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Review of Phase Change Materials Integrated in Building Walls for Energy Saving

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Abstract

Thermal energy storage systems (TES), using phase change material (PCM) in building walls, has become a hot topic within the research community in recent years. As more and more articles have been published, it is essential to review previous work so as to have a good knowledge of PCM walls in energy saving. Several aspects are discussed in this review, including the PCM thermo-physical properties, PCM types, PCM incorporation methods suitable for PCM walls, and specific application methods of PCM walls. Although it is known theoretically that PCM walls have a relatively good potential for energy saving, more researches focusing on real full-scale buildings and real operation conditions should be done to prove the authenticity and reliability of current study.

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Keywords: Phase change materials; Building walls application; Energy saving

1. Introduction

As the rapid economic growth worldwide, the supply of the overall energy consumption becomes tense gradually [1]. And, the building sector's energy consumption is the dominant around the world with a total of 30% share of the overall energy consumption [2]. Building energy consumption derives from a variety of sources, such as building envelope and equipment. Solar energy is believed to be very promising which is not only renewable but also non-polluting. There is always a time or space contradiction between energy supply and energy demand, such as peak-valley difference of electrical load and intermittent of solar energy source. Thermal energy storage (TES) can solve this contradiction and reduce energy consumption [3].

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The ability to store thermal energy is important for effective use of solar energy in buildings. As latent heat storage media, phase change materials (PCMs) are a series of functional materials taking advantage of high energy storage density in a narrow temperature interval [4]. PCMs added into building walls can make walls with high thermal capacity and thus contributes to reducing indoor temperature fluctuation, lessening heating and cooling loads, and lowering energy consumption. Moreover, modern construction tends to be lightweight. It would be beneficial to integrate PCMs into building walls, which affords an effective way to use solar energy and improve energy efficiency of buildings.

This paper is classified as a review of PCM integrated in building walls (PCMIBW).In this review, the thermo-physical properties, types, incorporation methods of PCM suitable for PCM walls are illustrated from Section 2 to Section 4.Finally, the specific application methods of PCM walls is discussed in section 5.

2. Phase change material (PCMs) integrated in walls

2.1. Selection criteria

Just like not all the PCMs can be used in thermal energy storage, as heat storage materials in building walls, PCMs must possess certain desirable thermo-physical, kinetic, chemical, technical, and economic characteristics. But, it must be noted that there are scarcely any PCMs that can meet all desirable criteria. In a practical application, thermo-physical properties such as melting temperature, latent heat of fusion, thermal conductivity and density of solid and liquid are the prior considered factors. And then additional measurements will be taken to make up for relatively poor properties of picked materials, for example, introducing a nucleating agent to avoid super-cooling and using fin designs or graphite to increase thermal conductivity of PCMs [5-7].

2.2. Types of PCMs

Over 200 compositions, organic and inorganic compounds, eutectics, and other mixtures have been considered as promising PCMs. A classification of the substances used for thermal energy storage was given by Abhat in 1983 [8]. Based on the chemical composition, the main three groups of PCMs used in building wall application are categorized in Fig. 1. Thermal properties of main PCM suitable for building walls discovered in literature are listed in Table 1, Table 2 and Table 3. The use frequency of different types PCMs in different areas worldwide are given in Fig.2.Though there are maybe some limitations, it also have some representativeness.

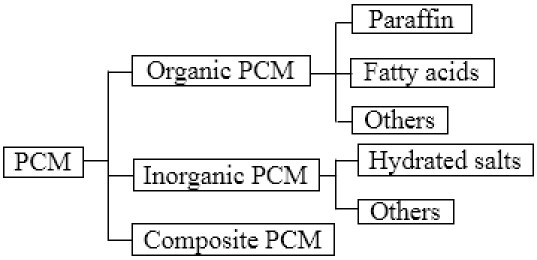

Fig. 1.classification of PCMs

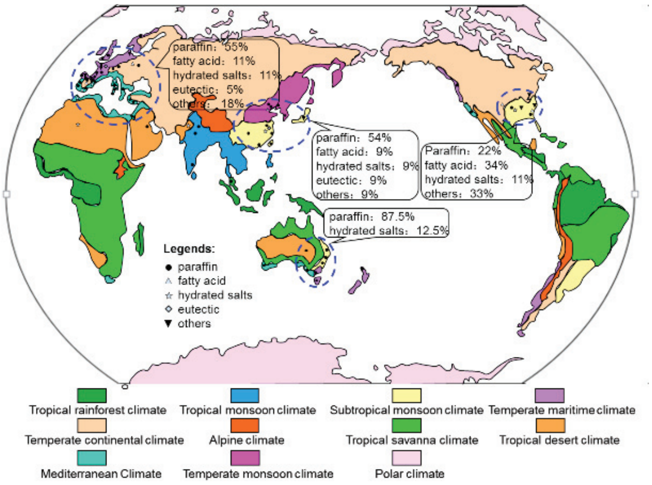

Fig. 2.the use frequency of different types of PCMs in different areas worldwide.

Table 1. Thermal properties of paraffin suitable for building walls

PCM	Melting Temperature ($^\circ C$)	Heat of fusion (kJ/kg)	Thermal conductivity ($w/m \cdot k$)	Density (kg/m^3)	References
n-Heptadecane	19	240	0.21		[9]
Paraffin C17	21.7	213		817(liquid)754(solid)	[10]
Paraffin C13–C24	22-24	189	0.21(liquid)	760(liquid)900(solid)	[11-13]
Micronalr DS5001	26	245			[14]
Paraffin：RT-27	28	179	0.2	800	[15]
Paraffin RT-18	15-19	134	0.2	756	[16]
Paraffin C18	28	244	0.148(liquid)		[13,17]
n-octadecane	28	179	0.2	750(liquid)870(solid)	[18]

Table 2. Thermal properties of fatty acids suitable for building walls

PCM	Melting Temperature ($^\circ C$)	Heat of fusion (kJ/kg)	Thermal conductivity ($w/m \cdot k$)	Density (kg/m^3)	References
Capric acid	30.2	142.7	0.2(liquid)0.12(solid)	815(liquid)752(solid)	[19]
CA and 1-dodecanol (CADE)	26.5	126.9	0.2 (liquid)0.12(solid)	817(liquid)754(solid)	[19]
Capric acid and palmitic acid	26.2	177	2.2	784	[20]
Capric acid	30	142.7		815(liquid)752(solid)	[21]
CA and 1-dodecanol (CADE)	27	126.9		817(liquid)754(solid)	[22]
MeP+ MeS	23-26.5	180			[23]
Butyl Stearate-Palmitate	17-20	137.8			[24]
Eutectic capric-myristic	21.7	155			[25]
Eutectic capric-stearic	24.7	179			[26]
Non-eutectic capric- lauric	19.2-20.3	144-150			[27]
Glycerin	17.9	198.7			[10]

Table 3 Thermal properties of hydrated salts suitable for building walls

PCM	Melting Temperature ($^\circ C$)	Heat of fusion (kJ/kg)	Thermal conductivity ($w/m \cdot k$)	Density (kg/m^3)	References
Hydrated salt	29	175	1.0	1490	[28]
CaCl2·6H2O	29	187.49	0.54(liquid)1.09(solid)	560(liquid)1800(solid)	[29]
Mn(NO3)2·6H2O+MnCl2·4H2O	27	125.9	0.6	1700	[30]
hydrated salts [water+CaCl2+ KCl + additives]					[31]
CaCl2.6H2O	29.9	187	0.53(liquid)1.09(solid)	1710(liquid)1530(solid)	[32]
Hydrated salt	31.4	149.9			[33]
Hydrated salt	25-34	140			[34]
SP25A8 hydrate salt	26	180	0.6	1380	[15]
sodium sulfate decahydrate	32.5	180	0.6	1600	[35]
Eutectic salt	32	216			[36]
Sodium thiosulfate pentahydrate	40-48	210			[37]
S27	27	190	0.48(liquid)0.79(solid)		[38]
L30	30	270	1.02(liquid)0.56(solid)		[38]

2.3 Means of PCM containment

PCM can be incorporated into construction materials and elements by direct incorporation, immersion, shape-stabilization and encapsulation.

2.3.1 Direct impregnation

Direct impregnation is the simplest, convenient and economical method in which PCM is directly mixed with gypsum, concrete or other porous materials. Khudhair and Farid [39] explained the different impregnation techniques. The volume occupied by the PCM in the pores is small enough to prevent from the isolation of the solid PCM crust.

The structure of the porous material transports the heat to the pores. Unfortunately, important leakage has been observed, in particularly by Xiao et al. [40]. Cabeza et al. [41] also reported an interaction between the PCM and its porous container. This interaction can deteriorate the mechanical properties of the container.

2.3.2 Immersion

The immersion technique is an operational approach easily. The construction elements (concrete and brick blocks, wallboards), which are dipped into the liquid PCM, absorb the PCM by capillary action. However, it is reported that PCM may leak especially after subjected to large number of thermal cycles. Also, it may affect the mechanical and durability properties of the construction elements by corrosion. The two points limit the development of this technique.

2.3.3 Shape stabilization

In this technique, Shape-stabilized PCM are prepared from a mixture of PCM and a supporting material. First, the mixture is melted and mixed with each other at high temperature, then cooled below the glass transition temperature of the supporting material until it becomes solid. The most common supporting materials found in literature are high-density polyethylene (HDPE) and styrene – butadiene – styrene (SBS). It is reported that these supports prevent the leakage of PCM. However, the thermal conductivity of shape stabilized PCM is not very high, resulting in the limitations of its application in latent heat storage systems.

Some researches on the preparation of shape stabilized PCM are given in Table 4, including the PCM, supporting material, and their mixed ratio and so on.

Table 4. Various studies on shape- stabilized PCM

PCM	Supporting material	Combination	References
Paraffin	High density polyethylene(HDPE)	Paraffin : HDPE (75:25)	[42]
Paraffin	High density polyethylene(HDPE)	Paraffin : HDPE (75:25)	[43]
Paraffin	High density polyethylene(HDPE)	Paraffin : HDPE (80:20)	[44]
Paraffin	High density polyethylene(HDPE)	Paraffin : HDPE (70:30)	[45]
Paraffin	High density polyethylene(HDPE)		[46]
Fatty acids	graphite	Fatty acids: graphite (92:8)	[20]
Paraffin	Stryrene–butadiene–styrene (SBS)	Paraffin : SBS (70:30)	[47]
Paraffin	High density polyethylene(HDPE)	Paraffin : HDPE (77:23)	[48]
Paraffin	High density polyethylene(HDPE)	Paraffin : HDPE (74:26)	[49]

2.3.4 Encapsulation

In this technique, PCM has to be encapsulated before being used into construction elements. Generally, two PCM encapsulation methods are reported-- macro-encapsulation and microencapsulation. Here, the microencapsulation is summarized.

The process that PCM particles are contained in a thin and stable shell (ranging from 1 μm to 1000 μm) is known as microencapsulation. Due to these advantages of preventing the leakage of PCM and high heat-conduction ability. Therefore, its chances of being incorporated into various construction materials are increased largely. The preparation of microcapsules is mainly divided into physical methods and chemical methods. The physical methods include pan coating, air- suspension coating, centrifugal extrusion, vibrational nozzle and spray drying, while the chemical methods include coacervation, complex coacervation and interfacial methods.

The summary of various studies on microencapsulated PCM incorporated in construction materials and elements is given in Table 5.

Table 5. Various studies on microencapsulated PCM

PCM	Shell material	Method	Capsule size(μm)	References
Paraffin	polymer shell	Spray drying	17-20	[50]

Caprylic acid	Melamine-resin	coacervation		[21]
n-octadecane	Gelatin+acacia	coacervation		[51]
n-docasane	Polymethylmethacrylate	Emulsion polymerization	0.16	[52]
Coco fatty acid	Gelatin+gum Arabic	coacervation	1000	[53]
Hexadecane/Octadecane	Melamine-resin	Insitu polymerization	5-20	[54]

3. Application methods of PCM walls

3.1. Combination of PCM walls and air/ventilation

The PCM trombe wall is a typical application method that PCM walls are combined with air. In the system, the air gap is formed between a single or double layer of glass or plastic glazing and the wall is filled with PCM [55, 56]. The wall is heated during the day by incoming solar radiation, melting the PCM. The heat stored is used to warm the room by natural convection at night.

Damien David et al. [57] developed a numerical model to evaluate the influence of convective heat transfer correlations for natural, fixed, and forced convection flows. The results show that the convective heat transfer highly influences the storage/release process. For the natural convection, the numerical results are highly dependent on the correlation used and the results may vary up to 200%. In the case of mixed and forced convection flows, the higher is the velocity, the more important is the storage capacity.

3.2. Combination of PCM walls and solar concentrators

A new system combining PCM walls and multi-surface trough solar concentrators has been reported by Haoshu Ling et al. ［46］. The schematic diagram of system can be explained by Fig. 3 and Fig. 4. Inside the PCM walls, there were several parallel vertical air tunnels, connected with the glass pipe of solar concentrators situated on the top of the system. During the daytime, the solar energy could be absorbed by solar collectors and then be used to heat the air in the glass pipe. The heated air was then supplied into these air tunnels. Thus, heat is stored in the PCM walls.

In this study, the actual structure of PCM walls is presented in Fig. 5.PCM wallboards are made by a mixture of concrete and GH-20 PCM (phase change temperature is between 7.1℃ and 25.9℃,and its heat of fusion can reach 213.4 kJ/kg). Experiment is designed to investigate the system performance and draw a conclusion that optimum operation conditions of the system were 0.4 m gap between air tunnels, downward flow direction for the heated air inside the tunnel, 0.26 m/s supply air velocity and 60℃ temperature for the supply air.

3.3 The optimization of PCM position

The PCM location have a significant effect on the performance of PCM walls. So the optimization of PCM position can improve the thermal performance of building walls [34].

The optimal location could be affected by the PCM properties (e.g., melting temperature, heat of fusion, and thermal conductivity), wall structure, and weather conditions. However, when information related to those aspects is determined, the optimal location of PCM could be found.

X. Jin et al. [18] developed a prototype PCM thermal shield (PCMTS) that its thermal performance was evaluated using a dynamic wall simulator in three different locations. The structures of the wall with and without the PCMTS are shown in Fig.6.Based on the analyses of the experimental results, the conclusions can be summarized as:

(1)The effect of (b) on the peak heat flux reduction was higher especially when the maximum interior surface temperatures increased. The impact of (c) on the peak flux reduction would be higher when the maximum interior temperatures decreased. There were almost no effects on the peak flux reduction for (d).

(2)For greater reductions of peak heat fluxes, the optimal location for the PCMTS should be within the first insulation layer of the wall from the internal side of the interior-most layer of the wall (e.g., the layer that is closer to the conditioned space)

Except for these findings, X. Jin et al. searched for the most optimal location that PCM layer was 1/5Lin a further study. The schematic of wall construction is represented in Fig. 7.

X. Shi et al. [58] carried out experimental assessment of positions (externally bonded, laminated within and internally bonded) of macro encapsulated phase change material in concrete walls on indoor temperatures and humidity levels. The results indicated that the model with PCM laminated within the concrete walls showed the best temperature control and was effective in reducing the maximum temperature by up to 4 ◦C. However, the model with PCM placed on the inner side of concrete walls showed the best humidity control and reduced the relative humidity by16% more than the control model.

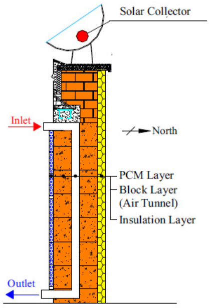

Fig. 3.sectional drawing of the system.

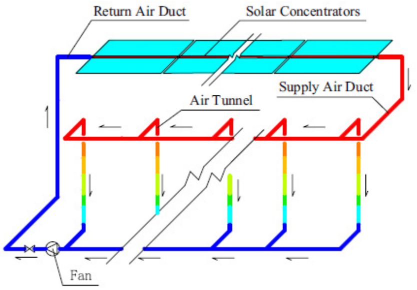

Fig. 4.schematic diagram of the heated air system

Fig. 5.actual structure of PCM wall

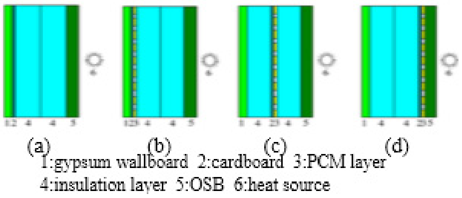

Fig. 6.construction of walls

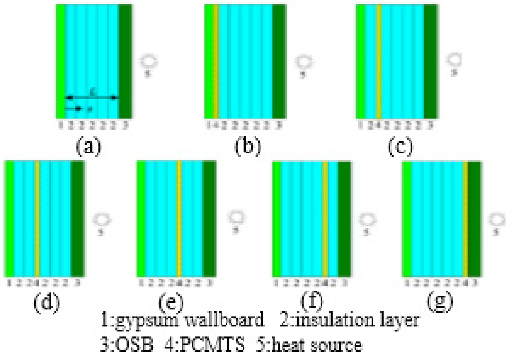

Fig. 7.schematic of wall construction

4. Conclusion

According to the research on PCMIBW, some new findings can be obtained. Firstly, parameters of thermal property can be summarized. The range of melting temperature varies between 19 to 28°C for organic PCMs and 25 to 35°C for inorganic PCMs, the heat of fusion is almost within the scope of 120 to 280 kJ/kg no matter which kinds PCMs, the thermal conductivity is close to 0.2 for organic PCMs and 0.6 for inorganic PCMs, the range of density is from 700 to 900 kg/m3 for organic PCMs and 1300 to 1800 kg/m3 for inorganic PCMs. Additionally, the application geographic locations are mainly concentrated on four areas of north latitude from 25 to 60 degrees and south latitude from 35 to 40 degrees, the use of paraffin is the broadest and the maximum use frequency is up to 87.5%. Finally, it must be noted that the practical engineering application on PCM walls is few, and researches show that the application of PCM walls is not proceed independently, but combined with other media or devices so as to strengthen the application effect.

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