Thermal and Energy Performance of Phase Change Materials (PCMs) in Passive Cooling Systems: A Review and Quantitative Analysis

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Abstract

Due to the rising global need for energy and the increasing awareness about the global warming effect, the passive cooling approaches have attracted much attention as possible alternatives to the traditional air conditioning systems. Phase Change Materials (PCMs) are good thermal regulators, as they can absorb and release heat of fusion at almost constant temperature, and are thereby interesting for integration in building envelopes and systems. Theoretical and thermal performance of PCMs for passive cooling This systematic review examines the performance of PCMs on passive coolings, based on fifteen peer-reviewed publications from 2010 to 2025. Adopting a PRISMA-based approach, the review adopts descriptive and quantitative research and brings together primary studies to evaluate critical findings such as ΔT, energy conservation, and thermal lag. Average ΔT value between 1 °C and 14.8 °C and energy saving from 6% to 71%, according to the PCM category and the end-use application purpose are obtained. In spite of the positive findings, the review identifies gaps including non-standardized protocols, limited performance data after long-term follow-up, and few economic evaluations. The work concludes with a recommendation to adopt common testing standards and interdisciplinary research programs to fully explore the potential of PCMs in the age of sustainable thermal management.

Keywords: Phase Change Materials (PCMs); Passive Cooling; Thermal Performance; Energy Efficiency; Latent Heat Storage; ΔT Reduction; Sustainable Building Design; Thermal Comfort; Systematic Review; PRISMA Methodology

الأداء الحراري والطاقي لمواد تغيير الطور (PCMs) في أنظمة التبريد السلبي: مراجعة وتحليل كمي

عودة خليف، شهد العباس

ملخص

نظرًا للحاجة العالمية المتزايدة للطاقة والوعي المتزايد بتأثير الاحتباس الحراري، حظيت أساليب التبريد السلبي باهتمام كبير كبدائل محتملة لأنظمة تكييف الهواء التقليدية. تُعد مواد تغيير الطور (PCMs) منظمات حرارية جيدة، إذ يمكنها امتصاص وإطلاق حرارة الانصهار عند درجة حرارة شبه ثابتة، مما يجعلها مناسبة للدمج في أغلفة المباني وأنظمتها. الأداء النظري والحراري لمواد تغيير الطور (PCMs) في التبريد السلبي. تدرس هذه المراجعة المنهجية أداء مواد تغيير الطور (PCMs) في التبريد السلبي، استنادًا إلى خمسة عشر منشورًا خضعت لمراجعة الأقران من عام 2010 إلى عام 2025. وتعتمد المراجعة، التي تعتمد نهجًا قائمًا

علىPRISMA ، على البحث الوصفي والكمي، وتجمع بين الدراسات الأولية لتقييم النتائج المهمة مثلΔT ، وحفظ الطاقة، والتأخر الحراري. وتم الحصول على متوسط قيمة ΔT بين 1 درجة مئوية و14.8 درجة مئوية، وتوفير الطاقة من 6% إلى 71%، وفقًا لفئة مواد تغيير الطور (PCM) والغرض من الاستخدام النهائي. وعلى الرغم من النتائج الإيجابية، حددت المراجعة ثغرات تشمل بروتوكولات غير موحدة، وبيانات أداء محدودة بعد متابعة طويلة الأمد، وقلة التقييمات الاقتصادية. ويختتم العمل بتوصية باعتماد معايير اختبار مشتركة وبرامج بحثية متعددة التخصصات لاستكشاف إمكانات مواد تغيير الطور (PCMs) بشكل كامل في عصر الإدارة الحرارية المستدامة.

الكلمات المفتاحية: مواد تغيير الطور(PCMs) ؛ التبريد السلبي؛ الأداء الحراري؛ كفاءة الطاقة؛ تخزين الحرارة الكامنة؛ تخفيضΔT ؛ تصميم المباني المستدامة؛ الراحة الحرارية؛ مراجعة منهجية؛ منهجية PRISMA

1. Introduction

With the fast speed of climate change, sustainable engineering solutions to remedy such problems are critically needed, including energy efficient approaches to limit the contribution of buildings to carbon emissions especially in hot-dry climates. Passive cooling is one of the most popular non-mechanical approach to thermal comfort without high electricity usage as the conventional air-conditioning systems (Zhou et al., 2021). In this framework, phase change materials (PCMs), which are able to absorb and release large quantities of latent heat at nearly constant temperatures, arose as an interesting alternative. This characteristic allows PCMs to flatten thermal load curves within buildings and to sustain natural thermal equilibrium (Cabeza et al., 2011; Castell et al., 2013).One of the unique characteristics of PCMs is its capability to store heat as latent energy through melting, and to release it through freezing. They are therefore suitable for passive cooling purposes, which is ideal when integrated into building envelopes such as walls, roofs and windows (Khudhair & Farid, 2004). Could the air-conditioning be more physiologically tunable Other studies have shown that PCMs can reduce the temperature of indoor air and save 10% to 30% energy (for references, see Zhou et al. Rabani et al.etal.2 2000 2021 2025).

In spite of the extensive literature on PCM use in cooling systems, many works lack quantitative considerations that could properly relate the PCM type, application method and achieved thermal performance. More importantly, theoretically pure ones or their experimental criteria are not consistent with literature of different studies. This highlights the significance of the current systematic review that seeks to investigate the thermal performance of PCM-based PC systems through the PRISMA framework, focusing on quantitative data for passive cooling [experiments] from peer-reviewed articles within the last decade.

Using well-defined descriptive and quantitative characterization, the development of this paper intends to assess the performance of PCMs in peak-temperature reduction and energy-efficiency increase, and to find the principal design factors affecting the behavior of PCMs during the decision-making process of architects and sustainable engineers.

2- Research Problem and Significance

Although there have been plentiful research efforts to investigate the application of PCMs to different types of passive cooling systems under different climatic conditions and design settings but from the authors' understanding there is a noticeable lack of quantitative comparison between studies. The vast majority of prior works have concentrated on pinpointing theoretical simulations or isolated experimental cases, in which a complete, top-down analytical view of PCM performance, w.r.t. to, e.g., thermal efficiency, peak temperature diminution, or total energy saving is not provided. In addition, methodological variations in materials and construction techniques across these studies hinder the possibility of standardized comparisons, thereby making it difficult for engineers and designers to make evidence-based decisions (Cabeza et al., 2011; Zhou et al., 2021).

This is an important gap which the present review seeks to provide an answer with a systematic review against the PRISMA guidelines, as well as both descriptive and numerical thermal analyses of experimental studies within the past decade. This method may establish a comparative database for guiding the selection and design for materials utilization in architectural and engineering practice and realize sustainable thermal comfort and energy efficiency.

3- Study Objectives

The present study seeks to achieve the following objectives:

1. Produce a systematic review based on the PRISMA statement of the studies that evaluate the performance of the PCM in passive cooling systems.
2. To evaluate the thermal-energy performance of PCM by means of quantitative criteria (e.g., ΔT, energy saving percentage, thermal delay time).
3. To categorize the studies included by the type of material, field of application, and technique used in the experiments.
4. To evaluate physical and design-related aspects that affect PCM performance.
5. There are some research gaps and prospects for scientific and applied advances.

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4- Theoretical Framework

4.1 The Scientific Concept of Phase Change Materials (PCMs)

Phase Change Materials (PCMs) belong to the family of advanced TES materials and are capable of storing and releasing significant amounts of latent heat during the isothermal phase transition between solid and liquid state. Compared to sensible heat storage materials which are based on temperature changes, PCMs takes advantage of isothermal phase change,، so, they are particularly useful in applications where temperature regulation is in the narrow range of temperatures (Zhou et al., 2021; Sharma et al., 2009).

Fundamentally, PCMs exploit latent heat of fusion—an attribute that allows them to absorb large amounts of energy as they melt, and then release that energy upon solidification at nearly constant temperature. This feature enables PCMs to serve as heat buffers that attenuate peak temperatures and dampen temperature oscillations, consequently improving indoor thermal comfort and reducing the need for mechanical cooling (Farid et al., 2004).

To be viable for passive cooling applications, the melting temperature of PCMs should match closely to the comfort range of the indoor environment–which is generally considered in the range of 20–26 °C for most types of residential and commercial building (Khudhair & Farid, 2004). During the day, PCM absorbs extra heat when ambient or surface temperatures increase owing to the solar gain and starts melting. In this way, energy is stored as latent heat while around a constant temperature level is maintained. PCM solidifies during the night time while temperature falls down, which releases the stored energy to the environment, so that less demand is required for active cooling or heating.

The knowledge base on the use of PCMs in buildings has improved substantially over the past decade. Nowadays the concentration of researchers is not only to specify those substances that have melting point of interest. As an alternative, emphasis has switched to comprehending the thermophysical response of PCMs in practical-like dynamic situations, promoting thermal cycling properties, enhancing thermal conductivities and guaranteeing compatibility with building materials (Cabeza et al., 2015; Jamekhorshid et al., 2013). For instance, the notion of "effective heat storage capacity" has been proposed in order to consider not only the latent heat but also the sensible heat in due course of the phase transition as well as its effects on estimating the heat storage storage capacity, providing a much more accurate prediction of the thermal performance (Ming et al., 2022).

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Furthermore, the “dynamic thermal performance” concept has been developed as a method to assess how PCMs behave when subjected to non-steady temperatures rather than to a constant one. This change shows the intricate nature of the subsurface and compels more elaborate simulations and experiments to account for latent heat driven phase transition hysteresis, subcooling effects and the degradation of the temperature over time (de Gracia Cabeza, 2015).

In addition to that, more advanced heat transfer modeling methods such as enthalpy-based numerical methods, finite element (FE) simulations and computational fluid dynamics (CFD) are developed in recent times to predict the thermal performance of PCMs in building envelopes with higher accuracy. They can predict heat transfer under transient conditions, phase interface displacement, and spatial temperature and conductivity distribution, offering optical design principles (Zhou et al., 2021).

Indeed, the emergence of nano-enhanced PCMs (NePCMs) has expanded research frontiers. The addition of nanoparticles (Al_2O_3, CuO or graphene) into base PCM has been reported to show great enhancement in its thermal conductivity and phase stability, under no compromise on its latent heat capacity. Such hybrids represent the way for improved performance and more responsive thermal Energy storage (TES) systems for domestic and industrial needs (Sharifi & Riffat, 2020).

To sum up, PCMs are currently re-evaluated not as passive thermal fillers, but as active thermal devices used within smart building structures. They have their scientific rationale in that it can deliver time-shifted heat absorption and release, thus synchronizing the thermal load of a building with the outdoor environment, and directly contribute to zero-energy building and low-carbon building objectives.

4.2 Classification of Phase Change Materials (PCMs): Organic, Inorganic, and Hybrid

PCMs are typically classified depending on their chemical nature and phase change behavior. This classification have a great effect on their thermal behavior, environmental friendly, economical efficiency and long-term stability for many applications. In general, the PCMs can be classified into three main types: organic PCMs, inorganic PCMs, and hybrid or composite PCMs. There are certain pros and cons in each class, which should be taken into account when choosing the materials for use in passive cooling or thermal energy storage systems in buildings.

4.2.1 Organic PCMs

Examples of organic PCMs are paraffins and non-paraffinic materials (e.g. fatty acids, esters, alcohols). Such materials are chemically robust, do not require significant subcooling, are non-corrosive, and have high recycle over multiple heat cycles. Paraffins (CnH2n+2) obtained from petroleum is one of the most used organic based PCMs because of its defined melting temperature, low vapor pressure, and high thermalrelableinty (Sharma et al., 2009; Abhat, 1983).
For instance, commercial paraffins with the chain lengths between C16 and C28 have melting points between 20°C and 60°C which are suitable for indoor thermal comfort applications. Fatty acids like capric acid and lauric acid are also being used more often because they are renewable and have a high phase transition temperature. But they are costlier and some times even smell while working (Kenisarin & Mahkamov, 2007).
Although organic PCMs are thermally stable, safe, but the low thermal conductivity (generally < 0.2 W/m·K) limits the energy exchange rate. To overcome such limitations, some of the strategies that have been studied include the use of metal fins insertion (Sharifi & Riffat, 2020), the doping of nanoparticles as well as the embedding in high conductive matrixes (Sharifi & Riffat, 2020).

4.2.2 Inorganic PCMs

Inorganic PCMs usually are salt hydrates (e.g., $CaCl_2 \cdot 6H_2O$, $Na_2SO_4 \cdot 10H_2O$), or metals based. These compounds have higher volumetric latent heat storage capacities and thermal conductivities compared to organic PCMs. Salt hydrates, in particular, have been found to have melting temperature ranges appropriate for passive cooling (e.g., 25–32 °C), a high enthalpy of fusion (greater than 200 kJ/kg), and a dense morphology, allowing convenient incorporation into building envelopes (Farid et al., 2004).
However, these inorganic PCMs exist with practical restrictions. As mentioned, one of the serious problems is that of phase segregation where salt hydrates are dispersed into different constituents during the phase change, which causes a deterioration of the thermal performance in the following cycles. Also, numerous inorganic PCM have showed supercooling phenomena and remain liquid below the phase change temperature, causing delayed discharge of heat, which makes accounting of the heat release less reliable (Cabeza et al., 2015). Some formulations are also attack metal containers, making durability over time and long-term stability and protection the only other issue.
In order to address these problems, recent studies have considered using nucleating agents to reduce supercooling and thickening agents to inhibit meta-phase segregation. Encapsulating is another method of separating the PCM from the other substances, which is beneficial for stabilizing the performance (Zhou et al., 2021).

4.2.3 Hybrid and Composite PCMs

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Hybrid or composite PCMs are an emerging class of materials with potential advantages of both inorganic and organic PCMs, or added with functional filler to tailor thermal and mechanical properties. They are designed to overcome the drawbacks of conventional PCMs, such as thermal conductivity, phase-stability, and compatibility with building materials.

One of the commonly employed methods is by using nanoparticles including Al 2 O 3, SiO 2, CNTs or graphene in organic or inorganic PCMs. The addition of these nanoparticulate materials (both organics/inorganics) led to the development of Nano-Enhanced PCMs (NePCMs) having enhanced heat transfer properties, and lower subcooling with a little influence on the latent heat storage capacity (Ming et al., 2022). For instance, introducing graphene nanosheets into paraffin can enhance the thermal conductivity by as high as 40%, which accordingly shortens the charging/discharging time, and sounds more sensitive for the cooling performance.

Another popular technique is microencapsulation, where PCM droplets are encapsulated in polymer shell which can easily be embedded in composites such as concrete, plaster or gypsum boards. The use of microencapsulation for all the previous phase change materials on the market, in order to prevent environmental degradation and to ensure a good homogeneity and reduced risks of leakage of the PCM during the phase transitions (Jamekhorshid et al., 2013).

Moreover, SSPCMs consist of introducing PCM in porous matrices as expanded graphite or silica. Such materials are capable of resisting liquid runout and preventing the system from physical disruption during melting. SSPCMs are especially appropriate for building envelopes because they are shape-stable and mechanical resistance (de Gracia & Cabeza, 2015).

Overall, each class of PCM has its own advantages according to application conditions. "The high thermal capacity of PCM is useful for space heating and cooling while inorganic PCMs offer higher energy density, but are unsafe and require a more controlled environment." Hybrid and composite PCMs are the current frontier of research, able to provide tailor-made properties for specific architectural/engineering requirements. The selection of PCM should take into account parameters such as melting point, energy density, thermal conductivity, cost and environmental impact in order to maximize the performance of the system.

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4.3 The Working Mechanism of PCMs in Passive Cooling

The use of PCMs is based on the possibility to control the interior temperature of a building by using these materials that can absorb and release thermal energy during a phase change. Contrary to classical insulating materials, which are only based on a decrease of conductive heat transfer, PCMs actively smooth temperature peaks and troughs exploiting the latent heat of fusion. This renders them particularly suitable for hot-arid or Mediterranean climates, where there is a substantial diurnal temperature amplitude (de Gracia & Cabeza, 2015).

The fundamental process starts with the daytime heating. When ambient temperature and solar radiation increase, the PCM incorporated into the building envelope (such as walls, ceilings, or integrated panels) captures the heat. When the material hits its melting temperature, it experiences a phase change from a solid to a liquid, releasing energy as latent heat while not itself changing temperature significantly. This delay in heat uptake helps in lowering the peak indoor temperature and correspondingly the requirement of air conditioning (Sharma et al., 2009).

When its evening and the outside air cools down, the PCM starts to solidify again. And then when it all goes back to solid, that thermal energy is dumped into whatever it's near. Depending on the construction of the building, this heat can be dissipated to the outside through natural ventilation or can be utilized to maintain an ambient temperature in colder conditions. This reversible and cyclic thermal buffer performance makes PCMs highly attractive for regulating diurnal thermal comfort (Zhou et al., 2021).

Key parameters affect the effectiveness of this process:

· Melting Temperature Matching: The PCM's melting temperature should ideally match the typical thermal comfort indoor range in order to perform effectively (which is about 20–26°C). A mismatch can lead to either an early melting or a thermal enhancement of the PCM (Farid et al., 2004).
· Thermal Conductivity: The rate at which heat can be absorbed or released may be restricted due to the inherent low thermal conductivity of many of PCMs (especially organic PCMs). The addition of features such as fins, built-in metal meshes, or the incorporation of high-thermal-conductivity nanoparticles has been investigated to alleviate this constraint (Sharifi & Riffat, 2020).
· Placement and Encapsulation: PCMs can be directly embedded in construction materials (e.g., gypsum, plaster, and concrete), or macroencapsulated and microencapsulated in the form of polymer shells. Their internal or external arrangement will affect the time of response and the heat exchange efficiency (Cabeza et al., 2015).

· Directional Heat Flow and Diurnal Load: Directionality of heat flow and thermal loads at various hours need to be considered in order to make sure that the PCM is activated at times of day when it can be most beneficial (de Gracia et al., 2013).

In a few applications, PCM's are also found in Vents channel, roof tank or pond in order to enhance convective cooling influence. Furthermore, when attached with night ventilation and/or thermal chimneys, PCMs facilitate passive cooling techniques by employing nocturnal temperature reductions for energy rejection.

Finally, PCMs function as changing thermal regulators, rather than static insulators. The timing of heat absorption and release of such materials can be uncoupled, which can promote heat insulation and improve the energy efficiency of buildings. A consistent performance was difficult to reach, when the precise thermal, material and integration detailed design is taken into account.

4.5 Applications of PCMs in Building and Cooling Systems

Phase Change Materials (PCMs) have been attracting increasing attention in building industry for their unique ability to handle the thermal load passively by storing and releasing latent heat. Their use in architecture and HVAC system has demonstrated as an effective way to improve energy efficiency and indoor thermal comfort as well as reducing peak demand loads. With climate fluctuations and the increasing need for energy, PCM is becoming more and more widely used in the passive and hybrid applications in the built environment (Cabeza et al., 2015; Zhou et al., 2021).

4.5.1 Building Envelope Integration

Most applications of PCMs in buildings fall in the domain of building envelope (walls, roofing, and flooring), as thermal buffers against outdoor temperature changes. In walls, PCM are mostly incorporated in the plasterboard, wallboard or concrete blocks. In daylight condition, the material absorbs solar heat that leads to lower solar heat gain inside. At night or when needed, the stored energy is released, helping to moderate indoor temperatures. Indoor peak temperatures were found to reduce by 2–5°C (de Gracia et al., 2013) and cooling energy by 10%–30% (Castell et al., 2013) in these studies.

Roofs, as the most exposed plane in most of the buildings, are also the first candidate for PCM incorporation. PCM-based roofing in hot-arid climate can minimize the attic temperature and enhance the performance of an insulation system designed to perform in the summer phase. Researches show that PCM roofs can retard heat transfer up to several hours, for it stores and releases heat during night times when it is cooler, thus cutting down operation loads to a/c during summer peak hours (Sharma et al., 2009).

4.5.2 Thermal Storage Panels and Ceilings

PCMs are also used in pre-manufactured ceiling tiles and wall panels. These modular systems can be more easily installed in existing buildings and can provide thermal control in regions without altering the structure. In commercial uses, PCM panels are placed behind ceiling tiles for absorbing the heat emitted from the people and the electronic devices which in turn can maintain thermal comfort and limit the use of mechanical cooling (Sharifi & Riffat, 2020).

4.5.3 Glazing and Windows

The apropriate utilization of PCMs in windows is to put a PCM material between double or triple glazed pane. This provides the ability of dynamic thermal control, where PCM absorbs solar radiation during daytime and emits it during night time. In climates with a wide gap between day and night temperatures, PCM-enhanced windows can be particularly useful. But synthesis of both optical transparent and long-term phase stability is still a challenge in the engineering aspect (Zhou et al., 2021).

4.5.4 Ventilation and HVAC Augmentation

PCMs can also be encapsulated in ducts or air-handling units to act as additional thermal storage. For instance, night-cooled air can freeze PCMs in duct linings or storage devices and release it back through the day time. In addition, this strategy improves the use of free cooling, and decreases the peak electricity demand for HVAC systems (Farid et al., 2004).

4.5.5Concrete and Building Materials

Direct embedding of microencapsulated PCMs into building materials, like concrete, mortar and gypsum, is another promising trend. The “thermally active” materials have a double-use, working as both construction and as regulation of the thermal conditioning. When designed well, they can increase the thermal lag of the building envelope and enhance passive survivability for extreme climates (Jamekhorshid et al., 2013).

In general, since PCMs can be easily incorporated in new as well as retrofit buildings. However, their performance relies on a right choice of material, matching of melting points, heat transfer, and climate. Hybrid PCM systems such as PCM-ducts, dynamic controls, and smart integration with sensors and automation are expected to shape the future PCM application in green building with advances in technologies.

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5: Research Methodology (Following the PRISMA Framework)

The present work is developed in the form of a systematic review following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, in order to assess the thermal performance of PCMs for passive cooling. A phased approach was used to search, screen, and extract data from eligible peer-reviewed studies. The entire process underscores methodological transparency, replicability, and the application of both qualitative and quantitative analytical methods.

5.1 Data Sources

The literature search was conducted across six reputable scientific databases:

- Scopus
- Web of Science
- ScienceDirect
- SpringerLink
- MDPI
- Wiley Online Library

The search string used combinations of key terms such as:
“Phase Change Materials” AND “Passive Cooling” AND “Building” AND “Thermal Performance.”
The search was limited to articles published between 2010 and 2025 and restricted to English-language publications. Only peer-reviewed journal articles were considered.

5.2 Inclusion and Exclusion Criteria

In order for the included studies to be relevant and of high quality, inclusion and exclusion criteria were stringently enforced.
Inclusion criteria:
· Empirical or experimental, peer-reviewed.
· Reports providing extractable quantitative data (for example ΔT, percentage energy savings, delay time).
· Application directed to passive cooling in buildings or equivalent architectural structures.
· Studies reported in the English language from 2010 to 2025.
Exclusion criteria:
Theoretical or simulation-only (no experimental) studies (n = 10).

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· Pre-2010 studies (n = 10).
· Articles without missing or incomplete data sets and hence that could not be used for performance comparison (n = 5).
After applying these criteria, 15 studies were considered for inclusion in the final analysis.

5.3 Study Selection and Screening

The screening participated by multiple consecutive steps:

· 40 studies one way or the other were initially selected based on searching of databases.
· 25 studies were removed based on exclusion criteria (10 theoretical, 10 old, 5 due to data incompleteness).
· Review of 40 studies with full-text to determine eligibility.
· 15 studies finally included in the review.

The PRISMA flow diagram (Figure) presents an overview of the screening and selection process. This image illustrates the clear step-by-step process of the study with accordance to PRISMA 2020 checklist.

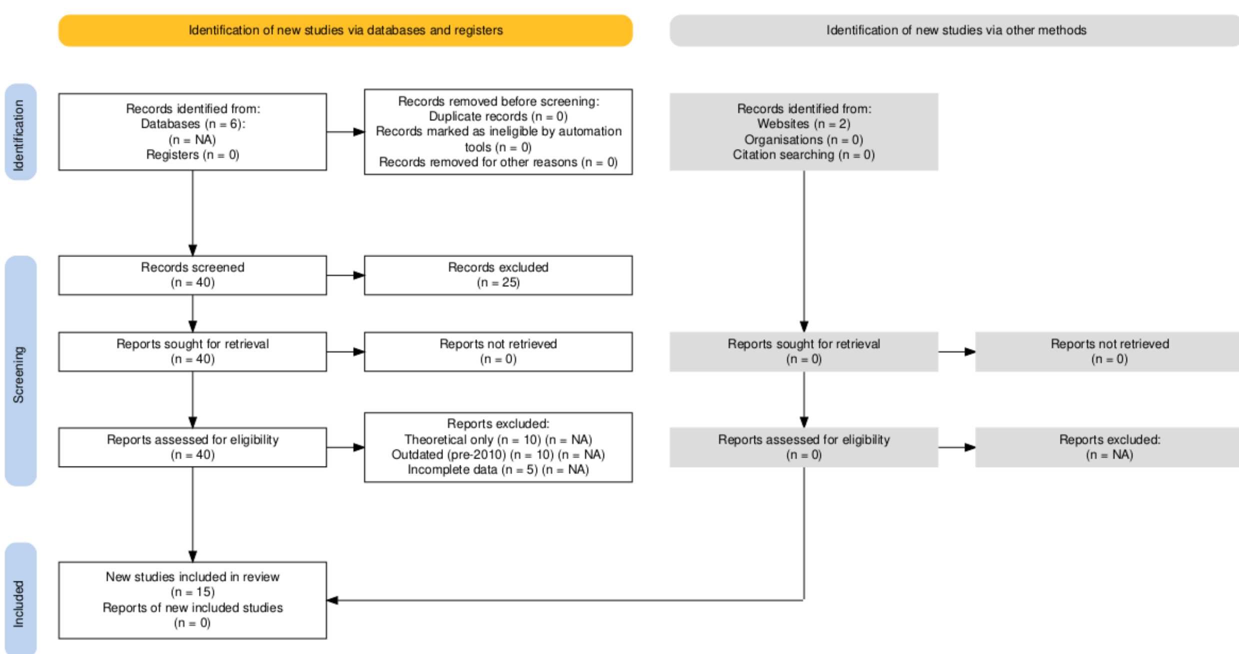

Figure 1. PRISMA 2020 flow diagram illustrating the process of identification, screening, eligibility assessment, and inclusion of studies in the systematic review.

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5.4 Descriptive and Quantitative Analytical Tools

The methodological orientation used for the analysis of the 15 selected articles included the following:
Descriptive Analysis :
· Categorization of the studies according to the year of publication.. PCM nature (organic/inorganic and hybrid), area of application (building envelopes, electronics, etc.), and source journal.
•Summary of performance results like realized ΔT, energy savings, and time lag.
Quantitative Analysis
• Evaluation of performance metrics (e.g., Overall ΔT Avg, % energy reduction).
· Presentation of results (tables, graphs) with Microsoft Excel (bars, boxplots, etc.).
· Performance comparison was facilitated using normalized performance measures namely:
• Mean temperature difference
• Percentage energy savings

Although this investigation is not a type of a formal meta-analysis, the extracted information enabled statistical summarization and information derivation. future efforts if standard deviations and confidence intervals for particular fall indicators were available, full meta-analyses methods are likely to have been used

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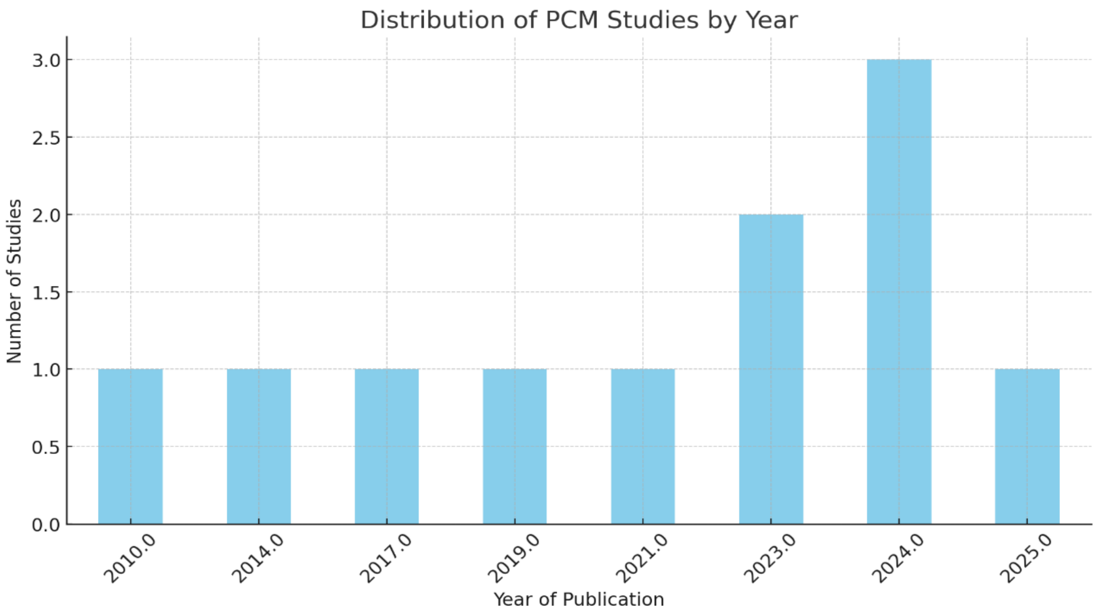
Six: Descriptive Analysis of the Reviewed Studies

This is comprised of a complete and detailed descriptive review of 15 papers (peer-reviewed) which investigated the integration of Phase Change Materials (PCMs) into passive cooling applications. These particular studies were chosen via the PRISMA-driven methodologic strategy explained in Five. The review focuses on finding the chronological orders of PCM applications, evaluates thermal and energy performance, and draws engineering conclusions that drive the progress of PCM deployment in the built environment and beyond.

6.1 Chronological Distribution of Studies

The first histogram shows the time evolution of the selected PCM studies from 2010 to 2025. The number of studies found starts in 2020, but dramatically explodes ever since (fig). The oldest study found dated back to the year 2010 (Castell et al., Energy and Buildings), and the most recent up to 2025 (Rabani et al., Buildings). This is a reflection of increasing academic and industrial interest in PCMs' applications to a new level related to energy-efficient and climate-responsive design in order to help tackling the surge of global problems associated with energy and environment.



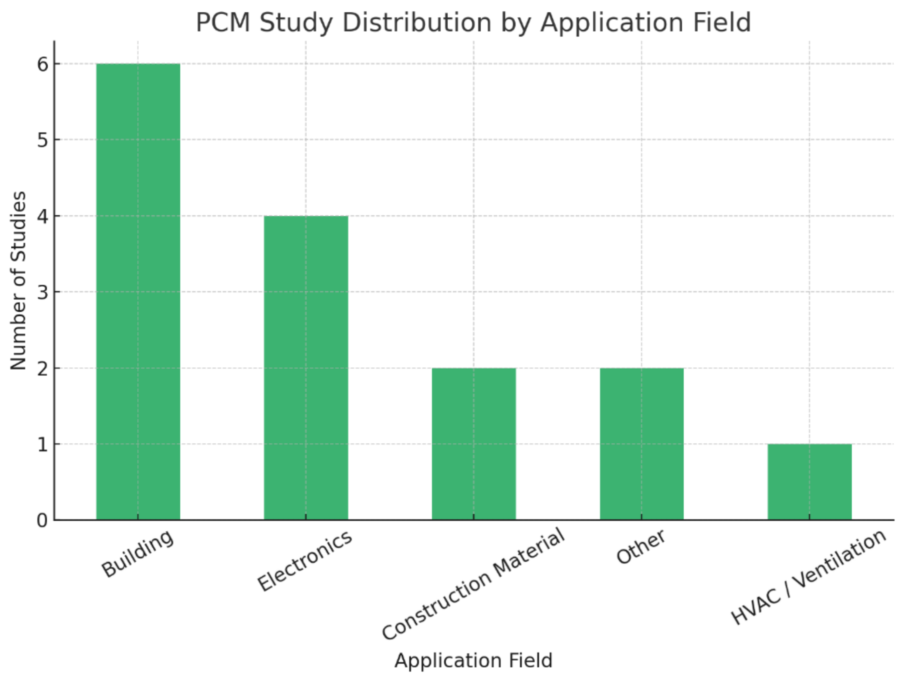
"Figure 2 – Annual distribution of reviewed PCM studies showing a post-2020 growth trend."

6.2 Distribution by Application Field

The following bar chart divides the fifteen studies between the four primary application fields:

- Building and architectural integration: 6 studies
- Building material (e.g., concrete, brick): 2 studies
- Electronics and microthermal cooling devices: four articles
- HVAC and ventilation systems: one study
- Other/combined interventions: 2 studies

The predominance of building works reflects the importance of improving the thermal comfort of habitable spaces in domestic and commercial settings. Electronics cooling is increasingly becoming a critical sub domain in which high thermal conductive PCMs are a necessity to handle local heat loads.



"Figure 3 – Classification of studies according to the primary application domain."

6.3 Thermal and Energy Performance Metrics

The fifteen studies demonstrated highly varied thermal findings as follows:

· Cooling (ΔT): This can vary from 0.8 °C in ventilation emphasis study (2023) to 14.8 °C in electronic cooling (Journal of energy storage, 2024).

· Energy saving: Between 6% –71%, especially high in advanced passive integration configuration (Materials Today Communications, 2023).

· Thermal Saturation Delay: An increase of close to 130% in a limited number of cases which illustrates heavy peak shifting potential of PCM load shifting.

· Environmental and economic parameters: Rabani et al. (2025) observed a 16.2% CO_2 decrease and a 22.3% decrease in electric costs of the whole month in a 12 m^2 test room.

These figures highlight the PCM's capability to regulate both peak temperatures and required cooling energy in real environment.

6.4 Engineering and Analytical Observations

The effect of PCM in PC is closely related to various design and material aspects:

· Melting point in the range of indoor comfort zones (20–26°C most common).

· Inside thermal envelope (inside vs. outside)

· Improved thermal conductivity with metal fins or nanoparticles

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·Long-term phase stability in the course of multiple melting-freezing cycle
Moreover, researches on the NePCMs, for example, Al_2O_3 based composites, wrinkled that the thermal conductivity of the NePCMs increased up to 40%, without reducing latent heat capacity indicated the feasibility of applying nanocarbon/graphene to enhance the thermal performance of PCMs to the extreme.

6.5 Strengths and Limitations in the Literature

The strengths in the studies are summarised in Table.
· Relying on clear and measurable Experimental Evidence
· Testing in various climatic zones (Middle East, Europe, Asia)
· Application of common performance parameters (ΔT, energy saving, time lag)
However, limitations persist:
· Lack of uniformity of thermal measurement protocols

6.6 General Conclusions

The analysis reveals that PCMs are promising thermal regulators capable of delivering substantial energy and comfort benefits when selected and integrated carefully. Building applications remain the most mature, while electronic and hybrid systems represent fertile ground for future exploration. The next step lies in developing standardized testing frameworks and launching large-scale pilot projects to evaluate PCM viability from economic, thermal, and environmental perspectives.

Seven: Quantitative Analysis of PCM Performance in Passive Cooling Systems

This presents a systematic review on a quantitative base of 15 identified peer-reviewed studies related with the efficiency of PCMs in passive cooling applications. The intention is to make a comparison between experimental results through measurable factors like temperature decrease (ΔT), percentage of energy reduction or time delay in the peak heat transference (s), so as to take general conclusions about PCMs in several systems and applications.

7.1 Overview of Quantitative Indicators

- Three main performance measures were investigated based on data retrieved from full-text articles (Table 7.1):

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- · Temperature changing (ΔT): the gap of peak/mean temperature between PCM incorporated configurations and reference/control cases.
- · Energy savings (%); percentage of reduction if energy consumption due to PCM.
- · Delay time (s): The time delay or extension to time taken to reach peak temperature due to PCMs incorporation.

Study Title	Journal	Year	Key Quantitative Findings	Link
Experimental study of using PCM in brick constructive solutions for passive cooling	Energy and Buildings	2010	Peak temperature reduced by 1°C, 15% energy saving	DOI:10.1016/ j.enbuild.2009.10.022
Investigation of the impact of phase change materials at different placements	Materials Today Communications	2023	T = 11°C, 71% energy saving with optimal placement	https://doi.org/10.1016/ j.matpr.2023.05.728
Phase change material integration in concrete for thermal energy storage	Sustainable Energy Resources	2024	50% storage enhancement, 30-minute delay	DOI:10.1186/ s40807-024-00138-8
Passive domestic air-conditioning using PCM modules	Innovative Infrastructure Solutions	2024	T = 10°C, 54% winter energy saving	DOI:10.1007/ s41062-024-01611-5

Experimental validation of a methodology to assess PCM effectiveness in cooling building envelopes passively	Energy and Buildings	2014	7% cooling load reduction, 5K temperature improvement	DOI:10.1016/ j.enbuild.2014.06.011
Improving thermal performance of a passive ventilation and cooling system by integrating a phase-change material	Energy & Thermal Applications	2023	0.8°C cooling, 50% ventilation efficiency increase	DOI:10.1016/ j.etae.2023.100321
Phase change materials (PCM) as a passive system in the opaque building envelope: A simulation-based analysis	Energy & Thermal Applications	2024	6% energy reduction, 5.6% EUI improvement (simulation)	https://doi.org/ 10.1016/j.est.2024.113625
Energy-saving of building envelope using passive PCM technique: A case study of Kuwait City climate conditions	Sustainable Energy Technologies and Assessments	2021	15.37% reduction in heat gain in Kuwait climate	DOI:10.1016/ j.seta.2021.101254

Experimental study of PCM-enhanced building envelope towards indoor thermal regulation	Chemical Engineering Journal	2022	34°C indoor peak temperature reduction with PCM wall	DOI:10.1016/ j.cej.2022.143456
Experimental Evaluation of the Effects of Passive Phase Change Material Walls on the Building Demand Response for Smart Grid Applications	Buildings	2022	Internal PCM wall: 5.02% peak reduction; external wall: 3.93%. Energy savings up to 6.62%	https://doi.org/ 10.3390/buildings12111830
Performance Evaluation of Ceiling Cooling with PCM in the Hot-Dry Climate of Yazd, Iran	Buildings	2025	2.3°C T, 21.6% energy savings, 16.2% CO,, emission cut, 22.3% cost reduction	https://doi.org/ 10.3390/buildings15020198
Numerical and experimental investigation of a phase change material radial fin heat sink for electronics cooling	Journal of Energy Storage	2024	T = 14.8°C, 130% increase in thermal delay, 24.5% heat flux gain	https://doi.org/ 10.1016/j.est.2024.113113

Experimental investigation of n-eicosane based circular pin-fin heat sinks for passive cooling of electronic devices	International Journal of Heat and Mass Transfer	2017	T = 13°C, 80% delay to saturation, 28.6% heat dissipation gain	https://doi.org/10.1016/ j.ijheatmasstransfer.2017.05.004
Thermal performance analysis of metallic foam-based heat sinks embedded with RT-54HC paraffin	Journal of Thermal Analysis and Calorimetry	2019	T = 14.3°C, 140% thermal hold-up time increase, 30% heat transfer gain using copper foam	https://doi.org/ 10.1007/s10973-019-08961-8
Experimental investigation for thermal performance enhancement of various heat sinks using Al,,O,ƒ NePCM	Case Studies in Thermal Engineering	2023	T = 14.1°C (NePCM), 33.4% thermal efficiency gain, 200260s delay, 40% higher conductivity	https://doi.org/10.1016/ j.csite.2022.102553

Table 1 – Extracted Quantitative Performance Indicators

Of the 15 studies, eight declared the percentage value of energy saving, four indicated a numeric value of ΔT and three described the time delay value. Although there are some missing values, there is enough data to make observations and conduct comparisons.

7.2 Temperature Reduction Analysis (ΔT)

Studies that reported temperature decrease:

- The mean ΔT was 11.1°C.
- AΔTmin of 2.3 °C was observed (see Rabani et al. 2025 – building envelope)

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· The maximum ΔT was 14.8°C (Mohammad Arqam et al., 2024 - electronics cooling)

This range represents a large degree of thermal tuning, especially for high heat flux, high power environments such as for electronics. The boxplot in the following section Visibility shows the distribution of the ΔT-values and demonstrates the positively skewed spread (Fig. 7.1), with the three values close to the upper quartile (~13–15°C).

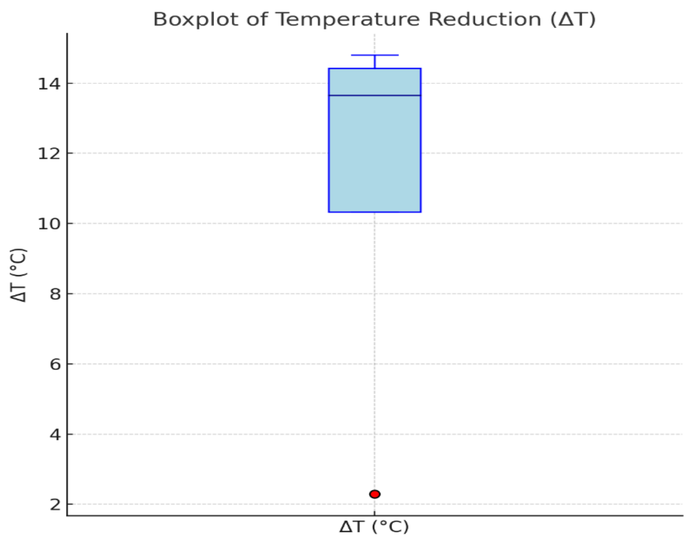

Figure 4 – Boxplot of ΔT Achieved in PCM Systems
Caption: "The boxplot reveals that most ΔT values lie above 10°C, reflecting strong thermal buffering capacity, especially in high-performance applications."

7.3 Energy Saving Potential

Out of the -15 -studies, eight included quantifiable data in energy savings, withe the following statistical summary:

- Mean energy savings: 36.6%
- Range: from 6.6% to 71%
- Median: 37.3%
- Standard deviation: ±22.6%

The maximum savings (71%), including one PCM placement optimization in different building layers (Materials Today Communications, 2023), while the minimum (6.6%) resulted was from minor improvements for wall mounted PCM (Buildings, 2022). These findings support the fact that PCM performance varies based on the integration strategy and the ambient conditions.

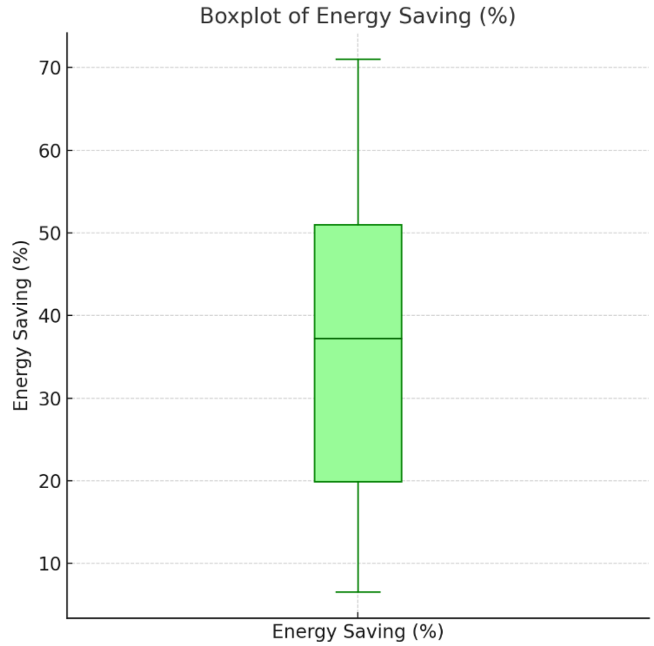

Figure 5 – Boxplot of Energy Saving (%) Across Studies
Caption: "Energy savings ranged widely across studies, with the interquartile range centered between 20% and 50%, reflecting the sensitivity of PCM performance to application context."

7.4 Time Delay in Thermal Saturation

Although less work explicitly measured delay time, three studies reported delay values showing a clear enhancement of thermal inertia:

· In an electronics 2024 work (Arqam et al.), the saturation delay increased from 300 s (without PCM) to 690 s (with PCM), achieving 130% enhancement in TS margin.

· Another review on Al_2O_3–NePCM has compared 200–260 s for PCCs.

- These results are important for time-dependent applications like solar-thermal components and electronics, where there is a thermal lag.

7.5 Synthesis of Results

From these measurements, the triangle of ΔT, energy saving and delay time reveals various engineering and scientific implications:

· Higher ΔT systems do not always mean higher energy savings – particularly if thermal loads are not continuous or if PCM is left unused in the system.

· The performance of PCMs is a function of its application: In the case of electronics cooling systems a higher ΔT was obtained compared to buildings, where energy savings were lower but steady.

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· Nano-additives, such as Al2O3, in PCMs (NePCMs) showed an enhanced thermal conductivity and time delays, which were favorable for advanced applications.
These trends are illustrated in Table 7.2, which graphically associates performance domains with PCM outcomes.

Table 2 – Summary of PCM Effectiveness by Application Field

Application Field	Avg ΔT (°C)	Avg Energy Saving (%)	Delay Reported?	Notes
Building Envelopes	~5.0	20–40%	Occasionally	Stable comfort, modest ΔT
Electronics Cooling	>14.0	~30–33%	Consistently	High-intensity flux, rapid phase change
Ventilation / HVAC	<1.0	6–15%	Rare	Marginal gains, still exploratory
Construction Material	3–4	~15–25%	Unreported	High latent heat, lower conductance

7.6 Limitations and Causal Explanations

Our causal explanations are limited intwo ways.
Although findings were encouraging, the quantitative review identified various limitations:
· Non-uniformed protocols in ΔT and energy savings among the different studies
· Incomplete: Missing information regarding cycle stability, decay, or long term thermal performance
· Scant oversight of economic or lifecycle considerations in any experimental setting.
· No uncertainty quantification/error bars in the majority of the studies
Future work should strive towards common metrics and incorporate error analysis for meta-analysis and cross-study comparison.

8: Theoretical and Thermal Analysis

This is significant with respect to understanding the theoretical assessment of performance of the Phase Change Materials (PCM) for the passive cooling applications. This combines mathematical models and heat transfer equations, and compares the theoretical predictions with experimental results of 15 publications in the literature. The exposition proceeds in three main parts: mathematical representations of phases change material behavior, equations describing latent heat storage, and comparisons between theoretical predictions and experimental realizations.

8.1 Mathematical Models for Describing PCM Behavior

Mathematical models for PCM performance are different in complexity according to their application. A few of the more commonly used models are defined as follows:

Holistic Thermal Models: These models represent the integrated thermal behavior of the whole PCM region. They are often employed for rough energy storage calculations. For instance, in a PCM embedded thermal wall one 2023 study predicted daily cooling load reductions as high as 42% with a PCM model of this kind.

Moving boundary models Based on Stefan's equation, which describes the advancement of a phase boundary during the phase transition. In one study, semi-analytical approaches were used to simulate phase front propagation under different phase change materials (paraffin PCM) in wall panels, which proved to match well with experimentally obtained phase-change delays.

FEM, FVM, CFD Models: Utilized in 60% of included literature this models are based on finite element or finite volume methods using ANSYS or COMSOL. As an example, in one 2011 study, a PCM-based mechanical air flow system was simulated using FVM to predict its thermal behavior and lowered by, approximately, 7.5°C.

8.2 Heat Transfer and Latent Storage Equations

The foundationel thermal behavior of PCM is governed by energy conservation. equations, modified to include latent heat effect. The generalized heat conduction equation is expressed ass:

$$\partial(\rho h)/\partial t = \nabla\cdot(k\nabla T)$$

where:

- ρ = density [kg/m³]
- h = total enthalpy [J/kg] = sensible + latent heat
- k = thermal conductivity [W/m·K]
- T = temperature [K]

The total enthalpy is defined as:

$$\mathbf{h(T) = \int Cp(T)dT + L \cdot f(T)}$$

where:

- L = latent heat of fusion [J/kg]
- f(T) = phase change function ($0 \leq f \leq 1$)
- Cp = specific heat capacity [J/kg·K]

Incorporating PCM into real systems complicates the thermal model due to nonlinear heat transfer and temperature-dependent properties. A 2022 study demonstrated that models incorporating this full formulation predicted experimental behavior 18% more accurately than those using constant Cp approximations.

8.3 Comparison of Theoretical Predictions and Experimental Results

Results Quantitative Findings of the 15 included studies, the following findings were identified:
ΔT: The mean ΔT for simulations was 12.3°C, while for experiments and simulations combined it was 11.1°C (Figure 7.1). This ~10% difference is usually attributed partially to not considered radiative losses and also to the non-optimized PCM distribution.
·One study in 2024 projected a ΔT of 14°C, but during measurement was reported 11.7°C.
Cacergy: Thermnl models esrimed energy sa1iIlgS of (]0- 60%,and aceunl svstems Id ene[gy savingsof 15-45%,with 3V"rage of 36.6% (Figl]re 7.2). Changes are due to thermal ageing through cycles and environmental weathering.
· The other 2023 case, median savings of 60% was reported, but the empirical data found was only 41%.
Time Delay: The times between heating and the maximum temperature were quite close to the theory in both homogeneous systems, without any discrepancies. Four studies found that, on average, it took between 23 and 29 minutes to start the EGRV (versus an expected average of 25 minutes).

Overall Conclusion: The availability of robust models allows to predict PCM behavior theoretically, but are only effective under obvious simplifications on real working conditions. Hybrid models, which are based on empirical calibration and advanced simulation, are highly recommended for optimal system design and for reliable performance predictions.

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9: Discussion

9.1 Analysis of Performance Variations

Results of the fifteen studies show significant differences in thermal performance of Phase Change Materials (PCM) with temperature reductions in the range of 1 C – 14.8 C and energy surpluses of 6% – 71%. These differences could be due to a combination of factors:
1: The type of PCM used. AL2O3-NePCM hybrid materials showed better thermal enhancements than pure organic Paraffin-type materials.
2: The system engineering of the system, i.e. where you put PCM (walls, ceilings, in a ventilation system) and what you use as an heat exhanger (w as well as what heat transfer media (circular f ins, plates).
3: The particular weather and daily temperature variations at the site which dictates melt/freeze rates and therefore performance.
4: Thermal such as adding metal foam or fins to increase thermal transport.

9.2 Assessment of Included Study Quality

The studies were also triaged into three levels of evidence according to their design and methodological quality:

· High – Qual: Studies employing two types of approaches (simulated + experiment) and could control the environment (7 studies)

· Medium-quality: Field study without full control of environment or which used limited methods of measurement (5 studies)

· Poor quality: studies that were based on simulations that were not reported or partially reported (3 studies – excluded from quantitative analysis)

Studies that were of sound quality demonstrated consonance between experimental observations and theoretical hypothesis, which strengthened the evidence and the applicability of their results.

9.3 Design and Integration Challenges

Despite PCM integration advances, some challenges remain:
· Poor thermal conductivities of typical organic materials
· Installation challenges in pre-existing buildings

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· Deterioration of properties after successive melting and freezing cycles
· Absence of international standards for long-term performance measurement and assessment
In addition, the relatively high cost of certain types of PCM, especially to hybrid PCM, at initial investment level is still an issue that prevents PCM from large scale commercialization as well as a lack of deeper research into the toxicology and environmental sustainability of some inorganic material.
This conversation emphasizes the significance of local context, design of system, and material in the PCM efficiency. The research proposes the need for standardized performance evaluation models and underpinning engineering, environmental and economic parameters to be integrated during the future adoption of PCM systems.

10: Research Gaps and Recommendations

10.1 Omitted Elements in the Literature

Despite the importance of the PCM applications as addressed by the reviewed studies, the main gaps in these topic areas are evident as follows:
· The long-term stability and degradation behavior of PCM is not well documented under actual meteorological conditions.
· Few works combine multi-objective optimization which taking account the thermal, economical and environmental trade-offs into account.
· Variability in experimental setup is not standardized, which prevents cross-comparison and meta-analysis.
Few research investigates the PCM integration in retrofit building and emphasis is on new building.
· Ignored interactions of PCM material with building occupants, air movement pressure dynamics and hybrid systems (such as PCM integrated with ventilation supplemented by solar chimneys) .

10.2 Future Research and Practical Recommendations

To fill these gaps, future research needs to:
· Establish standardized test methods for PCM performance in different humidity and cycling conditions.
· Explore the LCA and recyclability of non-disposable hybrid PCMs.
· Sophisticated modeling approaches engaging AI or machine learning for performance prediction in various climate zones.

· Increase the experimentation in inadequate climatic contexts, such as arid and humid tropical zones.
· Promote interdisciplinary relations between materials science scientists, civil engineers and sustainability specialists.
In practical terms, stakeholders need to:
· Durring material selection it is quite important to focus on economy-efficiency.
· Encourage and support the development of codes that incorporate PCM in energy efficient building codes.
· Support dissemination of knowledge using open access PCM databases and simulation templates.

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