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# USE OF PHASE CHANGE MATERIALS THERMAL ENERGY STORAGE SYSTEMS FOR COOLING APPLICATIONS IN BUILDINGS: A REVIEW

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## Abstract

Sharing of renewable energy and reduction of conventional energy consumption as attempts in ameliorating environmental issues such as global warming became the main concern for current developing scientific engineering research. And, with the remarkable increase in the cooling and heating demand in the building sector world widely, the need of a suitable technology that permits to the improvement of building thermal performance. Utilizing phase change materials (PCM) as thermal energy storage strategies in buildings can meet the potential thermal comfort requirements when selected properly. The current research article presents an overview of different PCM cooling applications in buildings. Active and passive classifications are presented. A summary of the used PCMs and their respective properties are also offered. Studied systems are proved to be efficient in reducing indoor temperature fluctuations and energy demand during cold seasons, with the capability of triggering load reduction or shifting.

## 1. Introduction

Recent and current developing research efforts have been focusing on the share of renewable energy with the remarkable increase of energy demand all over the world. According to the Kaya identity, the total carbon emissions that leads to global warming is influenced by economic growth, the intensity of energy consumption, population growth and intensity of carbon emissions [1]. However, researchers and policymakers have attributed carbon emissions' high-intensity to energy consumption resulting from rapid economic growth and the amplified usage of fossil fuel [2]–[4]. Taking the United States (U.S.) as an example, more than 90% of greenhouse gas emissions including CO<sub>2</sub>, that causes the change in climate, are caused by the combustion of fossil fuels [5]. According to the International Energy Agency (IEA), the respective increase in the primary energy production and CO<sub>2</sub> emissions have reached 49% and 43% over the past 20 years. In the European Union (EU), the building sector is the main source for energy consumption that accounts for about 40% of the total energy usage [6]. However, the environmental crisis is at the beginning, where the expectations show that the energy demand in the building sector will reach a rise of 50% by 2050, with the space cooling demand being tripled at the forecasted period [6]. For that, researchers seek potential solutions to ameliorate energy conservation and energy storage as an attempt on the path of demolishing the crisis of global warming. Developing the novel technology to promote energy efficiency and conservation in buildings has been one of the major issues of governments and societies, whose aim is reducing the energy consumption without affecting the thermal comfort in the wide range of weather conditions [7]. An extensive technique, regarding cooling improvement by

reducing the energy demand in building sector, is the application of phase change materials, known as "PCM", which have received much attention and became a topic with a lot of interest among architects and engineers in the last four decades [8]. PCMs work as latent heat thermal energy storage strategies that absorb the excess energy in buildings filling the gap between energy supply and demand, which makes it a promising technology [9]. Currently, the use of phase change materials (PCMs) have been widely developed in different fields including applications covering a wide temperature range from -20°C to 200°C for heating, cooling and hybrid mixing of heating and cooling [9].

Plenty of review articles are published in the field of phase change materials thermal energy storage (PCM-TES). J. Heier et al. [10] reviewed the literature focusing on combining TES to buildings where they concluded that the use of PCM and Thermochemical materials for energy storage (TCM) require more research due to their reliability problems especially subcooling, fire retardation, and low energy transfer rates regarding PCM and lack of material and system studies for TCM. A review on PCM for cooling applications in buildings was conducted by F. Souayfane et al. [6]. Five main applications were discussed: Free cooling, solar cooling system with PCM, PCM air conditioning systems, evaporative and radiative cooling systems, and PCM in building envelope with emphasis on active and passive systems as well as the principle of ventilated facades and its applications. A massive recent review paper conducted by K. Du et al. [9] reviewed the applications of PCMs in cooling, heating and energy generation in four temperature ranges: low temperature range (-20°C to 5°C), medium-low temperature range (5°C to 40°C),

medium temperature range (40°C to 80°C) and high temperature range (80°C to 200°C).

The current review paper presents the cooling applications of PCM-TES in buildings and summarizes the used PCMs, their properties and incorporation methods.

## 2. Phase change materials integrated in buildings

### 2.1 Phase change materials concepts and classifications

A. Sharma et al. [11] included in their study that different types of thermal storage of solar energy are divided into two categories: (1) Thermal and (2) Thermochemical (see Fig. 1). Jaykumar H. Petal et al. [12] stated that, fundamentally, TES is subdivided into three categories: Sensible heat storage, Latent heat storage, and Thermochemical heat storage (TCM-TES). Nevertheless, due to the lack of commercially available TCM-TES systems, and due to high material costs and unknown lifespan [10], the main categories for TES techniques are: sensible heat storage and latent heat storage [5], [8]. Deciding which storage technique to use, it is important to detect the ratio between the building's envelope size, used materials and their volume with their respective thermal mass which represent the most significant factors influencing the thermal response [8]. In their study, Morrison and Abdulkhalik [13] showed that for air-based system, the storage volume of a rock-bed unit (which is a sensible TES method) is 4 times greater than that in a system utilizing Sodium Sulfate Decahydrate ( $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ ) and double that in a system utilizing paraffin wax (which are latent TES methods). Consequently, lightweight construction incorporated with PCM-LHTES, having high storage density, is more efficient, especially with their capability of storing energy between 5 and 14 times more heat per unit volume than sensible heat storage materials like water, masonry and rock [14].

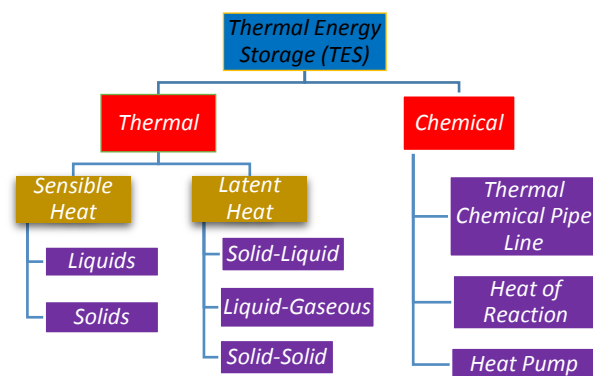


Fig. 1. Different types of thermal energy storage [11].

Phase change materials are “latent” heat storage materials that undergo a phase transition between liquid and solid that occurs isothermally upon melting (heat storage) or solidifying (crystallization recovery). During phase transition from solid to liquid, PCMs store thermal energy in the form of latent heat by an endothermal process that dissolves the PCM's chemical bonds, and reject it exothermally when being cooled to recover

its solid state [6], [11], [14]–[17]. PCM then is said to act as a thermal reservoir [18]. Phase change materials that undergo phase change between liquid and solid are classified into three main categories: Organic, In-organic, and Eutectics [5], [15], [19]–[21]. These categories are subdivided into further categories based on the chemical components forming the PCM. Organic compounds are either Paraffin-based or non-paraffins: Fatty acids, sugar alcohol, and glycol. In-organic PCMs are either salt hydrates, molten salts, or metals. And, eutectic PCMs are mixtures containing organics, in-organics, or both [22].

### 2.2 Phase change materials incorporation methods

PCMs can be integrated into building envelopes and elements by five incorporation methods: (1) Direct impregnation (direct mixing), (2) immersion or imbibing through materials' pores, (3) shape-stabilization, (4) microencapsulation and (5) macro-encapsulation.

Direct impregnation is a method where liquid or powdered PCM is directly added to building materials such as gypsum, concrete or plaster or insulation materials such as cellulose during manufacturing. The technology of imbibing is referred to the dipping of manufactured building materials into melted PCM bath to allow the absorption of the latter through the materials internal pores [23].

The majority of PCMs used for building materials undergo a phase change between solid and liquid phases, which permits the possibility of leakage and diffusion of low viscous liquids through building materials. For this purpose, shape-stabilization, macro-encapsulation and micro-encapsulation methods are more suitable for long term applications [24]. Shape-stabilization refers to the dispersion of PCM into another phase of supporting material such as: high density polyethylene (HDPE) or a composite such as: styrene-butylstyrene (SBS) with powder like HDPE and graphite or carbon fibers, to form a stable composite Shape-stabilized PCM material [25]. Macro-encapsulation involves the usage of any type of container that are usually larger than 1 cm in size. Such containers include: tubes, spheres or panels. Microencapsulation refers to packing of PCM in capsules that range from less than 1  $\mu\text{m}$  to 300  $\mu\text{m}$ , where the end product (mPCM) is formed of an outer shell, consisted of organic polymers or silica, and the PCM filling the center [24].

## 3. Use of PCM-TES for cooling applications in buildings.

PCMs applications are suitable for both new buildings and retrofitting of existing ones [24]. The technique of incorporation, melting range, and desired utility characterize the functioning mode of the used PCM-TES system. PCM-TES can be used for heating, cooling or for both heating and cooling which is referred as hybrid systems. Each mode is subdivided into passive and active categories. J. Heier et al. [10] states that the difference between active and passive systems is the driving force of charging and discharging the store, where

active storage utilizes pumps or fans however passive storage depends only on temperature difference between the store and the surroundings.

According to F. Suayfane et al. [6], the cooling demand in the building sector has increased rapidly due to: (1) High need for occupants' comfort, (2) Rise of buildings internal heat gains, (3) the impact of urban heat island felt in overcrowded cities, and (4) the reduced cost of cooling equipment. Integrating PCM into buildings can both decrease the cooling cost and improve the thermal comfort during hot seasons.

### 3.1 Cooling passive applications

The adaptation of PCM in passive application includes integrating them in: AC systems, solar absorption chillers, evaporative and radiative cooling techniques, solar chimney, ventilated façade, geo-cooling and ice storage.

Shiuan-Man Wang et al. [17] studied the daily thermal performance of a (30cm × 30cm × 3cm) mPCM honeycomb wallboard. The prepared module, with 8-mm core cell aluminum honeycomb plate that is filled with mPCM, resulted in an effective thermal protection period reaching 4h, 4.7h and 4.7h for cases 1-3 respectively, and heat releasing periods reaching 2.8h, 3.3h, and 3.8h respectively. This indicates that the indoor conditions influence the thermal performance of the tested wallboards. K. O. Lee et al. [23] performed field tests on two identical prototype rooms subjected to full weather conditions. The research was directed to investigate the thermal performance of PCM-enhanced cellulose insulation installed in the cavities of a building walls. Results showed that: On average, peak heat fluxes were time delayed by about 1.5 h, an hourly peak heat flux reduction of 26.6% from the sum of all four walls was achieved, and the relative average cost savings were 3 cents/m<sup>2</sup>.

H.J. Alqallaf and E.M. Alawadhi [26] analyzed the thermal behavior of a building concrete roof with vertical cylindrical holes filled with PCM numerically with experimental validation. The study focused on determining the effect of the holes dimensions, particularly the diameter while maintaining the volume constant, and the impact of the melting temperatures of the used PCM as well as the operating month. Results showed that heat gain can be reduced more with larger PCM holes diameter, and that the PCM melting temperature has a great impact on the heat gain during summer. For best performance, the authors concluded that the selection of the suitable melting temperature should be based on the operating month and working hour period, where according to the results, the heat flux at the indoor surface of the roof can reach a reduction value of 12.04 to 17.26% depending on the operating month, during working hours of 12-5pm. A numerical analysis on the thermal behavior of a PCM-filled double glazing roof for cooling energy consumption reduction and thermal comfort improvement was prepared by C. Liu et al [7]. The study showed that the effect of the semi-transparent property of the glazing and the zenith angle on temperature time lag, transmitted solar energy, and the total transmitted energy is large.

The thermal performance of a 15 m<sup>2</sup> office cubicle integrated with bio-based PCM in its ceiling was experimentally investigated by Tor A. Vik et al. [16]. The study comprised different scenarios including suspended ceiling with PCM covered with ceiling plates, and that without supporting ceiling plates. The used PCM was Bio-PCM with the code Q23 M51. The chief results showed that when using exposed PCM integrated in suspended ceiling and in one wall of the room, a drop of operative temperature reached 3.3°C allowing the operative temperature to remain under 26°C during operative hours revealing that the recommendation of Norwegian building code is achieved. The author recommended including void ventilation for PCM inside the walls by down and up holes, allowing more ventilation at night and the usage of a PCM with slightly higher melting temperature. Finally, the authors stated that although the exposed PCM in building have great benefits, it is challenging in terms of acoustic and aesthetic concerns.

T. Silva et al. [27] performed an experimental study of the thermal performance of a window shutter containing PCM and validated a numerical model based on their results utilizing CFD analysis. Experiments involved a real scale test cell with two identical compartments each utilizing window shutters, one with PCM and the other lacking it. Results indicated that the compartment with PCM shutter perceived a decrease in the maximum indoor temperature of 8.7% and an increase of 16.7% in the minimum indoor temperature for the night period. A respective corresponding achieved delay of 1 hour and 30 minutes of the maximum and minimum temperature peaks were observed. An experimental investigation of the adaptation of PCM in a novel triple-pane window (TW) was presented by S. Li et al. [28]. The authors aim was to solve the two problems of double-pane windows with PCM (DW+PCM) presented as: night latent heat release into the room during and overheating risk from completely melted PCM. It was shown that a respective reduction of 2.7°C and 5.5°C on the interior surface of the TW+PCM compared to DW+PCM and TW corresponding to a reduction in the heat entering the building through the windows of 16.6% and 28% respectively. This ensured the evasion of overheating risk.

Y. Li et al. [29] performed a numerical analysis of an integrated double skin façade (DSF) and PCM blind system using ABSYS Workbench FLUENT software. The study was based on comparing the temperature and velocity fields of a DSF with PCM blinds and another with conventional aluminum blinds. Results showed that the average air temperature and the outlet temperature from the DSF experienced a reduction due to the improvement of the convective heat transfer between the cavity air and the blades caused by the PCM. PCM blind was proven to be capable of absorbing a large amount of cavity heat in excess, thus contributing in effective thermal management for minimizing DSF's overheating effect.

A numerical investigation of a composite Trombe solar wall integrated with microencapsulated PCM was performed by E. Leang et al. [30] using Dymola Modelica software. Results

showed that compared to concrete storage wall, large capacity of recovered heat was achieved the mPCM storage wall. Furthermore, the 4cm mPCM storage wall triggered a phase time delay almost 4 times shorter than that obtained of the reference wall. In the experimental aspect, a study by P. Thantong et al. [31] on a solar wall collector with PCM integrated to the wall of a prototype house that was compared to another identical reference house. Results revealed that the solar wall with PCM delayed heat transfer and accumulated more heat with a reduction of 59.63% in heat entering the house compared to the conventional wall in the reference room. Such results guaranteed that a solar wall with PCM is capable of lowering heat accumulation, promoting the use of solar energy and saving electricity from using AC systems.

### 3.2 Cooling active applications

Active applications for cooling in buildings are categorized as: Free cooling, passive solar façade with PCM and the integration of PCM in building elements including: Trombe walls, floor and tiles, building walls, ceiling, roof, windows and shutters.

Integrating PCM into various heat exchangers for improving air-conditioning systems and increasing their COP was the aim of D. Zhao and G. Tan [32] in their numerical analysis. A shell and tube latent heat storage unit was installed in a combined system utilizing an AC system. Water and air were the two media incorporated in the charging and discharging processes of the latent energy. It was clear from the results that the achieved effectiveness of the latent heat storage system is higher than 0.5. A case study of replacing conventional cooling tower by the proposed PCM system shows that the COP value increases by 25.6%.

A solar-driven air conditioning system with integrated PCM cold storage is modeled using TRNSYS software by Y. Allouche et al. [33]. The simulations were performed for satisfying the cooling demand of a 140 m<sup>3</sup> space in Tunis, Tunisia. Results without cold storage indicated that the comfort temperature was exceeded in more than 26% of the time, however, with cold storage of high indoor temperatures periods diminished significantly. The authors concluded that applying latent heat storage with PCM, as low temperature thermal energy storage, is highly recommended for ejector solar cooling, where more stability is given to the AC system with the improvement of COP and solar thermal ratio values could reach up to 100% with the contribution of PCM.

O.G. Pop et al. [34] provided a numerical study for the energy efficiency of a fresh air-cooling system equipped with a PCM-TES in a virtual office building under various climate conditions. After evaluating the PCM energy efficiency in fresh AC system, savings of 7 to 41% in electric energy consumption can be achieved based on particular local conditions leading to reduction in carbon impact.

The application of PCM in assisting Geo-cooling systems for cooling commercial buildings was the topic discussed by P. McKenna et al. [35]. The research included a numerical approach using TRNSYS software for modeling the system. Geo-cooling alone was capable of meeting the cooling demand for 84% of a four-month cooling season, however this

percentage increases to 99% when using TES with the system. Compared to a system based on a reference ground-source heat pump (GSHP), the authors stated that, with more advanced TES control strategies, electricity savings of 24% to 45% could be achieved by combining geo-cooling with TES in a small lightweight commercial building.

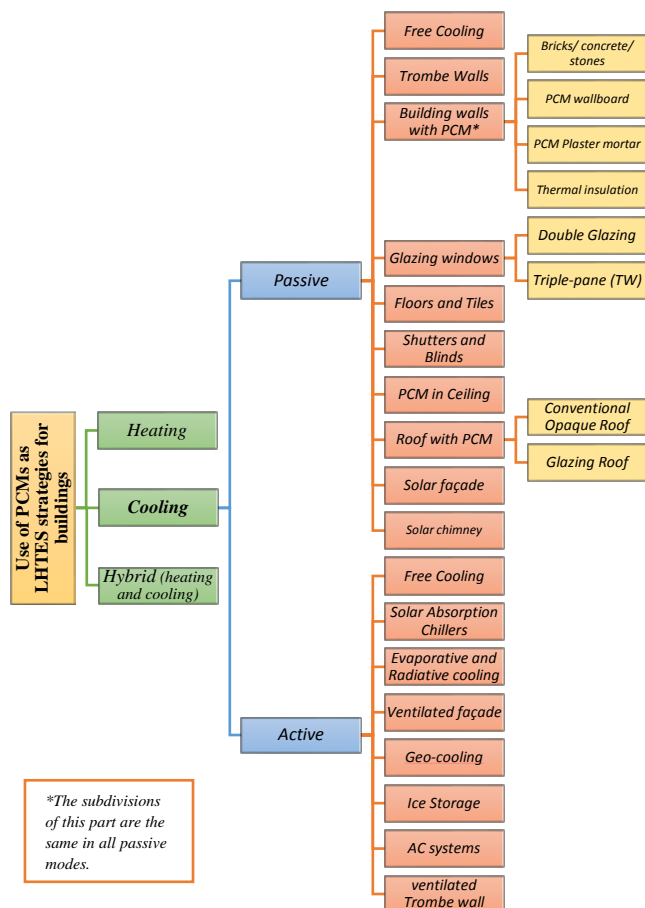
A summary of the used PCMs in active and passive cooling applications is presented in Table 1.

**Table 1** Properties of PCMs used in buildings for cooling.

Used PCM	Incorporation method	Application	Melting point, °C	Latent heat, kJ/kg	Ref
RT22	-	Free active	22	200	[32]
RT28HC	Macro-encapsulated	Free active	25.6-27.1	251	[36]
PMMA-MAA (methyl methacrylate)	Micro-encapsulation	Building envelope	23.68	170	[37]
Paraffin/polymer shell	Micro-encapsulation	Honeycomb wall	37	166.54	[17]
Paraffin/cellulose	Direct mixing	Walls	28	60.45*	[23]
A22	Macro-encapsulation	Concrete roof	28	230	[26]
A32	Macro-encapsulation	Concrete roof	32	215	[26]
A38	Macro-encapsulation	Concrete roof	39	190	[26]
-	Macro-encapsulation	Double-glazing roof	27-29	205	[7]
bio-PCM Q23M51	Macro-encapsulation	Ceiling	23	-	[16]
RT28HC	Macro-encapsulation	Shutters	28	250	[27]
Paraffin MG29	Macro-encapsulation	Triple-pane window	27-29	205	[28]
PX35	-	DSF with PCM blinds	29-36	100	[29]
Micronal PCM® DS 5001 X	Micro-encapsulation	Trombe wall	26	110	[30]
RT20	Micro-encapsulation	AC systems	21.8	138.3	[34]
RT25	Micro-encapsulation	AC systems	25	133.7	[34]
RT27	Micro-encapsulation	AC systems	28.38	144.9	[34]
H <sub>2</sub> O + nucleating agents	Macro-encapsulation	Geo-cooling	0	-	[35]

\*This is the latent heat for the mixture of paraffin-cellulose not for paraffin itself.

Finally, a schematic diagram showing the classification of the applications for cooling strategies utilizing PCMs in buildings are illustrated in Fig. 2



**Fig. 2.** Schematic diagram for the cooling applications of PCM-TES in buildings as discussed in the current review article.

## 6. Conclusions

The current work presented a review on recent research work in the scientific community regarding the usage of phase change materials as latent heat thermal energy storage strategies applied to buildings: commercial and residential. Three application aspects were presented: Heating applications in buildings, Cooling applications in buildings and hybrid applications in buildings. Presented literature were classified into two categories in each studied aspect: Passive and active systems. The reviewed articles were presented and their thermal performance analysis was included. A summary of the used PCMs in each applications aspect with their respective thermophysical properties and encapsulation techniques are presented. It was shown that:

- PCM do serve as thermal buffers that prevails residential thermal comfort.
- PCMs are proved to be efficient for energy consumption reduction cooling applications such as HVAC in the active category and ceilings in the passive one.
- A plenty of commercialized PCMs are manufactured from organic compounds such as paraffin, however less concern in bio-based, inorganic, and eutectic mixtures is triggered.

- Novel applications in cooling systems are numerically analyzed with a large number of assumptions that reduces the accuracy of the results.
- Special focus must be given to optimization studies and economic analysis which is not observed in some literature.

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