INTEGRATION OF PHASE CHANGE MATERIAL (PCMs) INTO COOLING CEILINGS SYSTEMS: AN OVERVIEW

A DISSERTATION

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Submitted by:

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CANDIDATE'S DECLARATION

I, Shreya Sharma (2k23/MSCCHE/61) students of M.Sc. (Applied Chemistry), hereby declare that the project Dissertation titled "Integration of Phase Change Materials (PCMs) into Cooling Ceiling Systems: An Overview" which is submitted by me to the Department of Applied Chemistry, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Science, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma, Associateship, Fellowship, or other similar title or recognition.

Place: Delhi **Shreya Sharma**

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CERTIFICATE

I hereby certify that the Project Dissertation titled, "Integration of Phase Change Materials (PCMs) into Cooling Ceiling Systems: An Overview" which is submitted by [Shreya Sharma, 2k23/MSCCHE/61] student of M.Sc. (Applied Chemistry) Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Science, is a record of the project work carried out by the students under my supervision. To the best of my knowledge, this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

Place: Delhi **DR. RAMINDER KAUR**

Date: 20th, June 2025 **SUPERVISOR**

ABSTRACT

This thesis looks at the ways Phase Change Materials (PCMs) can be used in cooling ceiling systems, mainly for buildings that are being renovated. As PCMs are known for having a great amount of latent heat capacity, they help reduce changes in indoor temperature during the process of freezing and melting. New research shows that inserting PCMs into radiant cooling ceilings improves the temperature control well enough to eliminate the need for air conditioners. In renovations, PCMs can give a building better thermal mass and resulting in both better comfort and more energy savings. Literature studies have shown that adding PCMs to building envelopes, especially in ceilings, decreases peak temperatures in the home and keeps daily swings in indoor temperature stable. Some advanced methods like micro- and macro-encapsulation help stop liquid from leaking and maintain the battery's heat, as well as its stability over time. Though PCMs have poor heat-transfer capability and can wear out more quickly when the system has to go through many heating and cooling cycles. The use of materials such as graphene and carbon nanotubes explains how innovations are dealing with these issues. To sum up, blending PCMs with ceiling cooling systems has great potential to boost interior comfort and cut down energy use, as long as more research is done on the materials, how they should be used, and their future performance.

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Introduction

A growing demand for energy efficiency and sustainability of the building solution provision has made innovative technologies the leaders in contemporary architecture and construction. Among those new technologies that have gained much importance is the use of Phase Change Materials (PCMs) in thermal energy storage systems [1]. The built environment, more specifically, buildings, particularly in cities, contributes to an enormous amount of the global energy usage, of which a significant share can be attributed to heating, ventilation, and air conditioning (HVAC) systems [2]. To counter this problem, researchers and engineers have been investigating passive and hybrid cooling options that may save a significant amount of energy, and at the same time keep the occupants cool and comfortable. Two of them are cooling ceiling systems with the improvement of PCMs, which provide a promising direction [3]

Phase Change Materials have the capacity to absorb large quantities of latent heat and then release it in the form of phase changes under the typical solid-to-liquid transition and vice versa [4]. This is what gives PCMs an edge, particularly in places that require temperature regulation, where the concern is indoor temperature control. With PCMs embedded in the radiant cooling ceiling panels, the system will have the ability to capture some of the excessive heat in the building during the day and dissipate it once the night becomes cooler, hence flattening temperature peaks to minimize the dependence on HVAC systems [5][6].

The cooling ceiling systems work on chilled water or passive thermal storage and cool the interior spaces using radiation instead of completely leaning on the air-based systems of cooling. Having PCMs embedded in these ceilings does not add bulk or need any extra mechanical work, but increases the thermal buffering capacity of such a structure. The combination provides more uniform indoor conditions and better energy efficiency at homes and in businesses [7][8].

In recent years, there has been an increasing amount of experimental and simulation work on the use of

PCMs in cooling ceilings, to test the thermal performance of such systems, to assess their comfort advantages after installation, and to attempt to quantify their energy saving potential [6][9]. Although most researchers have supported and established the benefit of PCMs in decreasing the peak cooling loads and enhancing the thermal comfort, there are still some problems, like low thermal conductivity, degradation, and complexity of integration within the PCMs [10][11].

The theme aspect of PCMs in cooling ceiling systems that can be discerned in this review is the material types, encapsulation methods, integration approach, and experimental demonstration [12][13]. It discusses the existing literature, areas of knowledge gaps, and prospects of optimizing PCM applications in building design as well [14]. This paper will offer a wide picture of the extent and limitations of PCM-enhanced cooling ceilings regarding sustainable architecture and energy-saving construction processes by condensing the available research [6][15]. PCMs have the ability to feel and release heat in very small temperature ranges as they change from solids to liquids or back again. While transferring, they save energy when it gets hot and give it out as the temperature goes down, not changing much on the outside. That is why PCMs are used a lot in thermal energy storage systems when even indoor temperature needs to remain constant [16][17]. There are three main categories of PCMs called broad categories: -

Organic PCMs- Examples of these are paraffin waxes and fatty acids. Polymer compounds are not easily affected by chemicals, stay intact, and handle thermal changes well, but have low heat conductivity [18][19].

Inorganic PCMs – Salt hydrates and metals are the main components, and they have strong thermal conductivity, but the materials might suffer from subcooling, corrosion, and separation of the phases [19].

Eutectic PCMs- Various substances melt and freeze together at the same temperature, so their performance is easy to predict. They have barely been examined but could be adjusted for specific jobs in thermal science [20][21].

The typical use of PCMs in thermal management of buildings is when the air temperature is between 18–35°C, a level that is suitable for humans [22]. Because of this, they are useful in energy-efficient buildings because passive heating or cooling helps save electricity needed by heating or cooling units [23]. Below,

Table 1 provides a comparative overview of three main types of Phase Change Materials (PCMs): Organic, Inorganic, and Eutectic PCMs. Each type has distinct characteristics that make it suitable for different thermal energy storage applications.

Table 1. Comparison of Different Types of Phase Change Materials (PCMs)

Type of PCM	Examples	Key Properties	Advantages	Disadvantages	Reference
Organic PCMs	Paraffin waxes, fatty acids	- Melting point: 20–60°C - Low thermal conductivity - Chemically stable	- Chemically stable - No subcooling - Long thermal cycling life - Non-corrosive	- Low thermal conductivity - Flammable - High volume change during phase transition	[18][19]
Inorganic PCMs	Salt hydrates, metals	- High latent heat - Good thermal conductivity - Sharp melting point	- High storage density - Inexpensive - Compact systems possible	- Subcooling issues - Corrosive to metals - Phase separation possible - Shorter cycling life	[19]
Eutectic PCMs	Mixture of organic–inorganic compounds	- Precise melting point - Intermediate thermal properties	- Sharp melting/freezing point - Stable thermal behavior - Wide design flexibility	- Complex formulation - Limited availability - Can be expensive	[20][21]

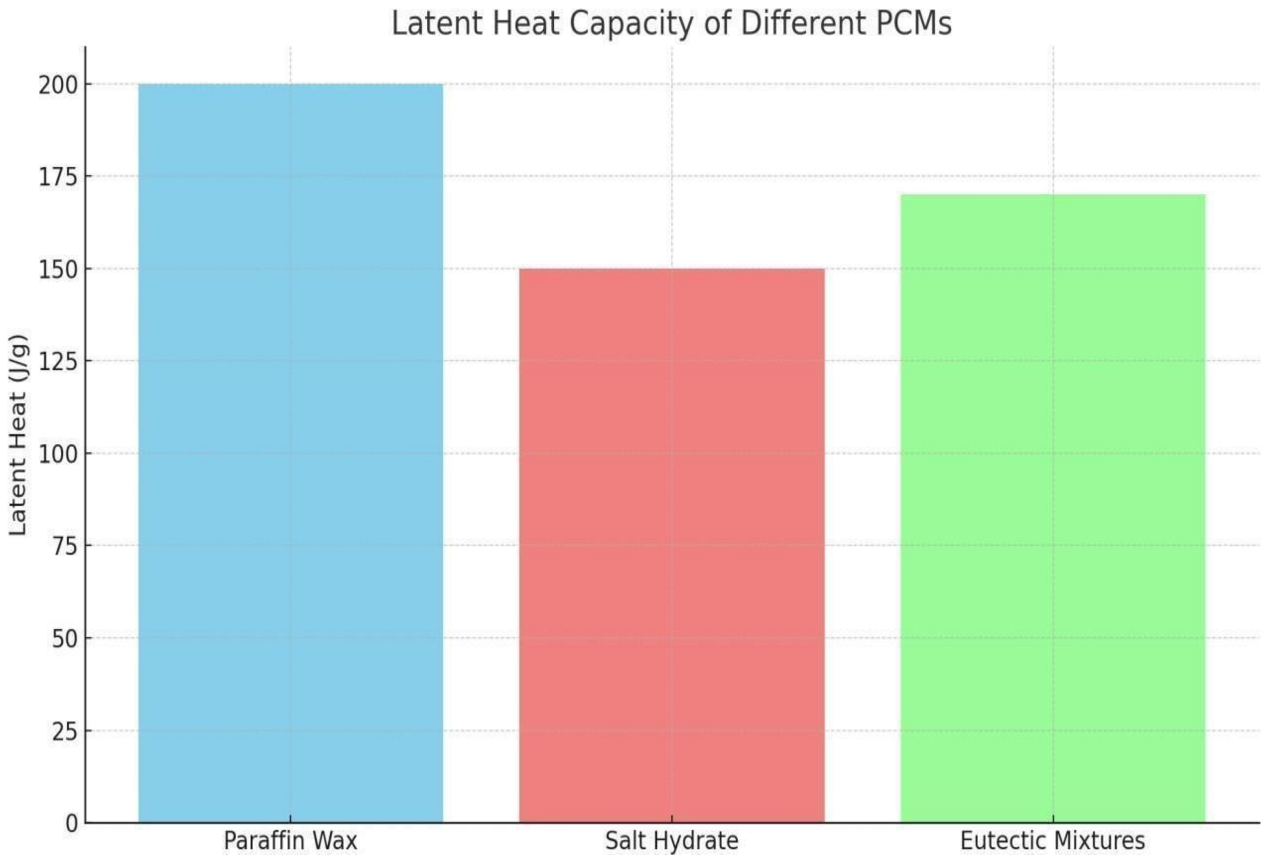

Fig 1: Showing Latent Heat Capacity of Different PCMs

It visualizes how different types of PCMs store thermal energy, highlighting their latent heat capacities.

1.1 PCM Encapsulation Techniques

Encapsulation is crucial to ensure PCMs operate safely in both building and cooling systems, without incurring any durability or leakage risks. The following sections will provide details about three main methods of encapsulation, including their advantages and disadvantages [3][24].

1.1.1. Macro-Encapsulation

The primary concept of macro-encapsulation is to contain large volumes of PCM (greater than 1 cm) in tubes, pouches, or panels. The types of materials and basic forms used are-Usually, the shell options are HDPE, LDPE, PP, and any kind of bottles, tins, or mild steel containers, and plastic pouches. AMD equipment, 3D Additive Manufacturing technology can create several shapes like cylinders, packets, flat pouches, and panels as required [3][24].

Some applications for macro-encapsulation can be as follows: -

An option for using reinforcing steel is adding it to building walls, ceilings, precast slabs, or floor systems. For example, you can put pouches into clay bricks or cement panels.

The advantages of using the macro-encapsulation are-

- It works with any variety of heat transfer fluids.
- It is prepared for quality handling, simply shipped, and easy to customize for installation elsewhere.

Challenges

- Paying attention to compatibility ensures that corrosion or decay is not able to damage the shell-PCM.
- There could be large amounts of dead space and not much heat transfer through large-sized capsules.
- Risks caused by problems with valves or hoses may develop as time passes.

1.1.2. Micro-Encapsulation

Micro-encapsulation puts each PCM drop (1 µm–1 mm size) inside a microshell [25].

The types of shells and the process of making them include [26][27]: -

- Shell materials are formed by polymerizing the precursors inside the core, for example melamine-formaldehyde, PMMA, and many others.
- Usually, organic electronic devices use sol-gel derived silica or titania coatings to raise thermal

conductivity and strength.

- The way a shell is made determines if it is one type of structure or several nested types.

The advantages of using micro-encapsulation are:-

- When the surface is bigger than the volume, the temperature is likely to change faster.
- Excellent sealing of leaks is still guaranteed many times.
- Working on many surfaces such as plaster, slurries, and composite materials.

Some drawbacks to this technique are as follows:-

- It is more expensive to produce pharmaceutical products because they contain complex chemicals.
- It is important to design the shell–PCM interaction well because salts can corrode the metal shells, and not all organics require the same type of shell.
- When shell content goes up, the latent heat per mass may be lower.

1.1.3. Shape-Stabilized PCMs (SSPCMs)

Two-phase change materials where liquid and solid phases are shaped or formed are known as Shape-Stabilized PCMs (SSPCMs) [3][24].

Concept

Structural or porous matrices found in SSPCMs keep molten PCM from escaping while using no hard outer walls .

Supporting Matrix Materials

Matrixs

Having this type: Expanded graphite, exfoliated graphite, carbon nanotubes, graphene—these give extra strength and allow heat to flow better.

Commonly found in cement-based building materials are diatomite, silica fume, bentonite, kaolin, and expanded vermiculite.

Polymer gels use organogelators like HSA and DBS to keep the PCM trapped in networks [28][29][30].

Fabrication Methods

Vacuum impregnation: The applied pressure under a vacuum helps PCM travel through pores to reach maximum loading.

Direct absorption: The material gets absorbed directly by the capillaries.

Sol-gel: Put PCM inside a matrix of silica and titania made from inorganic precursors [28].

The advantages of using shape-stabilized PCMs are: -

- No need for a special shell, which makes handling leaks much easier.
- Loading of PCMs can go up to nearly 90% volume fraction in hierarchical porous-metal structures.
- Better strength and better transfer of heat through the materials added.

The challenges that are faced due to this technique are:

- Precise design of the matrix is necessary for the process of uniformly impregnating porous materials.
- When salts are used, there may be problems due to incompatibility with other parts of the soil (the matrix).
- Longevity is threatened for dental implants as thermal cycling might gradually weaken the

matrix.

Below, Table 2 explains a side-by-side evaluation of macro-encapsulation, micro-encapsulation, and shape-stabilized PCMs in terms of size, conductivity, leakage control, cost, and suitability for building use.

Table2. Comparative Summary of PCM Encapsulation Techniques

Name of the Technique	Scale & Shell	Thermal Conductivi-ty	Leakage Control	Productio-n Cost	Suitability for Building Integration	Reference
Macro-encapsulati-on	PCM >1 cm in bottles/pouches/pan-els	Moderate limited by shell thickness	Good, must ensure seal integrity	Low–Medium	Good for retrofit; easy to handle, compatible with panels and slabs	[3][24]
Micro-encapsulati-on	PCM ~1 µm–1 mm in polymeric/inorganic microcapsules	High—large surface area, shell thin	Excellen-t, ideal for powders	Mediu m–High	Best for incorporation into mixed materials—plasters, paints, slurries; suited to lightweight building boards	[25][26] [27]

Shape-stabilized PCM	PCM embedded in a porous matrix or polymer gel network	Very High—conductive fillers	Excellen-t if matrix well-designed	Medium	Ideal for composite panels, thermal boards, and flexible panel systems using modern materials	[28][29][30]

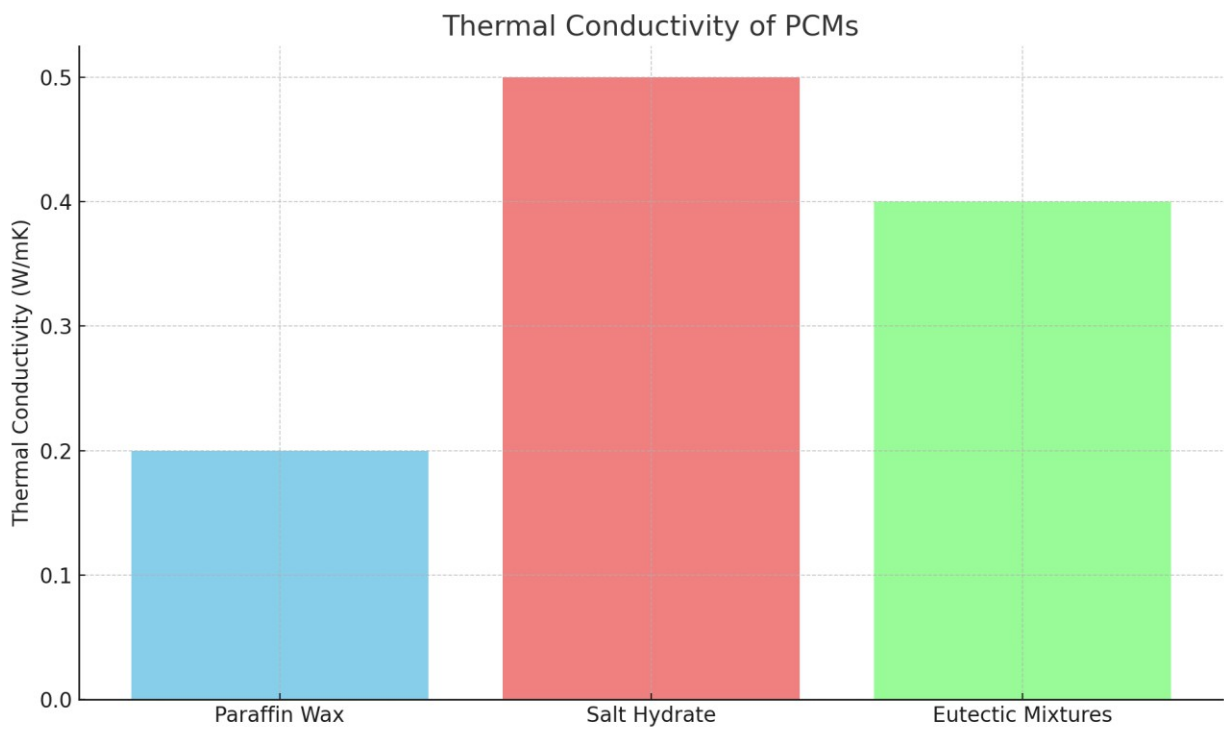

Fig 2: Showing the thermal conductivity of different PCMs

Illustrates the differences in thermal conductivity among various PCMs, emphasizing the limitations of organic types.

1.2 Applications of Cooling the Ceiling in Practice

The pouches can be fitted to ceilings when retrofitting, by using the suspended systems, or created by sandwiching [23][31].

Applying micro-encapsulated plaster allows professionals to include thermal mass in thin on-site ceilings [12].

SSPCMs in panels: Carbon sheets are perfect for ceiling panels in constructions, allowing for both renovations and new constructions [28].

Best practices for integrating PCMs with different additives to achieve better control over temperature

Low thermal conductivity – Low conductivity of the capsules reduces the usefulness of PCM. Copper coating, graphite, or metal foam fillers should be used for better effects [17].

Shell-Matrix Compatibility- Chosen shells should not react with the main content (avoid using salt-containing metal capsules in shells), and choose the correct type of shell for every PCM (organic or inorganic) [12].

Capsule integrity & Shape-Stabilized Composite Integrity – Capsules must not burst, and cyclical changes must not cause the shape-stabilized composites to lose their internal structure [29].

Thermal Cycling Durability – Assess the device by subjecting it to thousands of thermal cycles to guarantee that it does not lose its latent heat and stays intact [23].

Manufacturing and Cost- Ensure that the performance of the product is not harmed by keeping the expenses of material and labor reasonable. The method that uses less money is macro-encapsulation, but micro and SSPCMs are more reliable and can be integrated more, costing slightly more [32][33].

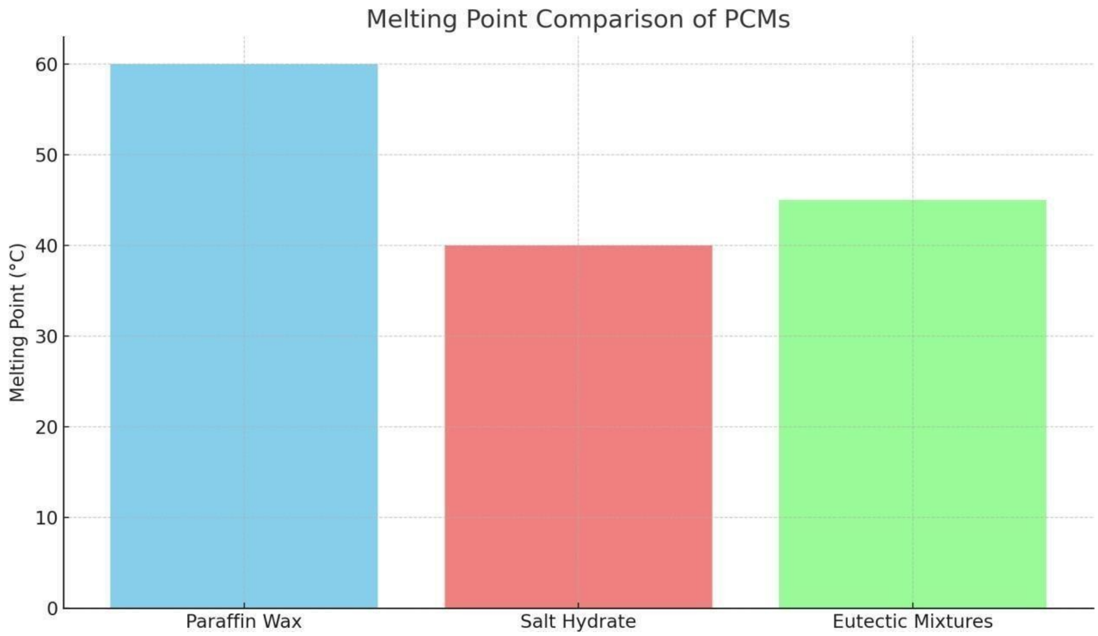

Fig 3: Showing the Melting point comparison of PCMs

Comparing the melting points of organic, inorganic, and eutectic PCMs aids in selection based on indoor temperature ranges.

1.3 Cooling Ceiling Systems

Cooling ceiling systems are referred to as radiant cooling ceilings and use chilled water running through pipes in the ceiling to help cool an area. The panels mainly cool the area by emitting radiation and partly by bringing cool air into contact with the things nearby [14][34]. Conventional air conditioners use forced airflow, while cooling ceilings make sure the temperature is more even, and they save energy by being more efficient. They are nearly silent, there are no drafts, and you can have better air in your home since such systems don't bring dust and particles into the air. Still, the efficiency of these structures tends to suffer from sudden heat increases, temperature changes, and changes in climate. PCMs help deal with these problems. The inclusion of PCMs can greatly contribute to saving energy in buildings. Energy used in buildings makes up 30–40% of the world's energy consumption, and a significant part of this goes to heating and cooling. Because energy prices are reaching new peaks, fossil fuels are being drained, and the planet is affected by climate change, effective ways to use energy sensibly in buildings are much needed [5][35]. Incorporating

PCMs in structures is a good approach to improving cooling. This type of battery is capable of energy storage through heat. You can save heat from the heat of the day and use it during the colder times.

Reduce Need for Air Conditioning – According to peak load management, lowering the maximum energy used by cooling systems during the days when it is needed the most [12].

Better indoor thermal experience – keeping the air temperature consistent.

Putting PCMs in ceilings, walls, or floors boosts the thermal inertia of the indoor space. As a result, temperature changes within the home decrease, and citizens rely less on artificial air conditioning and heating.

Most importantly, applying PCMs in ceiling cooling can improve these systems' performance since it allows them to tackle high heat loads without making the overall setup bigger or more costly.

The purpose of this review is to study the role of Phase Change Materials (PCMs) in cooling ceiling systems. There has been extensive research on PCMs in the construction industry, yet research on their use in radiant cooling ceilings is particularly important today since it benefits both new buildings and those being retrofitted [36][37]. When PCMs are placed in ceiling panels, the system improves its efficiency and has thermal storage, too. During times when the processor is most active, the PCM manages to absorb heat and hold back temperatures in the indoor area. When it gets cold outside, the material cools physically and slowly releases the energy it had stored, so space stays cool. Thanks to this, cooling demand decreases, and the number of high-use hours is lessened [3][38]. This review is meant to assemble and connect all the key literature focused on these key subjects:

- A range of PCMs that can be used in the ceiling setting
- Approaches to improve the strength and safety of products
- Methodologies for merging systems and ways to design systems
- Information about performance obtained from case studies and studies.

- Problems, difficulties, and what is coming.

The purpose is to show how PCMs can be widely applied in cooling ceiling systems to increase energy saving, improve indoor conditions for occupants, and contribute to sustainability [35].

Chapter-2

Literature Review

The behavior and performance of phase change materials (PCMs) in building applications, particularly radiant cooling systems, have been studied considerably over the last 20 years. The opportunity to use PCMs in cooling ceiling systems has drawn increasing attention because of the possibility to decrease the peak thermal loads, increase the comfort of building occupants, and facilitate the shift towards low-energy buildings [38][39]. An extended analysis of the literature shows some valuable thematic implications, which become the core of the additional investigation of this field. Considering the PCM according to their thermal performance parameters, which include latent heat capacity, melting temperature, and thermal conductivity [5][30][40]. The importance of a careful consideration of the match between PCM properties and the local climatic conditions was Zalba et al. (2003) and Farid et al. (2004). In cooling applications, the PCM of choice would melt at ordinary indoor comfort temperatures (approximately 2226 °C). The first interest in organic PCMs concerned the stability and non-corrosiveness of organic compounds such as paraffin waxes, but the low thermal conductivity of these substances tended to restrict the rates of heat transfer [18][30]. Conversely, inorganic PCMs, e.g., salt hydrates, demonstrated better conductivity, but had a problem of phase segregation and subcooling [19][41]. These pioneering studies gave material scientists a guideline to adjust PCMs and examine encapsulation methods that would lead to a higher efficiency of the whole system [42][43].

Based on material-related research, an extensive level of research was diverted toward experimental-based research on PCM-integrated ceiling panels. These studies were conducted in full-scale room configurations or test chambers in which PCM panels were installed either below the ceiling surface or PCM panels were embedded in chilled water ceiling panels [11][44]. The works by Mousavi et al. (2022) and L. Aye et al. (2023) are also valuable inputs to this body of work, given that they perform thorough analyses of the thermal and energy performance in Australian climatic conditions [22][45]. They found that the integration of PCM had the potential to limit the variation of indoor temperature by 3 °C and result in an evident increase in thermal comfort. In addition, PCM layers were found to contribute to the stability of the grid and energy efficiency because they could store surplus cool energy during off-peak hours and then release it during peak demand times, thus allowing chilled ceilings to operate longer [46][47].

Another very useful piece of information found in the literature is the development of numerical simulation and modeling strategies. Due to the intricacy of phase transitions and nonlinear heating transfer properties of PCMs, simulation-based tools have seen extensive use in forecasting long-term system behavior. Computational Fluid Dynamics (CFD) models and simulation platforms such as Energy Plus and TRNSYS have helped researchers to investigate the dynamic response of PCM layers in building envelopes [11][42]. According to Xu et al., (2017) and Jaffal et al., (2012) inclusion of PCM data in the simulation tools aided in the prediction of up to 25% annual energy savings, particularly in mixed and warm climates [48][49]. It was also through these simulation-based works that the testing of scenarios with different types of PCM, melting temperature, thickness, and room setup became possible: testing that would prove uneconomical had it been undertaken via physical experimentation alone [15][50][51].

Mousavi, Rismanchi, Brey & Aye (2021) carried out a complete review of PCM-embedded radiant chilled ceiling (PCM-RCC) systems and focused on the operations, detailed properties of the PCMs, and the related energy and comfort benefits [52][53]. According to the investigation, a PCM-RCC system usually provides more relief from heat and increased thermal comfort than a conventional air-only system, especially as nighttime cooling matches the daytime absorption of heat [16][33]. Yet, they pointed out that the results are mainly affected by how accurately charging/discharging cycles are managed and the design of solar panels [54][55].

In Melbourne, they studied the effect of PCM-embedded radiant chilled ceiling and found their experiments gave clear results (Energy Reports, 2022). Mousavi and his colleagues found that a cabin with PCM ceiling panels saw cooling load reduced by around 15-20%, more than 80% of the occupants were comfortable with temperatures within the Class B limits, and the peak loads were mostly shifted to hours when utility prices were lower. The findings of this experiment agreed with what they found earlier and placed greater focus on smart designs and proper controls [56][57].

Bogatu et al. (2021) focused on a new ceiling panel carrying water containing PCM, and they compared it with conventional radiant ceiling panels. Research found that their cooling power was 5.3–27.7 W/m^2, with an average of 11.3 W/m^2, and for 83% of the time, it maintained the second-highest comfort level. The new design boosted the engine's cooling system and made it simpler to regulate the power [13][24]. In 2025, Bogatu, Shinoda, Olesen & Kazanci made sure that a simulation model matched experimental data from the same macro-encapsulated panel. They studied how changes in supply water temperature, flow, and thickness of phase change material (PCM) shaped the design, which enabled them to make charts for architects and engineers to use early in the design phase. Their research revealed that PCM-ceilings can work by combining storage and cooling processes [7][9][58].

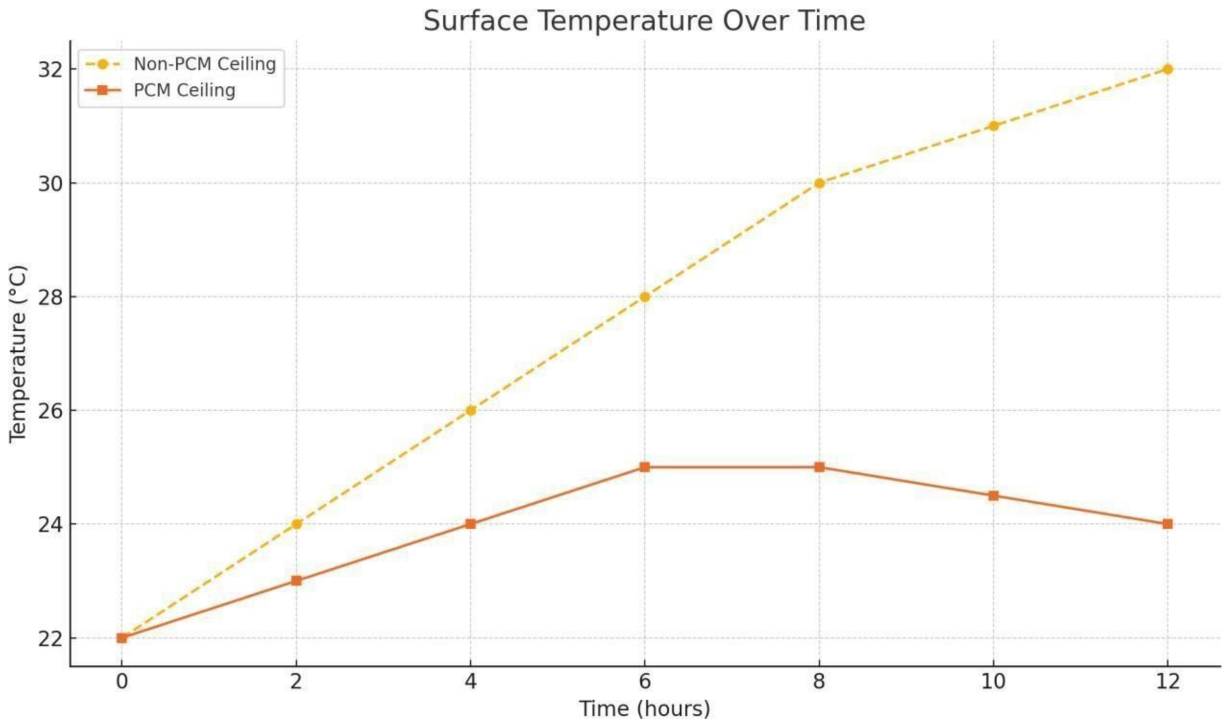

Fig 4: Showing Surface temperature over time

Demonstrates how PCM-embedded ceilings stabilize surface temperatures over a daily cycle, reducing indoor fluctuations.

Using real Melbourne test results, Mousavi et al. built a model that found PCM-RCC systems use 12% less electricity and run for 93% of the time during off-peak demand, and 5% additional electricity can be saved using advanced controls. It is clear from this that scheduled charging/discharging plays a crucial role in using the benefits of PCM-RCC [53][59]. According to Inayat & Raza (2019) in district cooling systems and Elaouzy & El Fadar (2022) on passive design, using PCMs is especially important for the big picture. The two researchers found that about 10% more energy could be saved in renewable-energy-powered PCM-buffered systems if climate sensitivity and active control are considered. Elaouzy & El Fadar went on to say that peak load steadied but highlighted the necessity to pay close attention when placing, choosing, and integrating

PCM solutions [60][61].

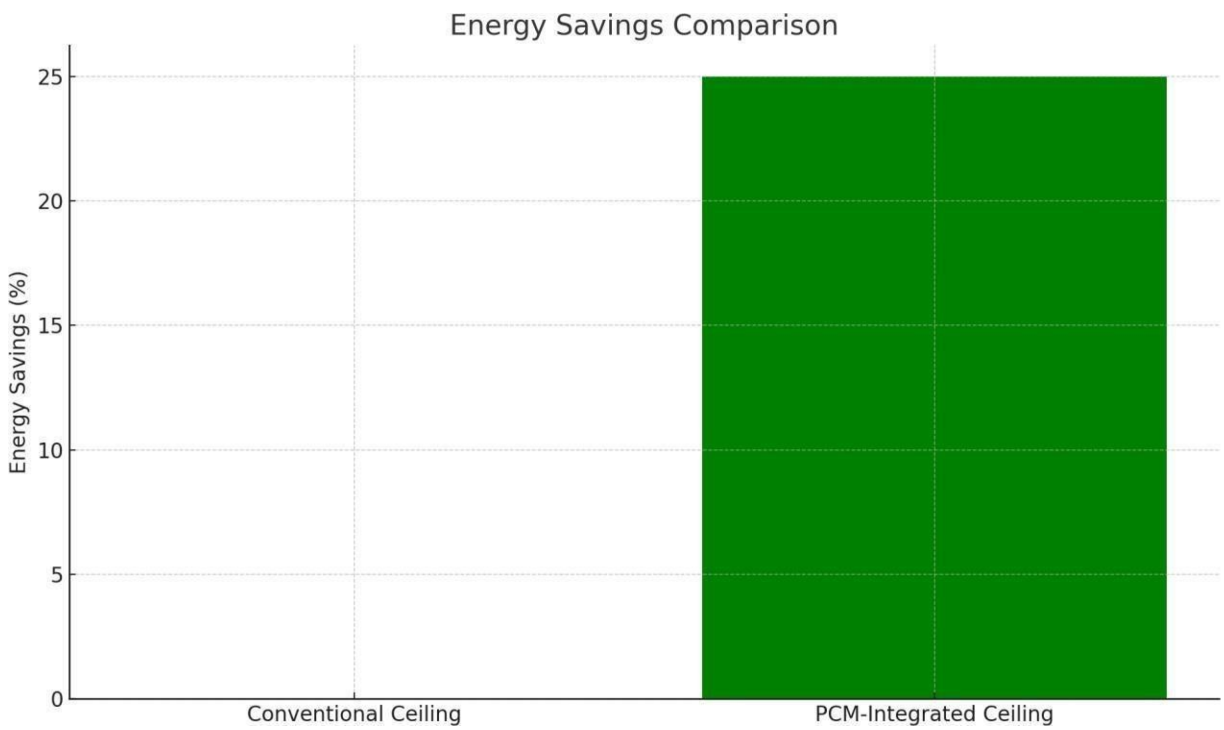

Fig 5: Showing Energy Saving Comparison

Depicts the percentage of energy savings achieved by integrating PCMs into ceiling systems versus traditional setups.

A study carried out in Yazd or a similar hot-dry place and reported by MDPI Buildings proved that PCM-ceiling panels can drop down the temperature in the room and on the ceiling by ~3.2°C and 5–10°C, respectively [1][53]. In another separate study by Yang et al., the use of both PCM ceilings and EAHE led to maximum temperature drops ranging from 2 to 2.7°C based on the storage strategies used, proving that such a system works for passive cooling [22][62]. Research by MDPI (2022), Bogatu et al, being discussed here, revealed that mounting PCMs on ceilings leads to saving up to about 20% of heating energy and cuts thermal energy loss from ceilings in half, making it very effective in reducing heat energy [57]. The results confirm what Yoshida and Jouhara reported earlier about the added effects of nano-additives that make the charging/discharging speed in the panel more efficient [63].

Thus Areas of improvement

1. After completing short demonstration projects, not many long-term results have been proven. Long battery operation can cause the problem of thermal cycling, PCM leakage, and possible shell failure, and these issues should be studied for several years [64].
2. According to research, control strategies that rely on predicting charging needs at night are vital. Even so, just a few places have introduced ML-based or real-time adaptive systems.
3. There is not much information directly comparing the cost and benefits of the different PCM types, their methods of enclosure, and how they will be added to the system. There has been little study of the environmental costs and emissions caused by products [65].
4. Most studies look at cultures found in temperate Western regions. Studies from South Asia, the Middle East, and tropical Africa are still few because of limited available data.

It is highly possible to use PCM-RCCs along with PV, solar water systems, thermally activated construction, and district cooling networks. But there is not enough research in real-life cases to prove its effectiveness [55][66]. Although these approaches help, they are still limited by high production expenses, difficulties in shaping them, and approvals.

Chapter-3

Applications and Uses of Phase Change Materials (PCMs)

PCMs are well known for bringing major changes to how energy is used in buildings. Because they can store and use thermal energy during phase change, they are perfect for lowering a building's heating and cooling needs [67][68]. Here, the focus is on finding out how PCMs are commonly used in cooling ceiling systems, building exteriors, and air conditioning units. It also focuses on how their performance has improved in regard to comfort in warm temperatures and the amount of energy needed [69][70].

3.1. Use of PCMs in Cooling Ceiling Systems

Radiant cooling ceilings allow for keeping indoor spaces comfortable without using a lot of standard air-conditioners. In them, chilled water goes through pipes placed in ceiling panels, releasing heat and cooling the room. Integrating these materials increases the system's abilities to store heat effectively [71]. When it is very hot outside, excess heat will cause PCMs inside cooling ceilings to liquefy and take up the heat. It is this way that the room can preserve a consistent temperature. As it gets cold overnight, PCMs solidify and use the stored heat to warm the environment. This kind of behavior reduces the amount of AC that needs to be used [72]. Mousavi et al (2022, 2023) discovered that adding PCM to radiant chilled ceilings made it possible to save up to 30% in energy. The case study in Melbourne revealed a major decrease in peak air conditioning and a better level of comfort enjoyed by the building's occupants [73][74]. Benefits of incorporating PCMs into the ceiling are:

- Using less energy at the busiest time of the day
- People inside the building feel more comfortable.

- Reduced the time that HVAC machines operate
- It is possible to use HVAC systems more effectively by reducing their size.

Challenges

- The money you will spend to buy PCM panels
- It is necessary to have accurate control techniques.
- Stability and performance for a long period in regular situations

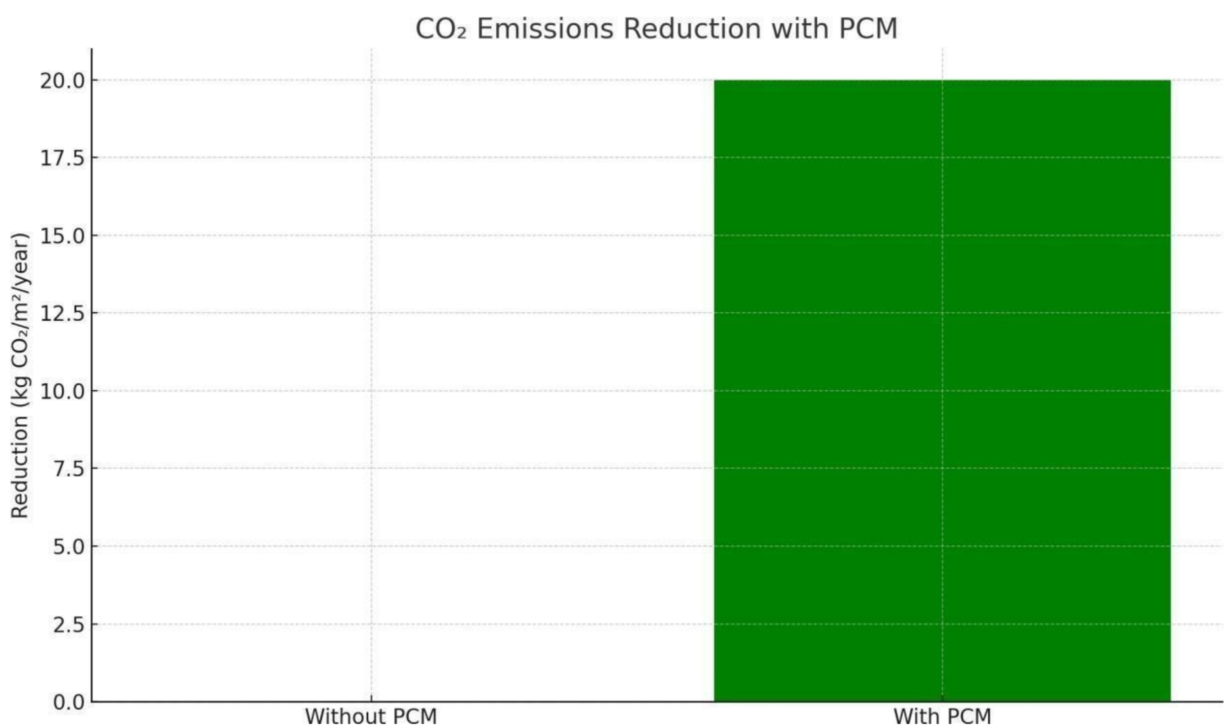

Fig 6: Showing CO_2 emission reduction with PCM

Highlights the reduction in carbon dioxide emissions when PCMs are used, supporting their environmental benefit.

3.2. Use in Building Envelopes

An area of application of PCMs that is gaining ground is the building envelope (walls, roof, and floor). These parts serve as a shield against external temperature changes in the first place [23][48]. By embedding PCMs in the construction material, it is possible to have the building absorb solar heat and ambient heat throughout the day, which melts the PCM. This heat is later deposited at night when the temperatures are low, and this keeps the indoors comfortably warm [47][75].

PCMs may be incorporated into:

- Walling gypsum boards
- Concrete roofing tiles
- Insulation panels and bricks
- Prefabricated modules come in panels.

Benefits

- Decrease in temperature fluctuations indoors.
- Better thermal lag effect.
- Increased comfort of the passive design.
- It applies to new and retrofit projects.

Limitations

- Needs thermal modeling to be correct
- PCM leakage or degradation possibilities
- Incompatibility with certain conventional materials

3.3. Use in HVAC Systems

The greatest energy usage in most buildings is by the heating, ventilation, and air conditioning (HVAC) systems. Incorporation of PCMs in such systems can greatly enhance energy storage capacities and the flexibility of such systems [2][76]. It is possible to install PCMs in AHUs to charge during off-peak time and discharge during peak periods. This feature of load shifting results in smoothing out the energy demand and lowering the operation costs [77].

Duct Systems and Ventilation Units PCM

- Ducts, PCM-lined ducts can pre-cool or pre-heat air.
- Enhance the stability of indoor air temperature.
- Limit compressors' on-off cycling.

PCM-based Thermal Energy Storage (TES)-

Thermal energy storage systems with PCMs enable HVAC systems to save surplus cooling or heating energy during the time when the demand is minimal and utilize it in the peak hours. It is especially efficient in the district cooling systems, Inayat and Raza (2019) examined [17][78].

Advantages

- Reduces energy use to off-peak times.
- Increases the responsiveness of the system.
- Ease pressures on the grid.
- Reduces carbon emissions

Integration Strategies

- Hybrid systems with PCM and PV panels.
- IoT and smart controls to manage PCM effectively.
- Demand prediction algorithms are AI-based.

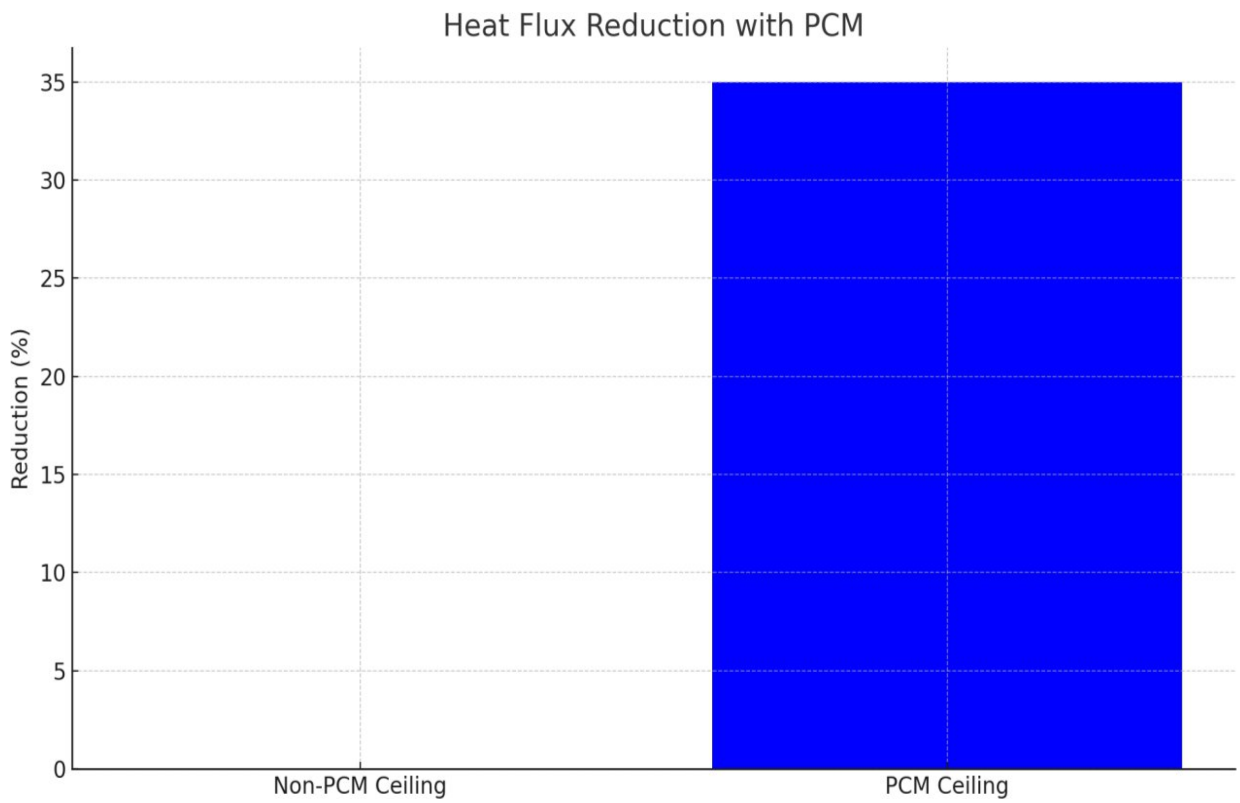

Fig 7: Showing heat flux reduction with PCM

Illustrates how PCM usage decreases heat flux through building elements, improving thermal resistance.

3.4. Energy savings and thermal comfort Performance

There are improvements in performance in relation to thermal comfort and energy savings.

The embedding of PCMs into the different parts of buildings leads to a significant increase in performance [79][80].

Comfort of Thermal

PCMs equalize the temperatures indoors by regulating heat gains and losses. The result is a higher level of comfort experienced by occupants without the need to often intervene with the HVAC. This advantage was mentioned by Jouhara et al. (2020) in the review of latent heat storage technologies [81].

Energy-efficiency

- Reduction of energy consumption by 40 percent in optimized buildings.
- Less demand peaks and HVAC running time.
- Enhanced building energy performance rating.

Environmental effects

- Reduced emissions of greenhouse gases.
- Less dependence on energy sources that are based on fossil fuels.
- It has a contribution towards green building certifications such as LEED and IGBC.

PCMs look like the hope of attaining sustainable and energy-efficient buildings. Their uses in ceiling cooling, building envelope, and HVAC systems have great potential to consume less energy and enhance cooling comfort [34][36]. Although issues concerning cost, integration, and control still exist, further research and technology developments are progressively making PCMs more expedient and successful in practice. Properly standardized, equipped with smart control systems and favorable policy frameworks, PCMs have the potential to become a mainstream element of contemporary building technologies [77][82].

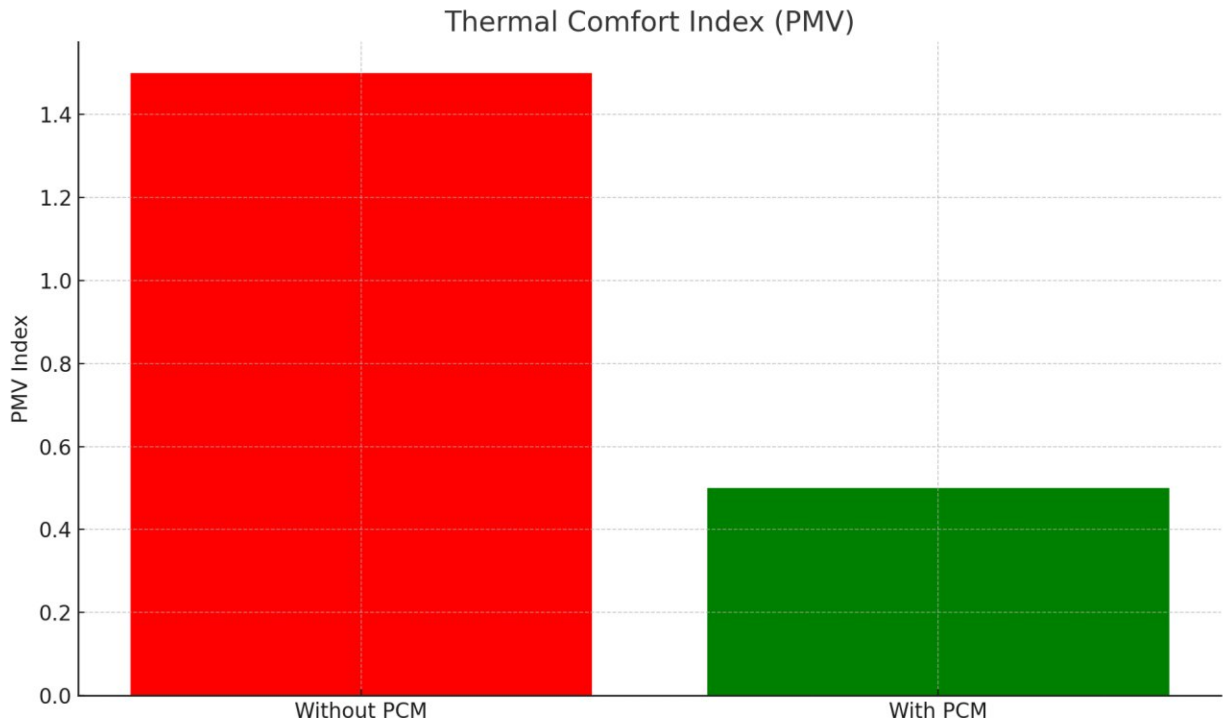

Fig 8: Showing thermal comfort index

Shows the improvement in indoor thermal comfort levels due to PCM application, measured by comfort indices.

3.5. Advantages of PCMs Cooling Ceiling System

PCMs Radiant cooling ceilings are a synergistic approach to current building energy management. The advantages can be listed as:

Thermal Storage Enhancement: PCMs add thermal inertia to ceiling panels that can be used to store unwanted indoor heat during periods of peak heating demand and then release it during off-peak periods. This thermal buffer works to levitate the indoor temperature profile, making the thermal comfort constant [34].

Passive Shifting of Load**:** Not only does this lessen the need to use energy at times of high tariffs, but it also decreases the load on the electrical network [14].

Optimization of HVAC System: PCM use can also result in the downsizing of HVAC systems as well as HVAC system run time, and this can mean a cut in capital and operations costs. It also prolongs the lifetime of mechanical parts as it makes them use less often [2].

Energy Savings and Operational Efficiency: Various research studies have calculated a 20-30 percent saving of energy in the case of the use of PCMs in cooling ceiling systems. Those savings are directly convertible to a reduction of operational costs and better building performance ratings [6][7].

Architectural Flexibility: The PCMs can be embedded in the normal ceiling tiles or panels, and because of this, their incorporation does not interfere with the architectural appearance. They may be applied to different types of buildings- residential, commercial, and institutional buildings [83].

Noise and Draft Free: Unlike the traditional air conditioning systems, radiant cooling ceiling operates in silence and without drafts, thereby improving the indoor environmental quality.

Chapter-4

Conclusions

The incorporation of Phase Change Materials (PCMs) into the building systems and specifically cooling ceilings has emerged as a revolutionary solution in the realization of energy-efficient buildings and comfortable buildings in relation to temperature. In this review, many features of PCMs, such as the types, encapsulation methods, integration methods, literature review, applications, and the general performance advantages, have been discussed intensively. It has concentrated on showing how PCMs have the potential to be involved in designing low-energy buildings, especially within passive and hybrid cooling systems. The final section summarizes the knowledge acquired in this review, identifies the particular advantages of PCMs in cooling ceiling systems.

As a result of the general investigation of literature and technological processes, it is possible to underline some important points:

Regulation Performance of Thermal: This capacity to store and give up large quantities of thermal energy in the process of phase transitions has allowed buildings to keep a comfortable interior climate without the need for regular mechanical heating or cooling interventions.

Efficiency Enhancements of Energy: Research results have cited cooling energy savings in the range of 15-40 percent, again depending upon climate, PCM, and building design.

Cooling ceilings as a Featured Application: PCM-embedded radiant cooling ceilings are one of several application areas that have demonstrated particular potential. As shown in experimental research and some studies by Mousavi et al. (2022, 2023), cooling ceilings with PCMs can substantially limit the peak cooling demand and improve thermal comfort by keeping surface and indoor temperatures at acceptable levels.

Cooling Ceilings as a High-Profile Application: Radiant cooling ceilings with PCM embedment have demonstrated particular potential in one of the many areas of application. As shown and proven by experimental investigations conducted by Mousavi et al. (2022, 2023), cooling the ceiling with PCM can notably decrease the peak cooling demand and improve thermal comfort by keeping the surface and indoor temperatures at an acceptable range.

Encapsulation Methods: The more advanced methods of encapsulation, such as microencapsulation, macro-encapsulation, and shape-stabilized PCM composites, are key to realistic applications. These techniques make the storage of PCMs safe, avoid leakage, and increase the thermal conductivity, thereby increasing the overall effectiveness of the system.

Environmental Impact: PCMs can help reduce the emission of greenhouse gases, as they allow decreasing the reliance on traditional air-conditioning systems that are commonly fueled by fossil fuel derivatives.

Retrofitting Potential: PCM technologies have a high potential to be used in retrofitting buildings that are already in existence, and hence make them energy efficient without causing major structural modifications. Such flexibility contributes to the global agenda of sustainable refurbishment and renovation of the built-in environment.

Future Research Needs and Recommendations

Phase Change Materials (PCMs) used to cool buildings and their ability to provide cooling in the future largely rely on standardized testing regulations and an intelligent control combination. Our testing today is not very consistent, and it is hard to tell the durability and real-world performance of PCM in different climates and real-life conditions. Consequently, harmonized international standards, which include lab-to-field comparisons, thermal heat cycle simulations, and accelerated aging, are needed to extrapolate towards long-term behavior [20]. At the same time, adaptive constructs based on predictive modeling, AI, and machine learning must be introduced to optimize the charge-discharge cycle of hybrid HVAC to accommodate various climates and usage patterns [3]. This dynamic control, combined with open-source platforms, would help PCM systems be smarter and more efficient in the domain of residential and commercial buildings. Such initiatives should also be in line with national codes, rating schemes such as LEED, IGBC and policies in financial support in order to promote large-scale implementation [84]. Carbon savings can be presented as incentives, and simulation programs such as Energy Plus and eQuest can have an impact on the regulatory integration [85].

Beyond enhancement at the system level, a widely expanded agenda of demonstrations at the field scale, across different seasons and building types beyond apartments and schools, to low-cost housing, is required to ascertain PCM performance at scale [16][12]. The feedback can be given long-term to report thermal comfort, maintenance, and cost-effectiveness, and fill the gap between laboratory results and user satisfaction. They also should conduct life-cycle assessments (LCA) and techno-economic analyses (TEA) to determine what the economy will gain by investing in it, what will be saved in terms of emissions of $CO2$, and what sort of impact production and disposal will have on the environment [38]. A greater emphasis should be laid on the affordability and local flexibility to design in developing parts of the world without much of power reliability and heat loads. Climate-resilient and sustainable infrastructure can be achieved through locally sourced bio-based PCMs, cost-efficient packaging, and NGO-led housing projects fulfilling the needs of the region [28]. All these steps will combine to make PCMs a mainstream product in energy-efficient architectures globally.

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