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Performance Assessment of Phase Change Materials Integrated with Building Envelope for Heating Application in Cold Locations

Qudama Al-Yasiri, and Márta Szabó

ABSTRACT

Phase change materials (PCMs) are increasingly investigated in the last years as successful strategy in many thermal energy storage applications. In the building sector, PCMs are utilised to improve building efficiency by reducing cooling/heating loads and promoting renewable energy sources, such as solar energy. This paper shows the recent research works on integrating PCMs with building envelope for heating purposes. The main PCM categories and their main characteristics are presented, focusing on PCM types applied for building heating applications. The main methods adopted to incorporate PCMs with building elements and materials are mentioned, and the popular passive and active incorporation techniques are discussed. Lastly, the main contribution to building energy saving is discussed in terms of heating applications. The analysed studies indicated that all PCMs could improve the building energy saving in the cold climates by up to 44.16% regardless of their types and incorporation techniques. Several conclusions and recommendations are derived from the analysed studies that are believed to be a guideline for further research.

Keywords: building efficiency, energy saving, passive heating, PCMs

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I. INTRODUCTION

The building sector plays a key role in the global energy balance as it is the leading responsible sector for a significant share of final energy-use and CO2 emissions [1]. Besides, building envelope shares the biggest of this ratio as it manages the thermal load between the indoor and door environments and controls the heating and cooling loads [2],[3]. Consequently, the use of efficient and sustainable technologies to increase building energy efficiency are progressively required [4],[5]. In this regard, the incorporation of phase change material (PCM) into building envelope components has been demonstrated to be a promising strategy for building thermal-energy performance improvement in terms of thermal comfort and energy-saving under various locations [6]-[8].

PCMs can store and release a considerable amount of heat as a latent heat during phase transition by around 5-14 times higher than the sensible heat storage materials, per unit volume [9]. They have been introduced as advanced thermal storage materials in many building applications to meet (or support) the thermal load on an annual basis. In general, PCMs are integrated into building envelope materials and elements, such as the roofs [10], walls [11],[12], floors [13], bricks [14], concretes [15], mortars [16], and transparent components [17],[18]. The main benefits of this integration are to save building energy by reducing thermal loads (cooling and heating loads), shaving and shifting peak load to off-load hours [19],[20]. The use of PCMs for heating purposes in buildings has a wide range of applications that can be summarised as presented in Figure 1.

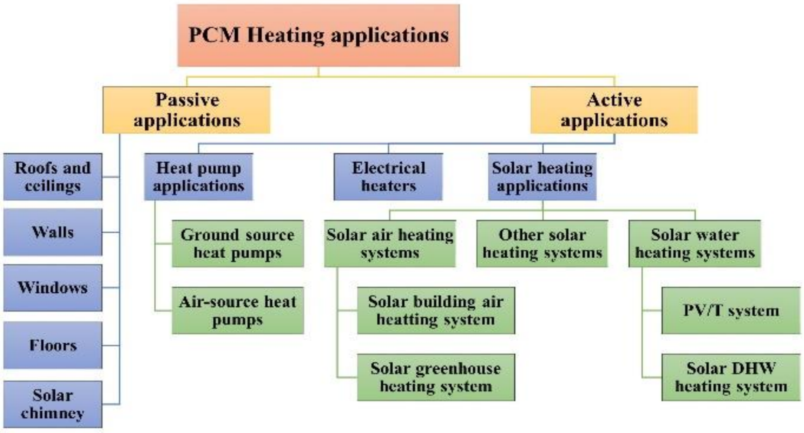

Fig. 1. General applications of PCM for building heating purposes

In this paper, the integration of PCMs into building envelope for heating applications have been discussed. The paper comprises several sections to cover all aspects of PCM heating applications. Section II gives a general overview of PCM categories with their main characteristics and a list of PCM candidates used for building heating applications. Section III deals with the possible methods and incorporation techniques adopted in the literature, whereas section IV discusses PCM's main contributions to the building energy saving. At last, several conclusions raised from the reviewed studies have been presented in section V.

II. PCM CHARACTERISTICS

Generally, PCMs are classified into three categories based on their chemical construction: organic, inorganic and eutectics. Organic PCMs are the widely available materials and further classified into paraffinic, and non-paraffinic PCMs such as salt hydrates, fatty acids, esters and glycols [21],[22]. Each category has its advantages and disadvantages resulted from their various characteristics [23]. PCM characteristics are requirements to be considered when studying their utilisation in buildings. These characteristics are mainly related to the PCM melting temperature, heat of fusion, thermal conductivity and density [7].

A. Melting temperature

Melting temperature is the temperature in which PCM's melting process, and the state change from solid to liquid. Melting temperature is the topmost property of PCM starts, which controls the utilisation of PCM thermal storage capacity. The variation of air-solar temperature should be adequately studied for the location under study to select the proper PCM with suitable melting temperature. For instance, a study carried out under Portugal's climate conditions considered air-solar temperature annually. The study found that the temperature varied between the highest 44 °C in summer and the lowest 5 °C in winter period [24]. Therefore, the suggested optimal PCM melting temperatures should be in the range of 10 °C to 30 °C. In general, each PCM category has a different range of melting temperature, making it suitable for a particular application, as shown in Figure 2.

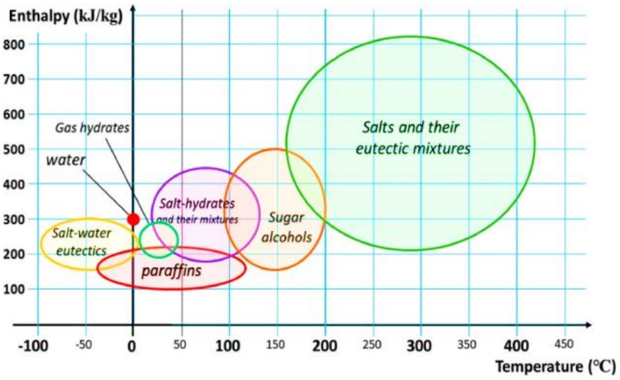

Fig. 2. Temperature range of PCMs [25]

B. Heat of fusion

The heat of fusion is defined as the quantity of heat required to change 1 g of solid to liquid under no temperature change (adiabatic process). It sometimes calls as the latent heat of fusion [26], as indicated in Figure 3. In PCM applications, the higher heat of fusion value allows more heat to be stored, making it preferable. The heat of fusion is almost within the range of 120-280 kJ/kg, regardless of the type of PCM [27].

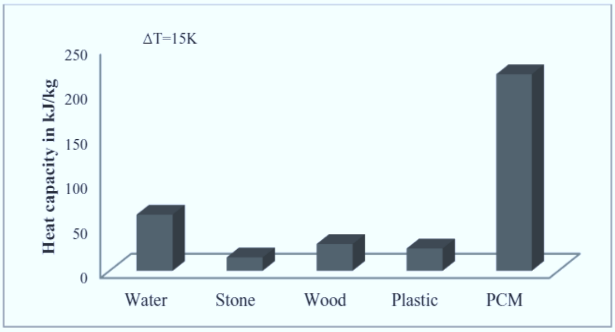

Fig. 3. Heat capacity of PCMs compared with other materials [28]

C. Thermal conductivity

Thermal conductivity is the ability of PCM to conduct heat. It is commonly known that all PCMs have low thermal conductivity by nature. Therefore, many enhancement techniques have been applied to improve PCM thermal conductivity such as emersion of nanoparticles, metallic foam, expanded graphite, metal inserts, fins, and macroencapsulation with high thermal conductivity containers [29]-[34].

D. Density

Density is commonly expressed as the mass of a material to its volume. Together with PCM's thermal conductivity, the density highly influences the rate of heat charging and discharging [35]. It has been reported that the density of organic PCMs ranged from 700 kg/m3 to 900 kg/m3 and from 1300 to 1800 kg/m3 for inorganic PCMs [36].

A list of PCM characteristics for different categories suitable for building applications under hot climate conditions is listed in Table I gathered from the studies reported in the literature.

TABLE I: THERMO-PHYSICAL PROPERTIES OF PCMS

PCM type	Category	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/m. K)	Density (kg/m^3)	Ref.
Paraffin wax	Paraffin	27–29	245	0.2 (Liquid)	770 (Liquid) 880 (Solid)	[37]
PureTemp 23	Paraffin	22.23-24.17	170.71	0.15 (Liquid) 0.25 (Solid)	830 (Liquid) 910 (Solid)	[38],[39]
RT-18	Paraffin	15-19	134	0.2	756	[40]
RT27	Paraffin	28	147	0.2 (Liquid)	750 (Liquid) 870 (Solid)	[41]
HS29	Paraffin	26-29	190	0.55 (Liquid) 1.05 (Solid)	1530 (Liquid) 1681 (Solid)	[42]
RT-27	Paraffin	28	179	0.2	750 (Liquid) 870 (Solid)	[43]
SP-25 A8	Hydrated salt	26	180	0.6	1380	
Hydrated salt	Hydrated salt	29	175	1.0	1490	[44]
CaCl2.6H2O	Hydrated salt	29.9	187	0.53 (Liquid) 1.09 (Solid)	1710 (Liquid) 1530 (Solid)	[45]
CADE	Fatty acid	26.5	126.9	0.2 (Liquid) 0.12 (Solid)	817 (Liquid) 754 (Solid)	[46]
LA–MA–SA	Fatty acid	29.05	137.1	N/A	N/A	[47]
CA–MA–PA	Fatty acid	18.61	128.2	N/A	N/A	[48]
CA–PA	Fatty acid	26.2	177	2.2	784	[49]
CA–PA–SA	Fatty acid	19.93	129.4	N/A	N/A	[50]

III. POSSIBLE INCORPORATION METHODS AND TECHNIQUES

PCMs can be applied for new and existing buildings during installation or refurbishment stage. They can be incorporated with building envelope directly (by impregnation or direct mixing), or as a separated element (via encapsulation, shape and form stabilised methods) [6]. Furthermore, they can be installed and utilised within the building envelope in a passive or active technique.

In the *passive technique*, the charging and discharging heat to/from the PCM takes place passively without any external means. Therefore, PCM's thermal performance is influenced by conductive heat flux exchange rate and natural convection currents between the PCM and heat transfer fluid (HTF). In such a case, exchanging heat between the PCM and air (outside and inside environments) is the main key-factor of this technology [51]. Moreover, the passive technique requires high heat transfer surface temperature to accelerate heat charging and discharging time [52]. Possible incorporation methods of PCM with building elements are shown in Figure 4.

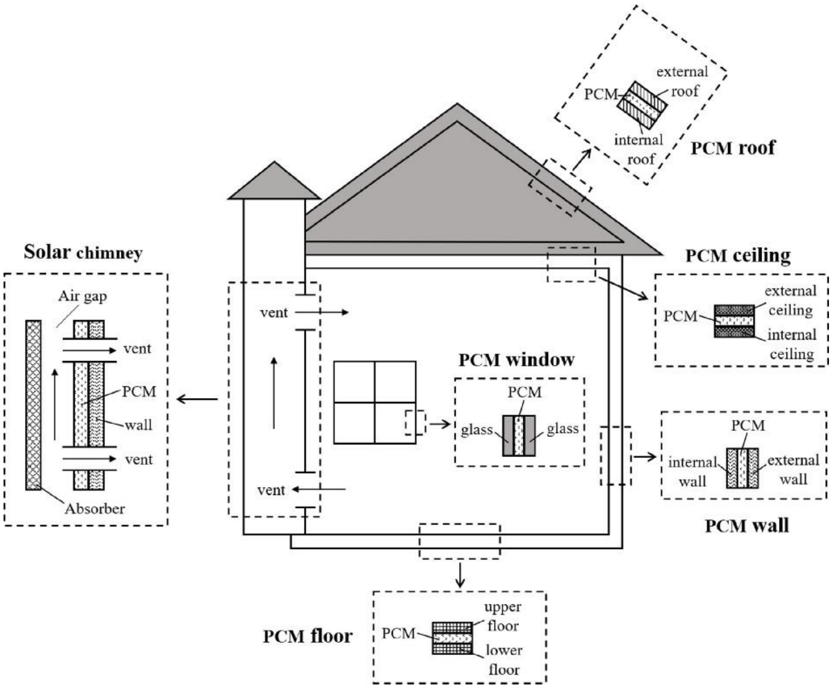

Fig. 4. Passive possibilities to incorporate PCM into building envelope [53]

For active technique, the HTF is forced to charge the heat to the PCM using different means such as solar collectors, blowers and pumps. Hence, the PCM's thermal performance and building element would be enhanced remarkably [54],[55]. The popularly investigated application in this method is utilising solar thermal energy to charge heat via solar collectors where air or water work as an HTF. For instance, when the water applied as an HTF, the heat harvested by solar collectors is transferred to the water and then, charged into the PCM integrated with the building envelope, as shown in Figure 5.

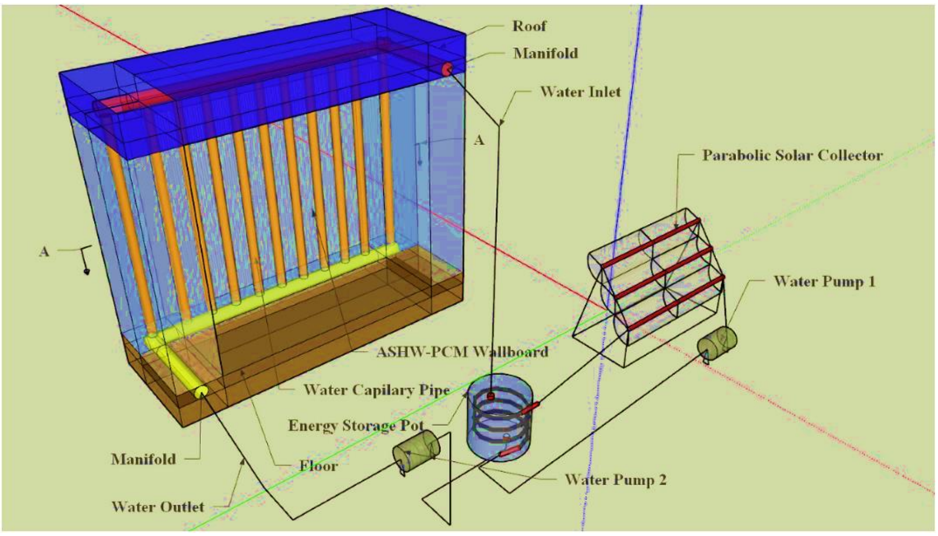

Fig. 5. Active solar water system coupled building envelope PCM [56]

In general, PCM's applicability into the building envelope, passively or actively, depends highly on PCM's melting temperature and the daily range of temperatures during the day and night to ensure full melting/solidification of PCM [13]. The possible passive and active methods reported in the literature are represented in Figure 6.

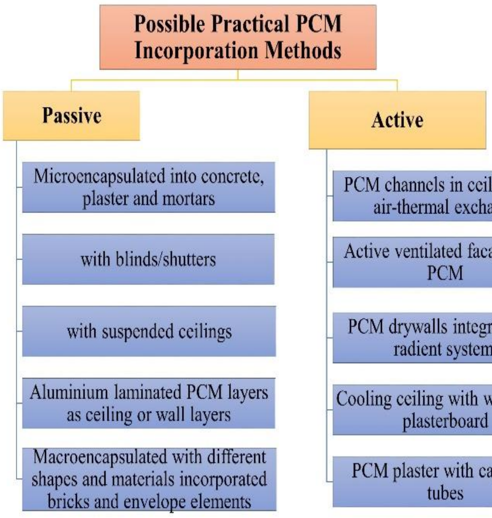

Fig. 6. Possible incorporation methods of PCM into building envelope [57]

IV. CONTRIBUTION OF PCM TO THE BUILDING ENERGY

For heating purposes under cold locations, PCMs mainly utilised in two ways: absorb the heat during day hours and release it during low-temperature nights. Secondly, restrict the heat escaping from the hot interior environment towards the exterior environment due to temperature difference. PCMs can absorb the heat resulting from relative high diurnal solar energy during day hours and release it during night hours due to temperature difference. Therefore, they can be applied as a heat supplier when it incorporates building envelope under cold climate conditions [58]. It has been reported that PCMs can increase the thermal storage of the building envelope, which is usually constructed from materials with low thermal inertia [59]. Seong and Lim [60] numerically studied the thermal benefits of PCMs have different melting temperatures incorporated lightweight building envelope under weather conditions of Seol, Korea. Considering the contribution to the heating application, PCM of 21°C melting temperature performed the best in heating load reduction and indoor temperature increase on an annual basis. Results showed that PCM could improve the building efficiency in which the peak heating load was reduced by 3.19% and the indoor temperature increased by 0.86 °C. Araújo et al. [61] studied the potential of eight PCMs with different melting temperatures (RT 15, RT 18, RT 21, RT 22, RT 24, RT 25, RT 26 and RT 28) for residential building located in northern Portugal. Numerical results obtained by EnergyPluse dynamic tool indicated that the RT 22 showed the best performance in which the heating needs were reduced by 8.22 kWh/m^2/year, representing heating energy saving of 13.2%. Hu and Yu [62] numerically studied the thermal response of building integrated with PCM (21.7 °C melting temperature) under Chinese cities' diverse climate conditions. Considering the cold conditions of Nanjing, the maximum monthly heating loads reduction of 0.8 kWh/m^2 in November, 2.2 kWh/m^2 in December, 1.4 kWh/m^2 in January, 1.9 kWh/m^2 and 1.2 kWh/m^2 in March which represent energy saving by 14%, 10%, 4%, 9% and 13% respectively. The study concluded that the maximum energy saving obtained in the coldest months in the year emphasises the applicability of PCMs. Guarino et al. [63] numerically and experimentally tested PCM wallboard (18-24 °C melting temperature) combined the south-oriented interior surface wall opposing a highly glazed façade under cold climate conditions of Montreal, Canada. The study aimed to increase the wall's thermal performance by storing the heat passes through the glazed façade to be released later. Results showed that the solar radiation was stored during day hours and released for 6-8 h after sunset which reduced the daily temperature swings (up to 10 °C) and heating requirements (more than 17%, yearly). Kong et al. [64] invented a hybrid system by coupling perlite-based composite PCM wallboard with a solar heating system. The hybrid system was placed to the inside of the tested room's wall and compared with another reference room without PCM (woring with heating radiators) for three working days under winter conditions of Tianjin, China. The analysed results showed that the daily heating energy consumption was reduced by 44.16% in the room provided with hybrid system compard with the other room without PCM. Moreover, the study concluded that such system could maintain the required comfort environment and enhance buildings' efficiency. A detailed summary of some similar studies is listed in Table II.

TABLE II: SUMMARY OF LITERATURE STUDIES DEALING WITH THE CONTRIBUTION OF PCM FOR BUILDING HEATING APPLICATIONS

PCM type (melting temperature, °C)	Location Country (city)	Building element	Incorporation technique	Study type	Contribution to the energy-saving (ES)	Ref.
PCM24D (21.9) RT21 (21)	Norway (Oslo)	Walls	Passive	Numerical	Energy reduction of 23% was obtained during the winter.	[65]
BioPCM- Q25/M91 (25)	Greece (Athens)	Walls	Passive	Numerical	The heating loads reduced by 1.54%	[66]
GH-20 (20–25.4)	China (Shanghai)	Wall	Passive	Numerical + Experimental	The heating load reduced by 10–30%, and 9–72% reduction of the heat lost from the interior wall surface was reached.	[67]
n-Octadecane (18.80–37.83) Beeswax (33.41–61.05)	United States (Miami and others)	Walls	Passive	Numerical	In Miami, ES of 7.8% and 6.4% achieved when *n*-Octadecane and Beeswax applied during the heating season.	[68]
RT-21 (21–22)	Spain	Slab	Active (solar air collector)	Experimental	energy-saving of 25% and 40% during the severe and mild winter conditions, respectively	[69]
Composite PCM: SP 29 (28-30) & RT 18 (17-19)	China (Shanghai)	Walls + roof	Passive	Numerical + Experimental	During the nighttime, the temperature raised by 6.93–9.48 °C for PCM room and the indoor air temperature fluctuation decreased by17.7–25.4% during the sunny time. In conclusion, the PCM has increased the heat released to the room and decreased the heat escaped from the room.	[70]

V. CONCLUSION

PCMs are among booming technologies nowadays thanks to their remarkable potential as thermal energy storage in different applications. In building applications, it has been proven that PCMs can effectively improve the energy efficiency and maintain acceptable thermal comfort on an annual basis. The current paper discusses the potential of PCMs to improve the heating energy saving when incorporated building envelope under cold locations. In this regard, the following conclusions are derived from the analysed studies:

1) Generally, the melting temperature of PCMs used for building heating applications ranged between 15 °C – 30 °C regardless of the type of PCM.
2) Most of studied PCM types were organic (Paraffins, fatty acids and hydrated salts) as they have a suitable melting temperature for building applications. Besides, there is no eutectics were studied in such applications due to their high melting temperatures which are not suitable for such application.
3) Most of studies discussed the incorporation of PCMs for building thermal applications were investigated passively. Besides, very limited ones considered the active technique using solar thermal and other renewable systems due to the complexity of coupling PCM with active systems.
4) Solar thermal systems integrated PCMs for building heat application has a significant role to increase the benefits of utilizing solar energy and building efficiency. However, emerge other heat sources with PCMs is still out of scope which can be a novel heat recovery systems.
5) Number of numerical studies are much higher than the experimental studies mainly due to a variety of simulation tools and complexity of incorporation techniques, especially the active ones.
6) The main thermal contribution to energy saving reported in the literature for PCMs applied under cold climates was presented in terms of decreasing the heating loads and maintaining a suitable thermal comfort throughout the year.
7) Energy saving by up to 44.16% can be obtained from integrating PCMs with building envelope which represents a huge contribution for building energy-saving by PCM technology.

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