



## Phase Change Materials in Cooling Technologies: A Systematic Review of Applications and Studies

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### ABSTRACT

Phase Change Materials (PCMs) are substances capable of storing and releasing thermal energy through phase transitions, primarily between solid and liquid states. Due to their high latent heat capacity and nearly constant temperature operation during melting and solidification, PCMs have gained considerable attention for thermal management and energy efficiency applications. This review summarizes recent investigations of PCM-based cooling systems across multiple fields, including building thermal regulation, photovoltaic panels, electronic devices, batteries, and domestic appliances. The integration of PCMs in these systems reduces effectively temperature fluctuations, peak loads, and overall energy consumption. This is enhancing system performance and environmental benefits. Various organic, inorganic, and eutectic PCMs have been analyzed according to their thermal properties, and selection criteria. Software can simulate the PCMs applications are ANSYS Fluent, EnergyPlus, and Design Builder. The findings highlight that optimizing the PCM design and integration strategies play a crucial role in sustainable cooling technologies, supporting the global shift toward energy-efficient and low-carbon solutions.

## 1. Introduction

The Phase Change Material (PCM) can be defined as a substance that change its phase mostly from solid to liquid because of absorbing heat [1]. Figure (1) represents the temperature profile of a PCM explaining that the temperature reduction occurs due to releasing the stored heat. This provides two different temperatures: storage and release ones. Indeed, the phase change materials store energy at a constant temperature during the phase change process such as changing from

solid to a liquid as shown in Figure (1). This means that the heat gain drives the phase change instead of rising the temperature [2].

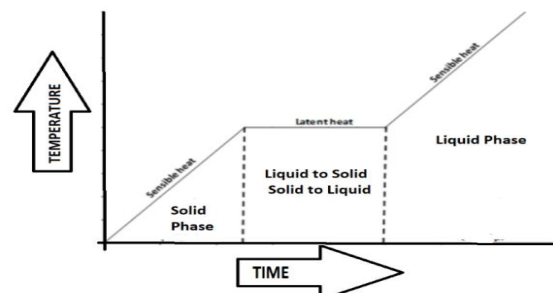


Figure (1). Phase Change Effect.

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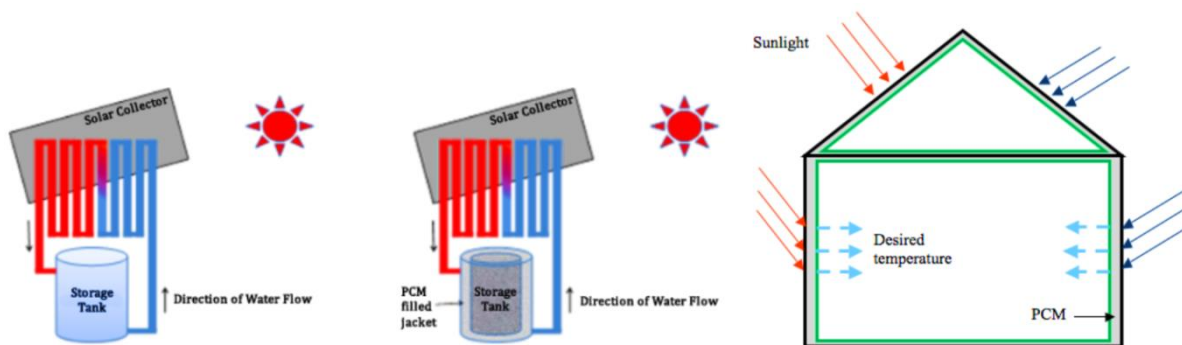
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The PCMs are used in cooling systems of solar energy, buildings, vehicles, catering, telecom shelters, electronics and so on. Figure (2) shows some examples of applications. To reduce the fossil fuel impact on the environment and its cost, studying the thermal energy storage for buildings heating and cooling. Indeed, the extreme warm or cold weather maximizes the cooling or heating demands. Indeed, if the cooling or heating systems have the ability to store the thermal energy, and then release them during the day or night, this mean that some peak loads percentage can be shifted to other hours of off-peak loads. This represents a better energy management and economic benefit for cooling systems [2].

Also, the selection of PCM depends mostly on: cost, safety, toxicity, environmental characteristics and useful life. For example, designing a passive PCM heat exchanger should be include: heat absorption, solar load, reflector design, heat rejection at off peak times and stress levels within the storage [1]. Moreover, Imran and Khan added that the factors that should be considered at selecting a phase-change material for phase-change cooling clothing were reviewed. Also, they investigated several parameters on cooling-clothing. These parameters are: the melting temperature, heat storage, PCM thermal conductivity, PCM dosage, covering area and location and using phase-change materials methods to reduce the temperature [4].



**Figure (2).** Some applications of PGMs.

## 2. The selection of PCMs

Depend on the change phase temperature and the latent heat related with that phase change. PCMs can be used for high temperature applications such as waxes, salts and paraffin, and for low temperature applications such as water (ice). Indeed, all outdoor equipment types can be cooled using PCMs [1]. There are several kinds of PCMs, and they can be classified as inorganic, organic and eutectic salt-water solutions. The inorganic once have low cost due to their availability, and high-energy storage ability. However, they are not suitable for practical applications [3].

Scientists worldwide have been started to investigate the PCMs including their specifications and applications. To simplify the previous studies about using the PCMs in

cooling requirements, this review illustrates them based on their usage field as follows:

### 2.1. Phase Change Materials investigations for buildings cooling.

To start with, Costanzo et al. showed that the effectiveness PCM in mats form installing within drywall partition air-conditioning system. They applied a dynamic simulations of EnergyPlus on a typical office building. The calculating performance parameters were: without PCM, with PCM mats, different thickness of PCM mats, melting temperature and three different geographical locations (Rome/Italy, Wien/Austria and London/UK). The results approved that the cooling load reduction depends on the PCM thickness and on the outdoor climate [5]. After that, Zhou et al. presented the novelty of using the PCMs in building cooling reduction. Their results showed that combining both of passive and active

systems with flexible transitions would improve the multi-criteria performance during the operating modes [6]. While, R. Zeinelabdein et al. investigated sixteen Thermal Energy Storage (TES) to offer sustainable buildings cooling during warm weather condition using a free cooling. The TES medium consists of metallic modules filled with RT28HC as PCM. To explain, the ANSYS Fluent software based on transient Computational Fluid Dynamics (CFD) simulation in addition to experimental data were used to achieve the results. It was found that the cooling system performance depends on the air flow rate. A free cooling system meets more than 40% of building cooling load and has it can save about 70% of building cooling energy load [7].

Another software is called Design Builder was evaluated the effect of Bio PCM Q23 and Bio PCM Q25 on reducing the energy consumption. The results showed that Bio PCM Q23 is less than Bio PCM Q25 in reducing the energy consumption [8]. In the same year, the building block thermal analysis investigated for passive cooling application. To explain, a concrete block contains several cavities from the outer wall side filling with micro encapsulated PCM (HS 29). The latent heat absorbed by PCM causing the PCM melting, and preventing the entry of heat into the living space causing a space cooling. The brick thermal performance analyzed using ANSYS Fluent, two-dimensional simulation and the transfer of both heat and mass in the PCM. The PCM effectiveness in the building bricks was calculated for different brick types: viz, normal solid bricks filled their cylindrical cavities with air and bricks filled their cylindrical cavities with PCM. It was found that brick filled with PCM reduces effectively heat flux for passive cooling application of buildings [9].

The combined effect of Phase Change Material (PCM) and thermal insulation was studied for a partition wall. This wall was separated a conditioned room from an adjacent local of a periodic thermal activity using a reference wall under the same thermal conditions. The results approved that the

combination mentioned above reduces the energy consumption of the conditioned local [10]. Also, Faraj et al. presented a summary of different PCM cooling applications for buildings classified into active and passive systems. The reviewed results showed that using these systems reduce both of the fluctuations of the indoor temperature and the energy demand during cold seasons [11]. Next year, McKenna et al. claimed that combining thermal energy storage with phase change materials reduces building cooling loads and increases energy efficiency. This study was done using a TRNSYS building and HVAC system model. It was found that partial charging and discharging increase the phase change material energy performance of the HVAC system thermal energy storage. Also, controlling the flow of heat transfer fluid maximizes the energy efficiency. In general, better energy performance can be reached due to higher charge and lower discharge loop flow rates [12].

The energy consumption for a building in a dry arid climate was studied by Bolteya et al. using a PCM type (RT28HC) and polyurethane insulating material. The effect of this type of PCM was calculated using Design Builder (DB) simulation software for different thicknesses starting from 6mm and ending by 36mm. The results approved that the PCM thickness of 18mm had a high thermal efficiency minimizing the cooling energy [13]. Also, Hai et al. used the finite element method to study a solar thermal panel. Their system consists of a cropper water-Al<sub>2</sub>O<sub>3</sub> pipe under a solar panel, elliptic fins were attached to this pipe and a chamber filled with CaCl<sub>2</sub>.6H<sub>2</sub>O represents a phase change material (PCM) under the panel. The results show that the melt of PCM starts at  $t=40$  min. Increasing about 10% PCM melting after 100 minutes can be reached using fins with a central hole. However, it minimized both temperatures of the output flow and the PVT. Less than 10% of building heat demand during the coldest months can be achieved using this system. While, during hot months, this system can offered about 33% of the energy required to heat water [14].

Haggag et al. claimed that the District Cooling System (DCS) performance can be improved using a phase change material (PCM) for absorbing and releasing heat because they offer latent heating and cooling for the environment. They investigated a Thermal Energy Storage system (TES) containing PCM. The PCM has the ability of storing the chilled water cooling during off peak time and releasing it at the peak time to reduce the peak load of cooling. They positioned the PCM containers towards the hot air as the pre-cooling unit is installed in a standard AC duct. This allows hot air to reach the test chamber at a certain velocity [15].

A year after that, Bakr et al. approved that the quality of thermal environment inside buildings depends on mechanical systems. Indeed, one of the best methods to manage the building thermally can be reached using phase-changing materials. The results cleared that the phase change materials have important role on gaining thermal comfortable conditions and saving energy by reducing the heating/cooling load [16]. While, the NEPCM magneto-hydrodynamic mixed convection was investigated inside a trapezoidal lid-driven cavity filled with hot elliptic obstacle by Younis et al.. The constant velocity of the upper cavity wall causes force convection, while the temperature difference between the cold walls and the hot obstacle causes the natural convection. The governing equations of this study depend on the Galerkin Finite Element Method (GFEM) and the MHD mixed convection system. It was found that increasing the Reynolds number reduces the maximum temperature around the hot elliptic region, and increases the entropy. Also, the heat transfer can be increased by changing the orientation of the hot elliptic with maximum value at the rotation angle of  $90^\circ$ . Moreover, increasing the volume fraction of NEPCM increases the heat transfer rate and the entropy generation [17].

During 2024, the PCMs incorporation of PCMs in concrete was investigated by Yu et al., especially its ability to transform building energy efficiency in addition to thermal management. The main types of PCMs

according to this study were: inorganic, eutectic, organic, and bio-based. Moreover, PCMs ease temperature fluctuations, improving indoor comfort and reducing energy consumption. However, the PCMs integration have a negative impact on the concrete mechanical properties [18]. Three materials: brick, concrete block, aerated concrete were studied by Özdemir and Gülten using three different insulation materials by considering two cases (with and without PCM) using the Design Builder software. According to their results, the combination of PCM and insulation material is preferred when the heating load is high. Moreover, in the cold places, it is more effective of using PCMs with low melting points, and the high melting points PCMs should be used in hot climate regions. Indeed, using the two melting temperatures instead of using a single melting temperature of the PCM in the building envelope as a more beneficial solution [19]. Also, the PCMs performance in tropical regions and their behavior were examined by Santos et al. using EnergyPlus<sup>TM</sup> software according to the constructive system. Their results approved that PCMs can effectively reduce energy consumption effectively [20].

Recently, Al-Khiami et al. approved that using the PCM reduces indoor temperature fluctuations and peak temperatures. Also, PCM can effectively maintain indoor temperatures, more stable and comfortable indoor climate without mechanical cooling system's needs [21]. While, the photo-thermal power storage, collection and their applications of building materials were reviewed by Dong et al.. An organic and inorganic PCMs detailed comparison was written in this paper. Heat storage performance can be improved using different technologies such as fins, packaging, and multiple PCMs [22]. While, Akeiber claimed that PCMs use the latent heat properties during the phase change to absorb and release thermal energy. The possible integration of PCMs in cooling systems was investigated for energy consumption reduction in several applications such as electronic devices, buildings and industrial process. These materials are used also for increasing the heat storage energy and reducing the temperature fluctuation. The

thermal management principles are investigated regarding to PCM, conduction, convection, and radiation mechanisms. The results provided new solutions for improving nano PCMs and composite materials [23]. A chapter of Barbhuiya et al. thesis introduced in details the Phase Change Materials (PCMs) and their buildings applications. It includes the background, context, objectives, phase change mechanisms, covering types, key properties, practical applications, energy efficiency, thermal energy storage, HVAC systems, the building based on passive cooling, heat recovery, and the integration with PCM. Moreover, different PCM types were discussed such as organic, inorganic, eutectic mixtures, and bio-based. Furthermore, enhancing the PCM performance methods were explained, for instance nano-enhancements, microencapsulation and hybrid solutions [24].

## *2.2 Phase Change Materials investigations for Photo Voltaics cooling.*

Starting with, Maghrabie et al. who reviewed several studies about the solar photovoltaics. They claimed that, when the temperature increases, the photovoltaics panel efficiency decreases depending on the solar cell type. Therefore, it is essential to control the solar photovoltaics temperature to improve photovoltaic panel efficiency, in particular at high ambient temperature. Most studies claimed that a high cooling capacity for the solar system can be gained using an inorganic phase change materials [25]. In this study, the performance of PV system was studied using a cooling system in two conditions: without and with PCM. There were three PCM types considered: soy wax, paraffin, and beeswax. The experimental data showed that PCM beeswax reduces the working temperature effectively at a certain condition. Also, both of PV with PCM beeswax increase the maximum power output of PV and maximum efficiency [26].

The MatLab software was used by Gad et al. to study a hybrid cooling of the photocell (PV) system effectiveness. This system consists of flat Heat Pipes (HP) and a Phase Change Material (PCM) heat sink. Three types of PCM were analyzed: RT25, RT35, and RT42. The results

approved that the cooling system of HP-PCM is better than the natural once. Also, the low melting point PCM has more electric performance efficiency than once of a high melting point [27]. While, Yousif et al. integrated the Phase Change Material system with the rear section of a Photovoltaic system to reduce its temperature. Two different methods were used in this study: experimental and numerical. To explain, a three dimensional model ANSYS Fluent was used to investigate the temperature numerically. Also, three different cases were studied: without using wax, with using wax, and using both of with wax and fins. The output data results approved that using wax and fins is the best to reduce the temperature and to increase the efficiency. Also, using fins causes a regular wax melting due to better temperature distribution [28].

Also, using the same software, another study was done by Alzgoool suggested a new design to improve the PV cells' performance using RT35 and fins as a cooling technique. The results approved that the RT35 reduces the PV panel's temperature by 16°C. Also, another 2°C reduction in temperature can be reached by adding rectangular fins. The results have been validated through ANSYS simulation as well as experiments [29]. Furthermore, two crystalline PV panel types (Mono and poly) have been investigated numerically using Solid Works and ANSYS-Fluent by Aljumaili et al.. They used the phase change material as paraffin wax (RT55) for cooling system. Their result approved that for poly crystals, the panel temperature was reduced and both of power output and efficiency improved. Similarly, for using the mono crystalline. In general, the mono is better performance than the poly [30].

Lately, Seto et al. studied passive cooling systems using Phase Change Materials (PCM). Three different materials have been investigated: traditional paraffin PCM, NePCM-Al<sub>2</sub>O<sub>3</sub>, and NePCM-ZnO. Their results approved that NePCM-ZnO reduces effectively the PV system's operating temperature compared to the PV systems without passive cooling [31]. Also, the cooling system implementation within a room wall combining a photovoltaic panel at wall outside was studied by Ahmed et al.. To

explain, the two phase change material layers were fixed in the wall and a Thermo-Electric Cooling (TEC) system inside the wall. One PCM layer absorbs the heat from the thermo-electric system to improve the cooling performance. While, the second PCM layer cools the PhotoVoltaic (PV) panel. They claimed that installing the TEC system on the roof maximizes its performance [32].

### 2.3. Phase Change Materials investigations for electronic devices cooling.

Gao et al. suggested the PCM cooling rate relationships with temperature gradient, mass and covering area. The investigation include three PCM melting temperatures, different mass, covering areas and two manikin temperatures. They claimed that the PCM cooling rate increases with the temperature gradient between the thermal manikin and the melting temperature. The cooling duration depends on PCM mass and latent heat [33]. Also, Ali et al. claimed that the heat can absorbed effectively when the PCM has greater fusion heat. Therefore, different PCMs were studied in personalized cooling vest to find their effect on the cooling performance [34]. Moreover, Hollis et al. controlled the peak junction temperature of phase change materials (PCMs) using a simulated modelled. They investigated latent heat storage in both single-sided and dual-sided package configurations. The results showed that the active controlling method for transient temperatures can be achieved by adding the PCM into two different styles of PE. Adding the PCM in a single-sided package reduces temperature fluctuations [35].

Also, Khan reviewed several studies of using the PCMs for cooling compact electronic devices. He found that some parameters have a major effect on efficiency and implementation, encapsulation [36]. While, Maqbool et al. explains some techniques of using PCM to maximize the heat sinks performance. These techniques are: fins, nanoparticles and metal foam [37]. Moreover, the LMPCMs thermo-physical parameters characterizing by large density and high thermal conductivity were concluded by Yao et al.. Also, several researches on the metallic PCMs thermo-physical properties were introduced. The super-cooling degree

factors based on the nucleation theory were presented. Furthermore, increasing the performance using LMPCMs instead of PCMs were validated [38]. Lastly, Kim et al. studied pressure effect on cooling effectiveness using a reduced-order thermal resistance model to assess heat transfer from the electronic devices [39].

### 2.4. Phase Change Materials investigations for batteries cooling.

Kim et al. investigated the effect of operating conditions on the cooling performance using PCM-integrated power devices. A Field's metal-impregnated copper foam composite was used as our thermal buffer integrating with a circuit board-mounted top-cooled gallium nitride. The results approved that the PCM can reduce the junction temperature. They used a simulation of a three-dimensional Finite Element Method (FEM) to validated their measurements [40]. While, managing heat in high-capacity ternary lithium-ion batteries was studied by Zhang et al. using nanophase change material emulsions (NPCMEs). Their experimental data showed that the thermal control performance and latent heat utilization efficiency of the NPCMEs reduces the battery pack's maximum temperature. Also, increasing flow rates reduced temperatures. However, nano emulsions the latent heat reduction of utilization efficiency increases system energy consumption. Moreover, the thermal management depends on the inlet temperature of the NPCMEs. To explain, the perfect inlet temperatures simplifies phase change latent heat usage [41].

Moreover, different thermal storage methods were investigated by Lee et al. to improve the vehicle warm-up performance depending on phase change materials (PCMs). The thermal energy lost due to engine cooling enhanced cold-start performance and reduces both of fuel consumption and emissions [42]. Also, Different operating conditions are applied to test a hybrid-based battery thermal management system by Balasubramanian et al.. A Al<sub>2</sub>O<sub>3</sub> nanoparticles have been added to improve the paraffin properties (Phase Change Material). Three ratios of the paraffin of 5%, 10%, and 15% were considered. Also, a three cases were investigated: active, passive and hybrid. In the

active method case, a counter flow water is circulated through the copper coil. The result approved that the temperature increased under natural convection and decreased under hybrid conditions [43]. Further, Herawan et al. optimized heat dissipation in the battery of the electric vehicle using paraffin and beeswax. They found that beeswax based phase change material is a more effective than paraffin-based PCM on thermal management for Li-ion battery.

To explain, the cooling system containing the beeswax steadily retained lower temperatures and slow down temperature rises. This controls the heating of battery perfectly leading to extreme performance for both of voltage stability and battery capacity maintenance [44].

### 2.5. *Phase Change Materials investigations for domestic appliances cooling.*

To start with Yu et al. who investigated the cooling process of a heat pipe using phase change materials (PCMs) in a multiple income heat system. Furthermore, at one end of the heat pipe, there were two fixed heat sources. Also, there was a container filled with different materials. This container wrapped outside of the middle heat pipe taking away the heat. The results approved that the temperature can be kept at lower value at evaporation process using the phase change material RT35. In addition, this PCM minimizes the required time of equilibrium temperature reaching [45]. The review paper of Shamseddine et al. discussed the applications and cases of super-cooling, super-cooling degrees and the factors affecting the occurrence [46].

Later, a comprehensive overview of PCMs in CTES applications were discussed by Al-Obaidi et al.. For instance, experimental and numerical studies, different fluids containing PCMs, factors affecting the PCMs thermal conductivity. Further, the factors that have the influence on the thermal conductivity are: nanoparticle-rich PCM, encapsulated PCM, solids volume percentage, and particle size [47]. Mane and patil suggested some prediction correlations for backup time and energy consumption of domestic refrigerator based on experimental data. These data consist of testing some PCMs such as potassium chloride (KCl), sodium chloride (NaCl), and sodium fluoride

(NaF) dissolved in water. This study shows that using different phase-change materials increases effectively both of cooling performance and energy efficiency of the domestic refrigerator [48].

A case of point, several software can be used to simulate the PCMs in domestic applications. For instant, Alkhazmi et al. studied the water tank performance containing phase change materials in a solar heating system of domestic water. Both of FORTRAN software and experiments were used to simulate the case dynamically to calculate the energy stored in the thermal storage and the temperatures over 24 hours. The paraffin wax capsules are the phase change material (PCM), and they placed as a storage unit inside the tank. The experimental data showed that using phase-changing materials in reduces the heat transfer speed from water tanks. Moreover, the theoretical results approved that the best thermal storage performance occurs when the thermal storage contains  $\frac{1}{4}$  PCMs of its volume [49]. While, Uddin et al. claimed that the Latent Thermal Energy Storage Systems (LTISS) have high energy density to store a significant thermal energy in the latent heat form at constant temperature into phase change materials (PCM). They examined the HTF flow direction effect on the strength and duration of natural convection in PCM of a container shaped as a vertical cylindrical shell-and-tube. The ANSYS Fluent software of 2-D axisymmetric was used in this study. The results approved that both natural convection and thermal boundary conditions cause irregular melting front in the PCM. different operating parameters were investigated such as temperature, velocity, and reciprocation period [50]. Another study was done by Masood et al. about using the phase change materials (PCMs) in thermal energy storage (TES) was investigated using ANSYS Fluent software in cooling systems by reducing the inlet temperature of air to enhance the air conditioners efficiency. Four AC duct designs were modelled and evaluated. The results approved that at a low air velocity, the pre-cooling performance increased and the outlet air temperature decreased. Also, the salt hydrate performance is better than paraffin for the cooling effect [51].

Lately, Khan has a comprehensive review that includes the effects of different process parameters, modelling approaches and experimental approaches for the refrigeration systems. The process parameters include: the PCM thickness, the PCM phase change temperature and the PCM position. He added that the phase change material (PCM) improves the efficiency of refrigeration systems and the frozen food quality. However, some consideration should be related to the PCM be taken at attaching the PCM system with the refrigeration system such as thickness, quantity, phase change temperature [52]. Also, another review inspected the PCMs performance on passive cooling for 15 different publications was written by Alabbas [53]. This review, adopted both of descriptive and quantitative researches evaluating several outcomes such as energy conservation, temperature difference and thermal interval. Also, this review showed the non-standardized protocols, long-term follow-up limited performance data, and some economic evaluations [53].

### 3. Comparative Analysis and Discussion

From the previous studies, Table (1) summarizes the major advantages and limitations for each application area. The comparison reveals that PCM technology offers significant benefits in all investigated sectors. But, there are some practical challenges. For example: low thermal conductivity, leakage problems, additional weight, and system integration complexity remain important barriers that require further improvement before a large scale implementation could be achieved.

#### 3.1 Performance Comparison of Different PCM Types

Various PCM categories have been investigated for cooling applications, including organic, inorganic, eutectic, and nano-enhanced phase change materials. The selection depends primarily on thermal properties, operating temperature range, latent heat capacity, thermal conductivity, stability, and economic considerations. Organic PCMs are widely used

due to their chemical stability and compatibility with different systems, while inorganic PCMs provide higher energy storage density but undergoes supercooling and corrosion issues. Eutectic mixtures offer relatively precise melting temperatures, whereas nano-enhanced PCMs, recently attracted the attention because of their improved heat transfer properties. Table (2) presents a comparison of the main PCM categories and their typical applications.

From Table (2), it can be observed that no single PCM type is considered universally suitable for all cooling applications. Instead, the optimal selection will depend on the specific requirements of the system, including some factors such as temperature range, thermal conductivity, cost, and long-term stability. Recent studies indicate that composite and nano-enhanced PCMs provide a promising solution for overcoming the limitations of the conventional materials.

#### 3.2 Comparative Summary of Representative Studies

Numerous studies investigated the application of phase change materials under different operating conditions using experimental, numerical, and hybrid approaches. However, the reported performance indicators and evaluation methods differ significantly among studies, making a direct comparison is difficult. Therefore, a comparative summary of representative studies is provided in Table (3) to highlight the investigated applications, PCM types, research methods, and key findings.

**Table (1):** Advantages and limitations of PCM cooling applications

Application	Advantages	Limitations
Buildings	Reduced cooling loads, improved indoor comfort	Low thermal conductivity, leakage issues
Photovoltaics	Improved efficiency and reduced panel temperature	Limited heat dissipation under severe conditions
Electronic devices	Temperature stabilization	Short cooling duration
Batteries	Increased safety and battery life	Added weight and volume
Domestic appliances	Energy saving and better thermal stability	Dependence on PCM properties

**Table (2):** Characteristics of Different PCM Types

PCM Type	Advantages	Limitations	Typical Applications
Organic PCM	Chemically stable	Low conductivity	Buildings, batteries
Inorganic PCM	High latent heat	Corrosion and phase separation	PV and TES systems
Eutectic PCM	Sharp melting point	High cost	Electronics
Nano-enhanced PCM	Enhanced heat transfer	Sedimentation and cost	PV and electronics

**Table (3):** Representative Studies and Main Findings

PCM Type	Advantages	Limitations	Typical Applications
Costanzo et al.	Buildings	PCM mats	Cooling load reduction dependent on climate and thickness
Bolteya et al.	Buildings	RT28HC	Optimum thickness of 18 mm minimized cooling energy
Arifin et al.	PV panels	Beeswax	Improved panel efficiency and reduced temperature
Alzgoool	PV panels	RT35	Temperature reduction of approximately 16°C
Balasubramanian et al.	Batteries	Nano-enhanced paraffin	Hybrid cooling gave best performance
Masood et al.	Air conditioning	Salt hydrate	Better cooling performance than paraffin

The reviewed studies constantly demonstrate that the incorporation of PCMs can effectively reduce temperature fluctuations, change peak cooling loads, and improve energy efficiency. Nevertheless, the magnitude of performance enhancement strongly depends on the selected PCM properties, environmental conditions, and system configuration.

#### 4. Research Gaps

Despite the significant progress achieved in PCM-based cooling technologies, several research gaps remain. Most existing studies have been conducted under laboratory conditions, while long-term field investigations and large-scale practical implementations remain limited. In addition, the absence of standardized performance indicators and testing procedures

makes comparisons among studies difficult. Conventional PCMs also possess relatively low thermal conductivity, leakage, phase separation, and long-term stability issues. Furthermore, techno-economic analyses and life-cycle assessments remain limited, despite their critical importance for commercial applications.

Future research has to prioritize the development of composite and nano-enhanced PCMs, advanced encapsulation methods, thermal energy storage systems (Hybrid), and strategies for optimization based on artificial intelligence. Such developments are expected to enhance system reliability and accelerate the adoption of PCM technologies in sustainable cooling applications.

## 5. Future Work

Although phase change materials have proven to be effective in thermal energy storage and cooling applications, several areas require further investigation to enhance their practicality and efficiency. Future research should focus on developing novel composite and nano-enhanced PCMs with higher thermal conductivity and better mechanical and chemical stability. Microencapsulation and macro-encapsulation techniques need optimization to prevent leakage, improve heat transfer rates, and extend material lifespan.

Hybrid energy storage systems that combine PCMs with other storage methods, such as sensible and thermochemical storage, can improve flexibility and performance under varying environmental conditions. Advanced numerical modelling and artificial intelligence-based optimization can also be employed to predict PCM behaviour and optimize system configurations. Additionally, long-term economic and life-cycle analyses are essential to evaluate the feasibility of large-scale PCM integration in real-world applications. Addressing these research gaps will accelerate the adoption of PCM-based cooling systems as a key solution for sustainable and energy-efficient technologies.

## 6. Conclusions

Phase Change Materials have demonstrated significant potential in improving the efficiency and sustainability of various cooling applications. Their unique ability to store and release large amounts of thermal energy at nearly constant temperatures makes them highly suitable for thermal management in buildings, photovoltaic systems, electronic devices, batteries, and domestic appliances. The reviewed studies confirm that proper PCM selection-based on melting temperature, latent heat, thermal conductivity, cost, and environmental impact is essential for achieving optimal performance. Numerical and experimental analyses often conducted using tools such as ANSYS Fluent, Design Builder, and EnergyPlus, have shown that PCMs effectively reduce energy consumption, stabilize temperature fluctuations, and shift peak cooling loads. However, challenges remain in enhancing PCM thermal conductivity, mechanical stability, and long-term durability. Future research should focus on developing advanced composite and nano-enhanced PCMs, improving encapsulation methods, and integrating hybrid systems to maximize cooling performance. Overall, PCMs represent a promising pathway toward energy-efficient and environmentally friendly thermal energy storage technologies.

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