stabilized paraffin, respectively. Zhang et al. [39] developed a simple method, the T-history method, of determining the heat of fusion, specific heat and thermal conductivity of PCMs. Temperature–time curves of the PCM samples are drawn and their thermophysical properties are obtained by comparing the curves with the temperature–time curve of the other known material (served as reference, usually pure water). It has the following salient features: the experimental system is simple; it is able to measure lots of samples and obtain several thermophysical properties of each PCM sample through a group of tests; the precision of measurement satisfies the need for engineering applications; and the phase-change process of each PCM sample can be observed clearly.

Marin et al. [40] developed a further evaluation procedure to determine specific heat c_p and enthalpy h as temperature-dependent values. The results obtained were present in the form of enthalpy–temperature curves. A discussion about the errors produced by this method and an experimental improvement are proposed too.

The T-history method was also improved by Hong et al. [41] by using an inflection point instead of the release point as the boundary between phase change and solid-state periods, and was successfully applied to a variety of PCMs such as paraffin and lauric acid, having no or a low degree of supercooling. It was found that selected periods for sensible and latent heat did not significantly affect the accuracy of heat-of-fusion.

4. PCM applications in buildings

Several PCM applications in buildings such as passive solar heating, active heating and night cooling are shown in Fig. 7. As mentioned above, PCMs incorporated in building envelopes (PCM walls, PCM roof or ceiling and PCM floor etc.) used for passive solar heating in winter can increase thermal capacity of light building envelopes, thus reducing and delaying the peak heat load and reducing room temperature fluctuation.

Together with a solar collector system, a PCM building component can store more solar thermal energy during the day and discharge the heat during the night, thus maintaining good thermal comfort of the room. With a heat pump or under-floor electric heating system etc., PCM building envelopes can store heat with cheap electricity at night and then discharge heat during the day, thus decreasing the space-heating load. The shift of electrical consumption from peak periods to off-peak periods will provide a significant economic benefit. Another application is a nighttime ventilation system with a PCM envelope for cooling storage. When the outdoor temperature is lower than the indoor air temperature, the ventilation system starts and the outdoor cooling can be stored in the PCM envelope such as a PCM ceiling or PCM walls, and

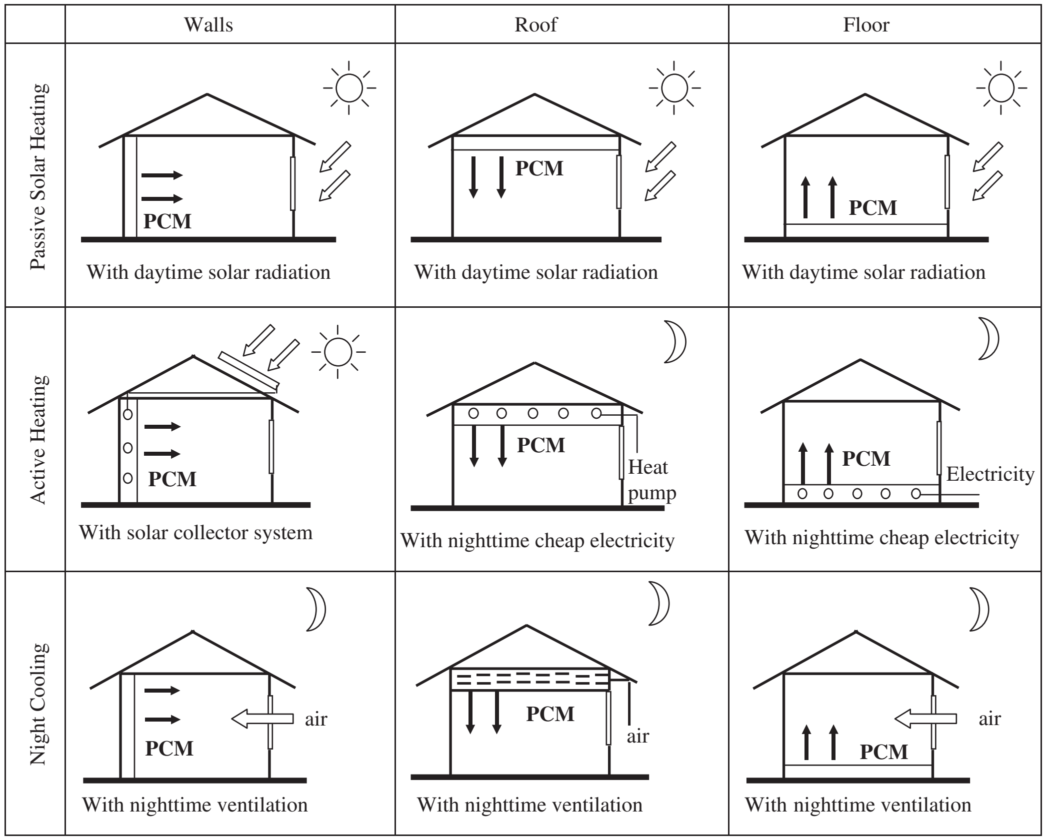

Fig. 7. The forms and effects of PCM building envelope (revised from Macro's presentation [42]).

then released during the day, which could decrease the cooling load of air-conditioning systems. The nighttime cooling storage can be achieved by natural ventilation or by fan.

One obvious advantage of a PCM building envelope is that the envelope of a building offers large areas for passive heat transfer within every zone of the building, which would add thermal storage for passive solar heating as well as create an opportunity for ventilation cooling and time-shifting of mechanical cooling loads [14]. The second advantage is the elimination of the usual requirement of a system such as cans, bottles, or pouches to contain the PCM [43]. Further, except for the expense of the PCM, little or no additional cost would be incurred compared with ordinary envelope components. In the followed parts, Section 4.1 describes the methods of incorporating PCM into the building envelope; Section 4.2 reviews the thermal analysis of PCM applications in buildings; and heat transfer enhancement is discussed in Section 4.3.

4.1. PCM incorporation method

Various means of PCM incorporation have been investigated in the literature. Hawes et al. [30] considered three most promising methods of PCM incorporation: direct incorporation, immersion and encapsulation. In addition, PCM can be used in the form of a single laminated board and combined with other envelope components [22,24].

4.1.1. Direct incorporation

This may be the most economical method because very little additional process equipment is required. Liquid or powdered PCM are added to and mixed with building materials such as gypsum and concrete during production. An example of the method is a laboratory scale energy storage gypsum wallboard produced by the direct incorporation of 21–22% commercial grade butyl stearate (BS) at the mixing stage of conventional gypsum board production [26].

4.1.2. Immersion

In this method, the porous building material (such as gypsum board, brick, or concrete block) is dipped into the hot melted PCM, which is absorbed into the pores by capillary action. The porous material is removed from the liquid PCM and allowed to cool and the PCM remains in the pores of the building material [44]. The great advantage of this method is that it enables one to convert ordinary wallboard to PCM wallboard as required, since impregnation can be carried out at practically any time and place [37]. Hawes and Feldman [45] examined the mechanisms of absorption and established a means of developing and using absorption constants for PCM in concrete to achieve diffusion of the desired amount of PCM. However, as Schossig et al. [46] pointed out, leakage may be a problem over a period of many years for this method.

4.1.3. Encapsulation

To escape the adverse effects of PCMs on the construction material, PCMs can be encapsulated before incorporation. There are two principal means of encapsulation: macro-encapsulation and micro-encapsulation [3]. For the first method, the PCM is packaged in tubes, pouches, spheres, panels or other receptacles and then incorporated into building products. Via macro-encapsulation, Zhang et al. [47] developed and tested a frame wall that integrated highly crystalline paraffin PCM. Results showed that the wall reduced peak heat fluxes by as much as 38%. However, macro-encapsulation has the disadvantage of needing protection from destruction and requires much more work to be integrated into the building structure, and is thus expensive. Another problem is the decreasing heat transfer rate during the solidification process with poor heat transfer coefficients of PCM in the solid state [46]. The second method, micro-encapsulation, is where small PCM particles are enclosed in a thin, high molecular weight polymeric film which should be compatible with both the PCM and the construction materials (Fig. 8). The micro-encapsulated PCM material has the advantages of easy application, good heat transfer due to the increased heat exchange surface and no need for protection against destruction [46]. However, it may affect the mechanical strength of the structure [3]. Hawlader et al. [48] investigated the influence of different parameters on the characteristics and performance of a micro-encapsulated PCM in terms of encapsulation efficiency, and energy storage and release capacity. Results obtained from a DSC show that micro-capsules prepared either by coacervation or the spray-drying methods have a thermal energy storage/release capacity of about 145–240 kJ/kg. Hence, micro-encapsulated paraffin wax shows a good potential as a solar-energy storage material.

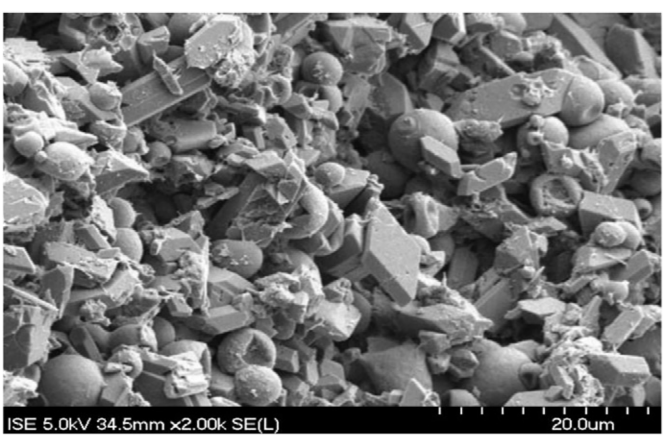

Fig. 8. SEM image of PCM micro-capsules in gypsum plaster. The PCM micro-capsules with an average diameter of 8 μm are homogeneously dispersed between the gypsum crystals [46].

In recent years, a kind of novel compound PCM, the so-called shape-stabilized PCM (SSPCM, Fig. 9) has been attracting the interest of researchers [38,50–52]. It consists of paraffin as dispersed PCM and high-density polyethylene (HDPE) or other material as supporting material. Since the mass percentage of paraffin can be as much as 80% or so, the total stored energy is comparable with that of traditional PCMs. Zhang et al. [49] tested the thermo-physical properties of developed SSPCM samples and performed experiments and simulations using this kind of SSPCM for space-heating in winter. The results show that applying SSPCM in buildings is a promising technique and should be studied further.

4.1.4. Laminated PCM board

PCM can also be laminated into a single layer and used as an element (such as inside wall lining) incorporated in the envelope. Darkwa and Kim [22,24] carried out experimental and numerical studies on the performance of manufactured samples of laminated and randomly mixed PCM drywalls. The specific findings observed were as follows:

(a) The laminated system achieved about a 17% reduction in time during heat recovery.
(b) A 20–50% maximum enhancement in heat flux was achieved by the laminated system.
(c) A 7–18% maximum enhancement in heat transfer rates was achieved with the laminated system. The results

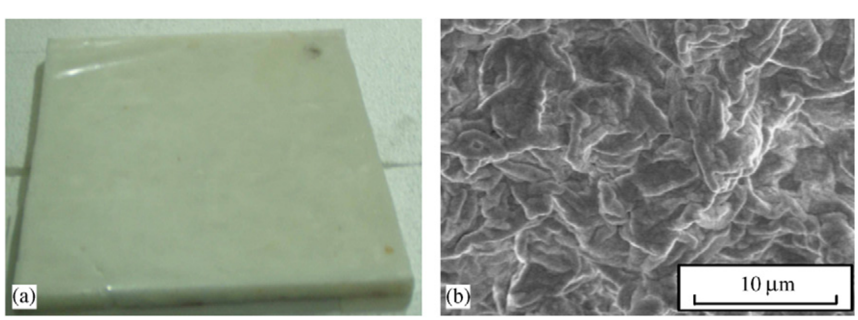

Fig. 9. The photos of the shape-stabilized PCM. (a) Photo of the plate and (b) electronic microscopic picture by scanning electric microscope (SEM) HITACHI S-450 [49].

showed that the laminated PCM drywall performed thermally better.

4.2. Thermal analysis of PCM applications in buildings

With the above methods, extensive advances have been made on the thermal performance of PCM applications in buildings such as PCM walls, PCM ceiling, PCM floor with electric heating, and night ventilation etc.

4.2.1. PCM walls

PCM has been successfully incorporated into wall materials such as gypsum wallboard and concrete to enhance the thermal energy storage capacity of buildings with particular interest in passive solar applications, peak load shifting etc.

Peippo et al. [13] were one of the first to discuss the use of PCM walls for short-term heat storage in direct-gain passive solar applications. The PCM considered was fatty acid. Approximate formulae were presented for optimum phase change temperature and thickness of the PCM wall. And direct energy savings of 5–20% were expected.

In Feldman et al.'s [26] experiment, a tenfold increase of energy storing capability was obtained by the direct incorporation of 21–22% commercial grade BS at the mixing stage of conventional gypsum board production. Scalat et al. [28] conducted full-scale thermal storage tests in a room lined with PCM (Emerest 2326) wallboard and the results show its efficient function as a thermal storage medium.

Athienitis et al. [53] performed an experimental and numerical simulation study in a full-scale outdoor test room with PCM gypsum board as inside wall lining. The PCM gypsum board used contained about 25% by weight proportion of BS. An explicit finite difference model was developed to simulate the transient heat transfer process in the walls. It was shown that utilization of the PCM gypsum board may reduce the maximum room temperature by about 4 °C during the day and can reduce the heating load at night significantly.

Neeper [14] examined the thermal dynamics of gypsum wallboards impregnated by fatty acids and paraffin waxes as PCM that are subjected to the diurnal variation of room temperature. He found that the diurnal storage achieved in practice may be limited to the range 300–400 kJ/m^2, even if the wallboard has a greater latent capacity. A wide phase-transition range would provide less than optimal storage, but would be consistent with application of the same PCM to either interior partitions or to the envelope of the building.

Heim and Clarke [15] conducted numerical simulations for a multi-zone, highly glazed and naturally ventilated passive solar building. PCM-impregnated gypsum plasterboard was used as an internal room lining. The results show that solar energy stored in the PCM–gypsum panels can reduce the heating energy demand by up to 90% at times during the heating season.

Stoval and Tomlinson [43] have examined the shifting of heating and cooling loads to off peak times of the electrical utility and found it saved energy with pay back of PCM investment in 3–5 years.

For incorporation of PCM in concrete blocks, Hawes and Feldman's results showed increased thermal storage up to about 300% with improved PCM incorporation techniques [45]. Hadjieva et al. [19] investigated the heat storage capacity and structural stability at multiple thermal cycling of a composite PCM concrete system that consists of sodium thiosulphate pentahydrate ($Na_2S_20_3 \cdot 5H_20$) absorbed into porous concrete (filled up to as high as 60%). The obtained experimental results specify its limitations and applicability to phase-change thermal storage wallboard.

Particularly for Trombe wall, Onishi et al. [16] numerically investigated the effects of PCM as a heat storing material on the performance of a hybrid heating system with a CFD code. Simulated results indicated the effectiveness of PCM and suggested the possibility of developing low-energy houses with the hybrid system introduced in this study. The TIM–PCM wall system also showed the higher efficiency of solar radiation utilization and decreased heat losses by using corresponding PCMs [17,54].

Using TRNSYS, Ibanez et al. [55] evaluated the influence of walls/ceiling/floor with PCM in the whole energy balance of a building (free cooling). To minimize the quantity of used PCM and, therefore, the production costs of the panel, but to get an interesting effect of reduction of maximum temperatures, the following recommendations should be followed:

(1) The PCM should be included in the ceiling and west wall of the prototype room.
(2) The needed storage capacity of the panels for the maximum air temperature to be reduced enough is around 15,000 and 37,500 kJ/m^3.
(3) The PCM chosen for the climatic conditions and the design of this application should have a phase change temperature between 25 and 27.5 °C.

With these considerations, an average maximum ambient temperature decrease of up to 3 °C was obtained.

4.2.2. PCM floor with electric heating

Farid and Chen [56] numerically investigated the potential of under-floor electric heating with a PCM layer. It was found that a 30 mm layer of PCM having a melting point close to 40 °C is sufficient to provide heat storage for 1 day under the ambient condition investigated. The heater may be operated for only 8 h during the off-peak load period, while the heat stored in the phase-change material is sufficient to provide reasonably uniform heating throughout the entire day so that heat storage can be done during the off-peak electricity period only. Farid and Kong [57] constructed two concrete slabs, with one containing

PCM–$CaCl_2 \cdot 6H_2O$. Unlike the plain concrete slab, the concrete-PCM slab showed a much lower surface temperature fluctuation and maintained an acceptable surface temperature during the whole day even though the heating process was done for only 8 h.

Amir et al. [58] examined the thermal behavior of two electric heating floor panels containing, respectively, water and *n*-octadecane paraffin in a concrete structure, which is used to store electricity as thermal energy during off-peak hours and to discharge it during peak hours. It was reported that the paraffin panel, more compact than that with water (134 mm thickness versus 152 mm), stored more energy (2880 versus 2415 kJ/m^2) and provided more comfort since the daily temperature fluctuations at its surface were less important (1.3 versus 3.8 °C).

Lin et al. [1] put forward a new kind of under-floor electric heating system with SSPCM plates. Experiments were conducted in an outdoor house set up in Beijing PRC. The results showed that the temperature of the PCM plates was kept at the phase-transition temperature for a long period after heaters stopped working. More than half of the total electric heat energy was shifted from the peak period to the off-peak period, which would provide a significant economic benefit due to the different electricity tariffs for peak and off-peak periods. In their follow up work [10], a model was developed to analyze the thermal performance of the same heating system and the influences of various factors, indicating that the heating system could be used in various climates with a properly designed structure. Then, Xu et al. [59] optimized the system parameters such as the melting temperature, the heat of fusion, the thermal conductivity of the PCM, the thickness of the PCM plate, the covering material and the air-gap between the PCM plates and the floor.

4.2.3. PCM ceiling and window

Koschenz and Lehmann [21] developed a thermally activated ceiling panel with PCM (paraffin) for application in lightweight and retrofitted buildings. Their simulation and test results demonstrated that a 5 cm layer of micro-encapsulated PCM (25% by weight) and gypsum suffice to maintain a comfortable room temperature in standard office buildings. The necessary thermal properties of the ceiling panels were determined by simulation calculations and requirements for the materials were specified.

Weinlader et al. [34] investigated the properties of double glazing combined with PCM. Light transmittances in the range of 0.4 can be achieved with such facade panels. Compared with a double-glazing without PCM, a facade panel with PCM showed about 30% less heat loss in south oriented facades. Solar heat gains were also reduced by about 50%.

Ismail and Henriquez [60,61] studied the possibility of using a window with a PCM curtain to diminish the solar gain in buildings. This window is double glazed with a gap which can be filled with PCM that would prevent the temperature of the internal ambient from decreasing.

4.2.4. Night ventilation

Kang et al. [11] proposed a novel passive cooling system—NVP system. The PCM used was a kind of fatty acid, which was hung under the ceiling. Numerical and experimental studies on the thermal performance of the system showed that the system can prominently improve the thermal comfort level of the indoor environment and have great potential in the field of energy-efficient buildings.

Kang et al. [62] developed a general model for analyzing the thermal characteristics of various typical LHTES systems. The method used is called the alternative iteration between temperature and thermal resistance method. In this model, energy balance equations were expressed as coupling functions between fluid temperature and thermal resistance, which were calculated with alternative iterations. The model was used to study the variation of fluid temperature and the interface of solid and liquid phase of PCM versus time and axis position. Based on this method, dimensionless formulae were developed by Zhu et al. [63] to analyze the thermal storage and heat transfer characteristics in a PCM outside a circular tube with a heat transfer fluid inside the tube. Zhang et al. [64] presented a general model for analyzing the thermal characteristics of both heat charging and discharging processes of various LHTES systems having encapsulated PCMs. The use of the model is illustrated by analyzing the thermal performance of a typical PCM sphere packed bed.

4.3. Heat transfer enhancement

Inadequate heat transfer and overall reduction in thermal conductivities during energy recovery are identified as the main barriers affecting the performance of a PCM wallboard system. These are attributed to the formation of solid layers, which occur at the surfaces of PCMs during the phase change process and thus affect heat transfer capabilities. There is also a multidimensional heat transfer phenomenon, which makes energy recovery ineffective [22].

Velraj et al. [65] reviewed various heat transfer methods and conducted three experiments to augment heat transfer, and found that fin configuration and the use of Lessing rings were appreciable and highly suitable for solidification enhancement.

Stritih [66] numerically modeled the time dynamics of heat accumulation in a PCM solar wall system with fins for heat transport enhancement. It was found that the most influential of the parameters is the distance between the fins. The thickness of the fins not being as critical.

As mentioned in Section 4.1.4, Darkwa and Kim's experimental and numerical studies [22–24] have shown that laminated PCM wallboard performed thermally better than randomly mixed PCM wallboard by 7–18%. Further, in order to promote one-dimensional heat transfer rates, the laminated sheet must be thin and insulated at the back.

Xiao et al. [52] developed a composite material based on paraffin, styrene–butadiene–styrene triblock copolymer and exfoliated graphite. It was reported that in the composite, paraffin undergoes solid–liquid phase change, and there is no leakage of it even in the melting state. The composite exhibits high thermal conductivity and nearly 80% of the latent heat of fusion per unit mass of the paraffin.

Experimental results by Zhang et al. [67] also showed that some additives such as graphite could improve the thermal conductivity of SSPCM-paraffin greatly. When the mass fraction of graphite is 20%, the thermal conductivity is 221% higher than the original one. However, the mechanical intensity would decrease markedly when the mass fraction of the additives becomes large.

5. Future outlook

LHTES in building applications has attracted extensive research as discussed above. However, a lot of work still needs to be done to be able to apply these concepts in a reliable and practical way.

(1) *On PCM selection*: Efforts are still needed to determine suitable materials having suitable thermophysical characteristics that fit the load requirements for different forms of buildings in different climate areas and during different seasons. The adequate melting temperature, heat of fusion and heat conduction of the PCM should be the first concern.

(2) *On integration method of PCM with the building envelope*: PCM-wallboard would be an efficient means of incorporating PCM into building envelope since it is flexible for alteration and refurbishment of conventional buildings. The percentage of PCM to mix in -the board with conventional materials, the appropriate thickness and position of PCM panels in the building depend on the climate and architectural characteristics of the buildings [55]. The optimization of these parameters is fundamental to achieving successful PCM application in buildings.
Micro-encapsulation of PCM, particularly SSPCM, may be promising due to the above-mentioned advantages. However, the method of direct immersion is more economic.

(3) *On safety and long-term behaviour*: Before PCMs can be widely used in buildings, aspects of safety such as fire retardation for organic PCM, and mechanical destruction limit of structure should be further investigated. The long-term thermal behavior, the durability of PCM-impregnated gypsum boards and the fire rating need to be evaluated experimentally. Information on these aspects of PCM application is currently limited in the literature.

(4) *On heat transfer enhancement*: As mentioned in Section 4.3, inadequate heat transfer during energy recovery is another barrier hampering the development and application of PCM-wallboard systems, which makes it impossible to obtain a designed thermal output. Efforts are still in demand on this point.

(5) *On combination with natural resources and active systems*: How to fully use natural resources such as solar energy, night sky radiation, natural ventilation etc., in PCM buildings still needs to be further investigated. Also, the combination method of PCM building components with active systems such as a solar collector, heat pump etc., should be optimized to improve the system performance efficiency and indoor comfort level.

6. Conclusions

Previous, particularly recent, work on latent heat thermal energy storage in building applications has been reviewed in this work. When selecting PCMs, their phase change temperature should be close to the average room temperature and appropriate values should be required for latent heat and thermal conductivity. Other properties such as fire characteristics and long-term stability should also be considered for organic and inorganic PCMs, respectively. PCMs can be integrated by direct incorporation, immersion, encapsulation or as a single laminated panel. SSPCM is a promising encapsulation method due to the effectiveness in reducing the danger of leakage as well as its relatively low cost. Thermal analyses showed that PCM walls, floor and ceiling etc. can be effective in shifting heating and cooling load from peak electricity periods to off-peak periods, or storing solar radiation for use during sunless hours. PCM-wallboard is flexible for alteration and refurbishment of a conventional building. However, problems such as long-term thermal behavior, durability of PCM-impregnated wallboards, fire rating and heat transfer enhancement, combination with active systems etc. still need to be focused on in future work.

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