Al-Rafidain Journal of Engineering Sciences

Journal homepage https://rjes.iq/index.php/rjes

ISSN 3005-3153 (Online)

Phase Change Materials in Cooling Systems: A Sustainable Approach to Thermal Management

Hussein Jassim Akeiber

Iraqi Police College, Iraqi Ministry of Interior, Baghdad, Iraq

ARTICLE INFO

Article history:
Received 11 February 2025
Revised 13 February 2025
Accepted 03 March 2025
Available online 04 March 2025

Keywords:
Phase Change Materials (PCMs)
Active Cooling Systems
Nano-Enhanced PCMs
Building Energy Efficiency
Renewable Energy Storage

ABSTRACT

Recently, energy efficient solutions to conventional cooling methods were provided by the utilization of Phase Change Materials (PCMs). PCMs exploit the latent heat properties to absorb and release thermal energy during phase transitions, thus being good heat affecters in terms of temperature control in numerous applications. This paper investigates the possible integration of PCMs in cooling systems that have the potential to reduce energy consumption in buildings, electronic devices, and industrial process, as well as increase heat storage energy and reduce temperature fluctuation. A range of types of PCMs, including organic, inorganic, and eutectic, is explored with regard to their thermal properties, their advantages, and their challenges in applied systems. In this study, the principles of thermal management in regard to PCM, conduction, convection, and radiation mechanisms that determine the performance of PCM are elaborated. Discussion of the benefits of PCMs in active and passive cooling systems are provided, and attention is placed on reducing the reliance on mechanical cooling and on reducing carbon footprints. Low thermal conductivity, stability concerns and cost implications of a PCM are analyzed, an introduction to new solutions like nano enhanced PCMs and composite materials, is provided. Examples of PCM application in building cooling, battery thermal management and electronic cooling show huge efficiency improvement, especially in operations. Research directions for future are suggested to be advances in material science, machine learning based optimization, and the hybrid cooling technologies to achieve better performance of PCM. Proper addressing of existing limitations and utilizing innovative engineering strategies, PCMs can make a significant contribution to energy efficient cooling solutions in realizing global sustainability goals, and mitigation of climate change.

1. Introduction

1.1. Definition and Characteristics of Phase Change Materials

Phase Change Materials (PCMs) are special substances that accumulate and also discharge considerable thermal power whilst in transition from solid to liquid state. At some temperatures known as phase-change temperatures, such materials exchange energy and store or release latent heat with little change in temperature. For example, when a solid PCM goes above its melting point, it absorbs heat and becomes liquid; in other words, latent heat. On the other hand, temperature drop causes the PCM to solidify and transfer back the stored heat to the environment surrounding the PCM.

The main advantage of PCMs is their very high latent heat capacity compared to other inherent sensible heat storage materials. Unlike sensible heat storage, where you heat water, PCM storage does not involve temperature changes during energy retention (since it will be something near constant as it transitions between phases). Their unique feature has high

Corresponding author E-mail address: Husseinutm@gmail.com
https://doi.org/10.61268/4jmhc658

usefulness in applications where stability in temperature is required.

Organic materials (paraffin waxes, fatty acids etc), inorganic materials (salt hydrates etc) and eutectic mixtures of one of the two types can be classified into 3 main groups of PCMs. The thermal properties, stability, and non toxic nature make organic PCM to be often preferred for applications. Meanwhile, latent heat capacities and thermal conductivity in salt hydrates may be higher, yet they can suffer problems such as supercooling and long term stability.

Performance of PCM depends on several critical factors, which include latent heat capacity, thermal conductivity, specific heat capacity, freezing and melting points, long term stability, cost effectiveness and also include considerations of safety such as flammability and toxicity. These materials have a large latent heat capacity that results in them having large energy storing capacity in small volume space, which is very useful in applications where space is limited such as in climate control systems.

PCM’s also has a very important property that is the thermal conductivity, as it controls how quickly the PCM can absorb or release energy during its phase changes. Fast charging and discharging rates of stored thermal energy result from improved thermal conductivity are key to increasing system efficiency in cooling applications. The thermal conductivity of organic PCMs has been enhanced by encapsulating PCMs inside metallic foams or with the use of nanoparticles.

PCMs are integrated into building element such as drywall or insulating panels to maintain well indoor comfort levels in practical applications, typically within building cooling systems. The use of PCMs would help occupants keep their home temperatures more stable from day to day, and from one season to the next, while significantly reducing their dependence on the heating and cooling requirements by HVAC systems.

In addition to optimizing energy consumption use, PCMs also assist in achieving sustainability goals by substituting conventional mechanical cooling approaches that draw power; especially when they are large. PCM implementation helps enhance the usage of PCM across various sectors such as residential buildings, commercial spaces, electronic device cooling solutions and refrigerators, to mitigate carbon footprints associated with the use of the traditional cooling technologies.

However, it is challenging to real world applications with PCMs. One disadvantage of organic phase change materials is that their low thermal conductivity makes them less conductive and is reflected in longer times needed to reach a desired temperature change reaction. Moreover, the implementation of large scale would have financial factors that might hinder the acceptance in a broader level, especially on long-term benefits against the investments required.

These PCM properties need to be improved by innovations such as hybrid systems integrating existing technologies like thermoelectric devices or advanced composites to maximize Performance yet address existing limitations.

In a modern era of engineering that strives to develop sustainable solutions for thermal management through all branches of industries, including construction and electronics, one must have a comprehensive knowledge about phase change materials. As the advancements in material science aim to increase the efficiency and diminish the impact on the environment, a great benefit in already existent strong global focus on sustainable practices [1], [2], [3], [4], [5], [6], and [7].

1.2. Importance of Thermal Management in Mechanical Engineering

Effective thermal management is very important in the field of mechanical engineering since these systems can be adversely affected by temperature changes, and need to ensure that these systems can operate in a safe and effective way. As high performance devices and systems such as lithium ion batteries, electronic equipment and even advanced cooling technologies grow in their use, the role of skilled thermal management becomes more and more critical. Thermal management has notably received growing attention, particularly as the energy consumption savings afforded by energy efficient solutions become now increasingly sought in military, consumer and large industrial applications.

The energy efficiency aspect of thermal management is one of the most important things. In light of the growing demands for energy, energy reduction strategies aiming to achieve optimal energy consumption and operating temperatures are more critical than ever before. Poor heat management increases energy usage and makes waste heat generation one of the major environmental problems, including greenhouse gas and the climatic changes. What engineers here are doing is using phase change materials (PCMs) to convert cooling systems into storage systems for thermal energy during off peak hours, but releasing it when needed. Not only does this capability make energy more efficient, but it also decreases power demands from reliance on traditional cooling that is notoriously power hungry.

Additionally, heating the system is to be done properly, which enhances the reliability and longevity of the system. Components are subjected to improper temperature levels and therefore prone to early degradation or performance loss by material deterioration. For example, uncontrolled temperature rise in electronic devices can result in circuit failures, and reduce the service life of the equipment; therefore, we need to keep electrical equipment at optimal temperature range by implementing efficient thermal management techniques. The advantage of PCMs is in the fact, that they stabilize temperature changes: they absorb heat during power peaks and release it during temperature drops, but without additional external energy use. A natural function helps components and increases the lifespan of mechanical systems as a whole.

Robust thermal management solutions are further required for the growth of renewable energy technologies. Indeed, as societies shift away from dirty energy sources, thermal storage is becoming foundational in matching supply with the unpredictable patterns of demand of these technologies: solar and wind. In this capacity, PCMs function as buffers that can store surplus energy produced when output is above demand during peak production times for later use when output cannot meet demand. This feature not only improves the reliability of renewable energy sources, but also helps to stabilize the grid by keeping the power continuously supplied to it at an even level.

In addition, machine learning is becoming a critical element of developing thermal management ways for different sectors of mechanical engineering. Data obtained from operational conditions can be fed into machine learning algorithms in order for them to adjust dynamically the cooling strategies according to real time requirements and not to static parameters fixed at the design stage. Such intelligent control systems allow for more flexible thermal management options, which are able to quickly react to changes in the ambient or operational load conditions, for more sustainable applications in engineering.

The specific use for thermal management systems that take into account the environmental goals of sustainability can also be seen in the construction industry. Based on buildings contributing a large fraction of global energy use where much of that energy is consumed for heating, ventilation and air conditioning (HVAC), and as solutions to save energy and improve comfort, integration of advanced materials as if PCMs provide a significant opportunity to reduce total energy use. Architects and engineers can use PCMs in building designs or in HVAC systems to make structures that keep environments comfortable without putting heavy stress on the power grid.

Besides these benefits regarding the mechanical operations and efficiencies, the thermal management is also very important in many industries for safety. Accidents or catastrophic failures that occur due to the uncontrolled heating of hazardous materials or processes, which are sensitive to temperature changes (e.g. battery technology or chemical manufacturing), are not just an issue; they are necessary caused by the absence of precise control over the temperature profiles.

Ultimately, recognizing the importance of comprehensive thermal management principles establishes the foundation upon which future innovations can be built within mechanical engineering domains. Advancements like PCMs represent ongoing efforts aimed at maximizing performance while closely aligning with broader sustainability objectives geared towards environmental stewardship amid escalating global challenges associated with climate change, [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], and [22].

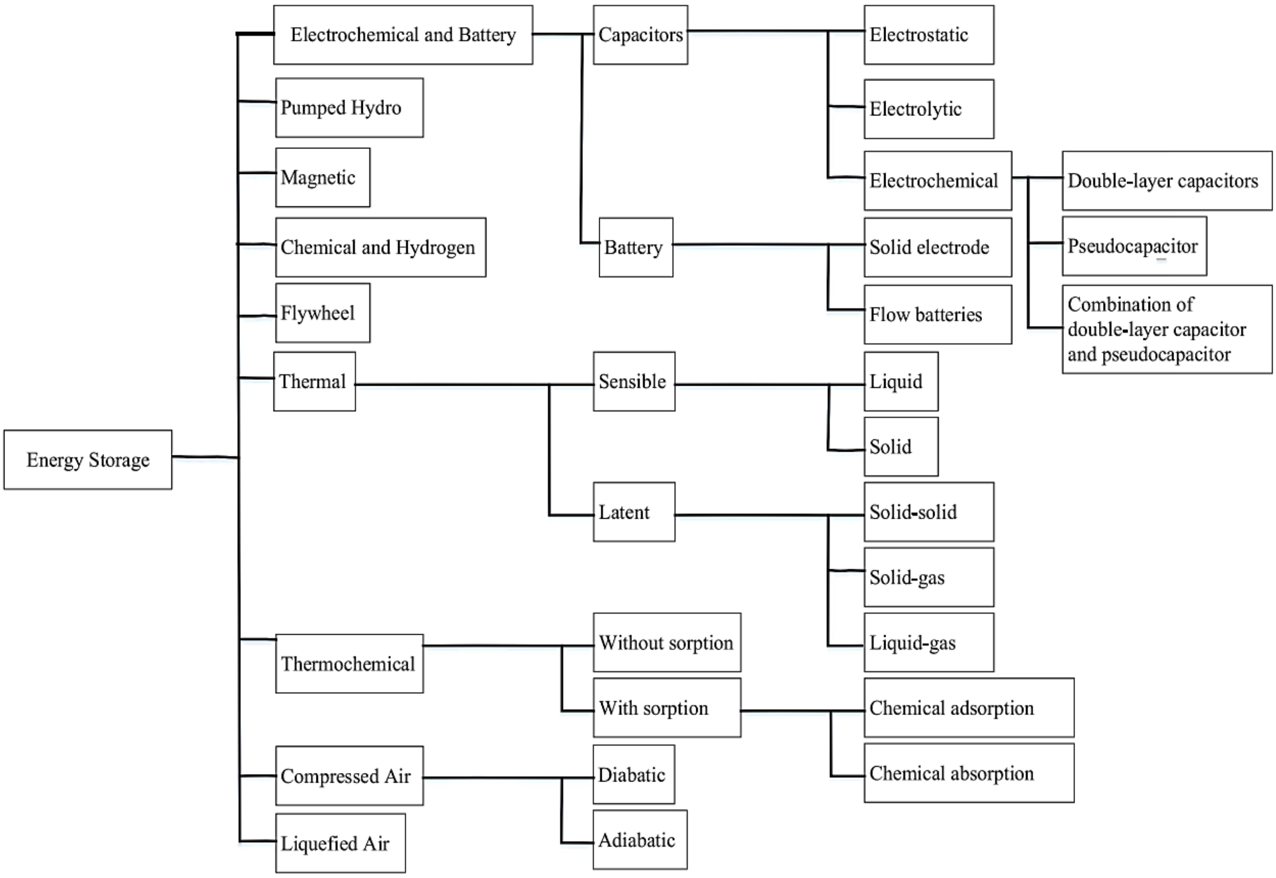

Figure 1: A classification of energy storage types, [11].

2. Principles of Thermal Management

2.1. Heat Transfer Mechanisms

2.1.1. Conduction

Heat conduction plays an important role in heat transfer and has an important effect on the performance of phase change materials (PCMs) in cooling system. The process of thermal energy transportation from hotter to cooler areas presented is a molecular and atomic interaction and vibration in solid structure.

Depending on thermal conductivity, specific heat capacity and latent heat, the efficiency of conduction in PCMs is determined. Therefore, thermal conductivity plays an important role in determining how quickly heat within a PCM moves through during phase changes. However, many traditional PCMs have low thermal conductivity that influences their effectiveness in rapid cooling applications. Technologies that store substantial latent heat include paraffins and salt hydrates but, if their conductivity is not improved, they are unlikely to dissipate or absorb heat adequately.

Improving the cooling performance of PCMs requires them to enhance the thermal conductivity. There are various methods engineered to increase conduction rates. The way to improve the effective thermal conductivity for PCM composites is to add the conductive fillers like aluminum foams and graphite, which can substantially increase the effective thermal conductivity. For instance, the presence of aluminum foam creates a network that improves the thermal pathways from one PCM particle to the other thereby accelerating melting and subsequent solidification during operation. Results from such research indicate that the combination of aluminum foams and high melting point salts (NaCl and KNO3) leads to higher energy storage efficiency and system responsiveness.

The second strategy to enhance heat transfer is to embed nanoparticles or nanostructure into the PCM matrix. The metallic nanoparticles such as copper or silver suffer high thermal conductivities, which could be combined with the PCM to strengthen the heat conduction performance of the hybrid material. In addition to increasing conduction rates, it increases mechanical stability under displaced operational conditions.

In phase change transitions, the material passes through solid to liquid or liquid to solid with absorption or release of latent heat, without large temperature changes. One characteristic of PCMs that makes them favorable for maintaining stable temperatures in cooling applications is that they can be used to absorb a great deal of energy during melting while staying at a constant temperature until fully transitioned.

Convection currents caused by density changes due to temperature fluctuations occur as a challenge during solidification but conduction is the predominant mechanism until the PCM totally reverts to its solid state. Engineers have designed fins to assist in conductive pathways in the PCM containers to give engineers more control of these processes. Embodiments of fins increase surface area contact with both phases and allow for optimized energy transfer through convection channel, when needed, during heating and cooling cycles. Fin designs that are well designed can dramatically reduce melt times from those systems without such fins.

High transient loads and practical applications make effective conduction crucial, in particular, for electronic systems or battery management systems (BMS). In devices in which PCM technology is used for thermal regulation, operational integrity is dependent upon optimal design considerations.

The role of computational simulations in examining heat conduction through different cooling systems with complex PCM geometries has recently been stressed. The passive systems are free convection, natural airflow types, while the active deals with the forced convection techniques with pumps that circulate specially engineered coolants to optimize performance in specific configurations.

Research ongoing is attempting to combine empirical validation with numerical analysis in order to understand what changes input variables have on output, e.g. peak temperature reduction under dynamic load. Such insights enable the development of future innovations to address the integration of various phase change techniques with standard conductive cooling systems in industrial chillers with sustainability features that aim to minimize energy consumption, and lessen the environmental effects that are relevant to ordinary course cooling actions.

The development of adaptive solutions to meet demands that change with technological trends represents an exhilarating frontier in thermal engineering, where the advancement of conduction efficiency in phase change materials through novel composite designs with state-of-the-art fillers enables the design of such solutions. This investment in terms of sustainability in line with the global developments of reducing carbon footprints and improving safety standards across the industries practicing thermal management strategies [5], [6], [11] as well as [23].

2.1.2. Convection

A major mode of heat transfer, convection, and plays an important role in both the operation of such phase change material (PCM) based cooling systems. There are two main types of what is known as this process that can be broken down into natural convection and forced convection. However, there are different implications for thermal management based on different principles and principles of operation for each type.

This natural convection occurs due to temperature and density differences in a fluid thereby causing fluid parcels to move on their own. Buoyancy induced flow occurs due to thermal gradients arises in PCM when it changes from solid to liquid or perhaps vice versa. In PCMs used in such systems, melting and solidification rates can be greatly influenced by this convection. To provide an example, as a PCM melts the less dense liquid will rise, and denser solid will sink. This movement improves heat transfer by bringing warmer areas to acquire the ambient cooler fluid around the PCM so that they can have main temperature distribution uniformly.

Design innovations, such as fins or structured geometries, also lead to increased thermal performance due to their effect on improving natural convection. Fins placed in a PCM storage unit increase the surface area that makes contact on the PCM and the heat transfer fluid (HTF), leading to more efficient convective heat transfer. As many studies exploring different fin arrangement, ones in which fins are put at a certain angle or length give notable improvements to melting rates. Fins are included in order to enlarge the surface area as well as influence the flow to better dynamics around the PCM increasing the overall energy absorption efficiency.

On the other hand, forced convection relies on external mechanisms, e.g. fans, pumps to push the fluid over the surfaces that control temperature. Reliable operation of this method is demonstrated in cooling systems using rapidly moving large volumes of fluid and combined with PCMs, it proves to have significant advantages in thermal management. Researchers have previously investigated different configurations for forced convection with PCMs in order to optimize airflow paths and velocities for highest exchange effectiveness among others.

Miss the benefits of forced convection as compared to natural convection – the latter being dependent upon temperature differences and buoyancy forces – forced convection allows for finer control on the heat transfer rates, independent of surrounding conditions. These studies for example demonstrate the ability of increasing the airflow velocity to considerably decrease the thermal gradients across battery cells upon operation, vital to parts like thermal management systems of electric vehicle batteries.

One interesting point about combining PCMs in forced convective systems is that they have synergistic properties. PCMs absorb large amount of energy stored in phase change cycles over small temperature fluctuations (stabilization), but usually possess low thermal conductivity that preludes fast heat transfer during charging or discharging phases. This limitation is addressed by the incorporation of forced convection to enhance transfer of energy to or from the PCM much more efficiently than conduction can alone.

In addition, hybrid designs that utilize natural and forced convective methods may be employed for maximizing heat transfer in such a variety of applications as cooling electronics and residential HVAC systems employing PV layered PCM systems for enhanced efficiency during peak loads.

To design an effective cooling system incorporating PCM, it is important to understand Nusselt number correlations of natural and forced convective scope. The Nusselt number represents the capability of convection compared to the pure conduction and is therefore a good indicator for performance evaluation under different operating conditions, for example for Reynolds numbers corresponding to laminar versus turbulent flows.

In summary, both convection modes have an important role in the cooling applications with phase change materials, but they have different regime and each has pros for a range of applications. This also includes scalability in terms of limiting spatial dimensions versus respective response times during transients occurring for the dynamic loads present in these systems.

Further research is necessary to further improve hybrid approaches that together with traditional HTFs incorporate nanofluids, that will be benchmarked over time against such objectives based on rigorous empirical data collected from a wide range of operational environments with which industries are currently dealing with contemporary cooling tasks they face, [5], [24], [21] and [25].

2.1.3. Radiation

Radiation is an important heat transfer mechanism used in thermal management system (TMS) particularly for cooling applications of phase change materials (PCMs). Unlike conduction and convection, the method by which radiation conducts heat is unique: radiation transfers heat by means of electromagnetic waves (waves seen by the human eye). It works irrespective of the medium since it does not depend on anything. Thermal radiation generally lies within the spectrum of from a few tenths to a few hundred micrometers, that is, in the infrared. Therefore, the knowledge of the principles of radiation is crucial for improving the cooling system performance based PCM.

Radiative heat transfer can lead to significantly lower efficiency of PCMs when they are considered for use in cooling systems. The ability of a material to absorb and emit thermal radiation depends upon the surface and absolute temperature of the material. As the materials are more effective at dissipating heat from surfaces, they are easier to keep these surfaces at lower temperatures in different situations. For instance, emissivity of a common construction material varies from 0 (perfect reflector) to 1 (perfect emitter) and thus, can influence the performance of the radiative cooling strategies.

In PCMs enhanced cooling systems, when a PCM used to absorb energy from solid to liquid, it will use some heat transfer mechanisms that will help to remove the excess thermal energy efficiently. At night or during lower times of the day when the ambient temperature drops and the surroundings eventually come to thermal equilibrium, radiative heat loss becomes quite important. PCMs can help keep the buildings thermally balanced without counting on additional energy input if they can be optimized to radiate stored heat at night.

The surfaces designed for optimal radiative cooling often pick particular coating materials or finishes that enhance the emissive properties and decrease reflectance. The research has shown that using coatings with high emissivity can make the overall system more effective due to greater thermal exchange through radiation.

Furthermore, knowledge regarding how photovoltaic panels coupled with PCMs interact with solar radiation during the daylight will also help in developing such proactive strategies. Solar panels do transfer sunlight into electricity, yet at the same time, they produce excess heat that needs to be closely handled. However, by including PCMs, the overheating is prevented as the excess heat is absorbed by the PCMs during the peak sunlight periods and utilized when needed, during peak energy demand times or when ambient temperatures drop at night.

It has been shown that further refinements to the advantages of radiative cooling are possible in environments of high solar gain when reflector surfaces are combined with high emissivity materials. Reflective surfaces, which aid in reducing the total absorbed solar energy and as a result increase the possibility of emitting thermal radiation from PCMs into the surrounding environment.

Additionally, the researchers are also trying to develop innovative ways to boost radiative efficiency with nanomaterials and sophisticated coatings for different thermal management issues in different applications ranging from cooling electronics to regulating temperatures of buildings.

Passive designs that involve PCMs coupled with active ones employing effective radiation principles have produced promising results for a number of sectors. For instance, inventive ventilation designs utilizing natural airflow along with the PCM properties can decrease reliance on traditional mechanical cooling approach.

However, there are still challenges related to material stability in terms of varying operational conditions and exposure given continued heating and cooling cycles of PCMs. Since material durability and therefore their radiant properties change with time, researchers seek to develop formulations or composites specifically engineered to be more resilient to changing with time (i.e., longer lasting) while still performing as expected under operating stress.

Advancements in understanding heating and cooling dynamics through radiative mechanisms significantly enhance both existing systems and new designs employing phase change materials as viable solutions for future sustainable practices across various sectors. From residential air conditioning options exploring passive strategies to commercial applications requiring robust management frameworks capable of responding dynamically to real-time environmental conditions, [11], [12], [15], [16], [26], and [27].

3. Overview of Cooling Systems

3.1. Types of Cooling Systems Used in Industry

3.1.1. Active Cooling Systems

In many applications where heat generation can be significant, heat in such systems is actively cooled. Mechanical components such as pumps, fans and chillers are used in these systems to transfer heat away from the sources. Liquid cooling has outstanding thermally compared to active cooling, as air-based systems.

Based on two primary categories, liquid cooling techniques are direct and indirect. In the direct cooling, components are immersed into coolant that takes heat directly in order to get effective heat dissipation with lowest thermal resistance as well as the quickening temperature. Coolant selection is important; usually, water or specially developed oils are used which have to have high thermal conductivity, low viscosity and stability under operational conditions.

Indirect cooling systems instead use their coolant, which is circulated through a closed loop system without direct contact, and the heat is transported. Thus, for instance, liquid can flow over cold plates or through channels next to heated parts. As can be seen, this method of improving heat transfer efficiency most commonly includes design modifications — such as higher surface area or multiple flow pathways.

Integrating Phase Change Materials (PCMs) into liquid cooled systems constitutes a notable advancement in the applied active cooling strategies. Although hybrid systems involving liquid cooling and PCMs have demonstrated promising results in improving temperature uniformity and thermal management, their thermal analysis is quite complicated. PCMs serve as thermal buffers; they absorb excess heat at peak loads and dissipate it when the temperature drops, which helps to stabilize temperatures and reduces the energetic demand by allowing components or components to act only at smaller or at less frequents times.

Consequently, research has shown that a hybrid Battery Thermal Management System (BTMS) consisting of a PCM bank along with an active liquid cooling will significantly reduce battery module temperatures during high discharge yet prevent bang as if temperature drops in colder climates. PCM integrated cooling plates provide innovative designs that improve the thermal performance while maintaining weight and volume.

Active liquid cooled BTMS have found applications in industries such as electric vehicles (EVs) which opportunistically use lithium ion batteries for the purpose behind high power load inserts and effectively manage the elevated temperature generated by the bibliography battery. Some applications may be able to use conventional air-cooling methods, but these methods are generally unable to meet the high performance requirements of today’s modern EVs, and especially when rapid temperature fluctuations are present, that can hurt the battery and reduce efficiency.

Despite these liquid cooled BTMS, engineers are working on refining these cold plates by refining the thermal conductivity of the materials, as well as fluid dynamics in well-designed channels, to boost the overall system efficiency. Spider web inspired channel designs are presented as creativity leads to more efficient thermal management solution.

Although active cooling technology has numerous benefits, power consumption related to mechanical components, as well as the need for maintenance at some point in time, remains challenging. Furthermore, minimum dependence on external energy sources was confirmed in PCMs with their role in passive elements that contribute to the enhancement of performance and fulfilling sustainability goals by curbing energy demand during peak hours.

Future work on acquiring the final set of hybrid models involves refining them further, optimizing the coolant type, flow rate, and PCM selection criteria for different application specific melting points. In addition, their effectiveness on other cases of interest beyond battery management or HVAC solutions are investigated.

Positive impacts to the active cooling system design are happening now due to the introduction of nano enhanced phase change materials that can greatly improve responsiveness. While keeping the energy consumption very low, which is a critical component of future invention efforts where we are striving to reduce environmental impacts but still generate excellent performance metrics for sectors that need to have excellent levels of thermal management.

Research continues to investigate the best active cooling methodologies and benefits are not only of interest to automotive industries, but also send to cooling data centers, requiring extreme temperature control during the critical tasks. Such an innovation is critical for achieving the correct balance between the operational efficiency and performance, which makes software continual development in this important engineering disciplines imperative, [9], [13], [17], [24], [28].

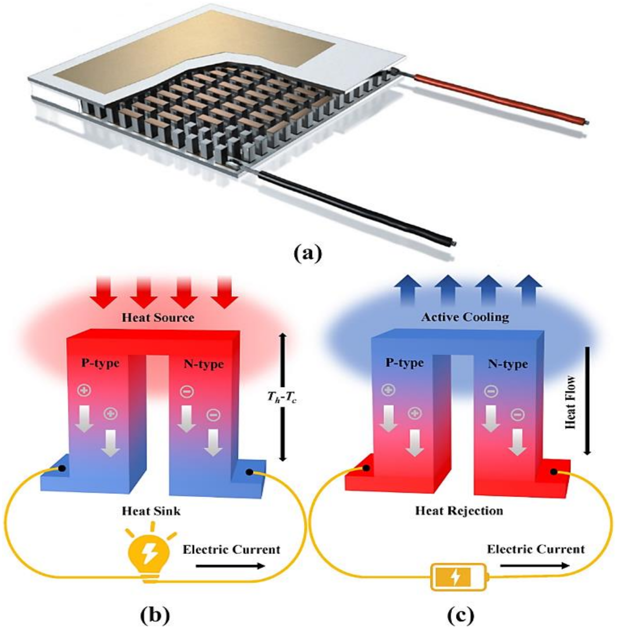

Figure 2: (a) Illustration of TE device; (b) Mechanisms Seebeck effect and (c) Peltier effect, [17].

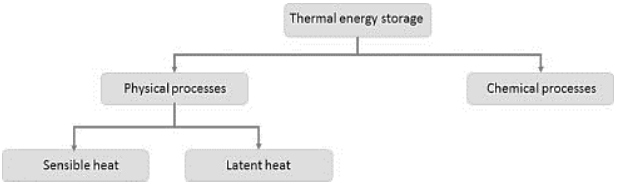

Figure 3: Methods for thermal energy storage, [11].

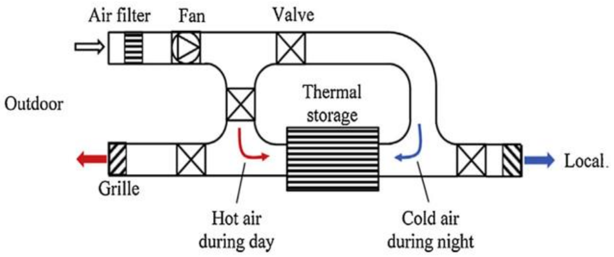

Figure 4: Installation of thermal storage for free cooling reproduced with permission of, Elsevier, 2013, [6].

3.1.2. Passive Cooling Systems

Natural process based passive cooling systems do not use external energy for temperature regulation, so they can be applied to buildings and for electronic thermos. Phase Change Materials (PCMs) play a key role in these systems since they can absorb and release thermal energy during phase transition in order to stabilize temperature fluctuations.

Integration of PCMs into the structure can substantially reduce mechanical cooling requirement in building design. Embedding these materials into walls, roofs, floors and windows offers an opportunity to capture excess heat during daylight hours and release it at night to improve indoor climate control and reduce the energy costs associated with traditional air conditioning. Aspects like climate, the melting point of a particular PCM, and the occupant behavior, affect the performance of passive cooling with PCM.

Results of research have demonstrated that embedding PCMs into wall assemblies can yield significant reduction of indoor temperatures during peak heat periods when the PCMs' melting point is appropriately selected based on local conditions. Through storing the latent heat in these materials, the need for active cooling solutions is reduced, making occupant comfort become even better.

Throughout the encapsulation of PCMs, efficacy in passive cooling is crucial. Since they facilitate integration with several building materials, macro-encapsulation techniques are favored. PCMs can be encapsulated into plasterboards or similar construction materials so they may be employed in modern architecture.

PCMs are also now recognized for their control of heat outside buildings where it is important to control temperature spikes to ensure performance and longevity of electronic devices. PCM based thermal management solutions are excellent for compact electronics that utilize highly dense processing chips such that size and weight remain critical characteristics, which can incur undesired overheating without additional power penalties associated with active cooling strategies such as fans or liquid coolants.

Aspects of the ability of PCMs to absorb substantial heat while being small makes them desirable for compact designs, in particular for portable electronics. According to research, paraffin wax or eutectic alloys can be used as PCMs for those mobile devices to keep them at a stable operating temperature, thus avoiding overheating during high usage.

The performance of conventional PCMs are enhanced with the advancements of PCNCMs. For faster charging and discharging during phase changes, researchers increased thermal conductivity of PCM matrices by adding nanomaterials. In other words, such systems utilize nanocomposite PCMs more efficiently in controlling thermal loads and respond to changing thermal needs more rapidly.

Passive cooling strategies with PCMs are becoming more popular in photovoltaic (PV) applications because they can maintain temperature levels without any additional energy costs demanded by the active cooling methods. By positioning the PCM behind the PV panels where outside airflow is not limited, the PCM can collect the excess heat generated by peak sunlight hours, and is heated gradually as temperatures cool, improving efficiency and extending the life span of the panels.

Indeed, there are still challenges to the practical use of PCMs in passive cooling systems. Organic polymers as additives are not material stable; repeatedly, organic PCMs may degrade or may incur problems with supercooling and thus not work for long periods. Poor integration due to poor contact between PCM materials and substrates can also hinder efficiency since poor integration results in lower heat transfer. Therefore, achieving optimal heat transfer through the PCM materials and substrates is also necessary.

However, cost considerations are important for the large-scale adoption of PCM technologies in the industry. However, while operational savings may be seen through decreased reliance on mechanical cooling, initial material costs are unlikely to encourage widespread implementation, especially for budget sensitive sectors such as residential construction.

Research still continues by refining encapsulation techniques to make encapsulation systems with higher latent heats while limiting degradation for greater adoption beyond present uses in building design and electronic device management. Overall, PCMs based cooling, particularly when combined with other cooling strategies, have a promise in reaching at least partly the sustainability goals and in providing comfort capabilities that take into account the turbulent climate of today, [6] and [9], [11] and [29].

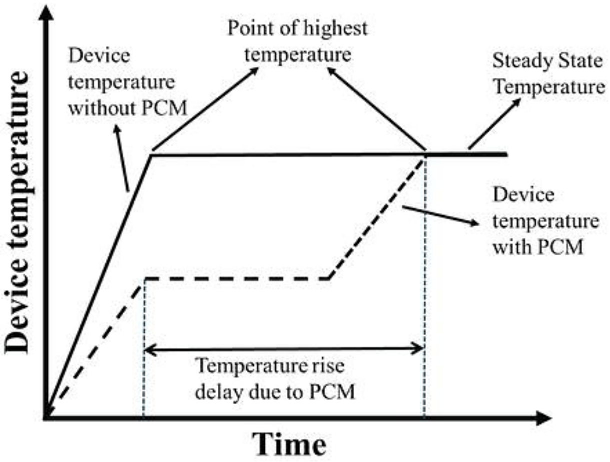

Figure 5: Comparison of temperature response of a heat dissipating system with and without PCM, [9].

4. Integration of Phase Change Materials in Cooling Systems

4.1. Mechanisms for Incorporating PCMs into Existing Systems

A large improvement in thermal management efficiency is achievable through the integration of phase change materials (PCMs) with existing cooling systems. Incorporating PCMs into cooling is a success if all the different mechanisms and strategies can work within the peculiar behaviors of these materials and their particular requirement by the variety of cooling scenarios.

PCMs are within a one foundational strategy of using PCMs within thermal energy storage systems. These systems are created to store, release heat during low demand periods, and shift the peak loads to less peak times. In air conditioning applications, its applicability is particularly good since demand varies through the day. Including PCMs in buildings allows to reduce the overall dependency of buildings from standard cooling means by placement of PCMs (if the volume of the structure is viable) to strategic building parts—ceiling or wall, for example. The choosing of these PCM materials is very dependent on their melting points being close to internal temperature profiles of the Should PCMs be chosen that have melting points near internal temperature profiles of the .

Hybrid cooling systems constitute another promising perspective in PCM integration. Usually classified as active and passive, these configurations utilize a blend between the active and passive approach by utilizing PCM technology merged with water or refrigerants. For instance, the admittance of liquid cooling combined with PCM technology is quick at transferring heat and gives in thermal buffering when there is a high calling for items. During peak operational hours, the PCM helps temper the resulting spikes by absorbing heat and going through phase changes. It not only enhances the efficiency of the entire system but also prolongs equipment life through reduced thermal stress.

For incorporating PCMs into existing systems, another crucial tactic is as improving the thermal conductivity of PCMs. In conventional paraffin based PCMs, the thermal conductivity is widely low; the inconveniences of low thermal conductivity include uneven melting and inadequate heat transfer rates. In order to overcome this issue, researchers are looking into composite phase change materials (CPCMs) consisting of common PCMs with thermally conductive fillers such as expanded graphite or metal foams. These composites are very effective in dissipating heat, maintaining the same behavior at the same and at different operating conditions.

In addition, the use of porous materials has been developed as a potential improvement of CPCMs to maximize the surface area contact between the PCM and its environment (or between different layers in multi-layer systems) for enhancing more efficient heat transfer during phase transitions. For example, nanoparticles have also been found to add substantially, in theory and generally in practice, to thermal properties without negatively affecting mechanical integrity.

Retrofitting buildings with embedded PCM components is an effective strategy to improve energy efficiency in HVAC systems, since the latter is practical for implementation within existing infrastructure. A careful design of these solutions is needed with respect to local placement and orientation within building structures or equipment layouts in order to fulfill minimum safety regulations.

BTMS loads show particularly significant advantage of PCM integration versus primary method cooling resources of air or liquids, due to PCM’s capability to cool without growing actively cooled resources at the same rate as the heat density output. In such cases, the best liquid circulation channel and PCM layers hybrid design is a one that ensures dissipation of excess heat arising during the charging cycle without compromising stable operational temperatures throughout all cells.

In addition, nanotechnology offers great advancement in making next generation PCMs that are specifically tailored for the specialized use in plethora of industries ranging from automotive to electronics manufacturing. They include not only the quest for better material properties but also ‘green’ approaches to enable environmentally friendly materials that comply with stringent sustainability goals and at the same time are able to match performance levels.

Passive systems with phase change technologies offer convenience of less maintenance than their active counterparts, which require pumps or fans (thus having associated with little cost linked to the collimate controls directly) in industrial environment.

The synergy with such advanced components as the heat pipe further extends the potential application scope of PCMs into further enhanced latent heat storage while simplified system architecture through integrated solutions which are adaptable for various scales from compact electronic devices to extremely large commercial buildings. Which require robust climate control efforts of which solar heat gain optimization strategies through smart material integration techniques are an important subset.

The need for incorporation of PCs calls for a multidisciplinary engineering approach that incorporates both mechanical engineering and innovative materials science techniques to maximize output and minimize input demands across a wide range of heating and cooling contexts. Tasks that lie at the forefront as industry strives to find sustainable alternatives among increased environmental awareness worldwide, [2], [3], [6], [8], [12], [13], [23], [24] and [28].

4.2. Comparisons with Traditional Coolants and Methods

Phase change materials (PCMs) can be utilized as a transformational approach to cooling systems as opposed to conventional cooling methods. Specifically, each conventional technique, such as air cooling, liquid cooling and hybrid systems have some advantages and disadvantages. Compared to air-cooling, which is simple and cost effective, air-cooling’s heat dissipation is poor since air has low thermal diffusivity and hence air proves to have uneven temperature distribution in battery packs. Thermal management is better in liquid cooling due to its higher specific heat capacity and thermal conductivity.

The direct and indirect liquid cooling systems can be classified. Thus, direct liquid cooling enables the coolant to deposit close to battery cells thus, improving heat transfer by convection. Nevertheless, this method relies on very strict sealing to avoid leaks that could lead to short circuits. The use of indirect cooling introduces more thermal resistance from avoiding direct contact.

PCMs present distinct advantages over conventional coolants by being able to absorb large quantities of heat during phase transition without the need for external energy for processes that may be associated with fluid pumping. The second property of PCMs that make them attractive is that they permit passive stability of temperatures for long durations. For applications like electric vehicle (EV) batteries, it means better efficiency for an electric vehicle (EV) battery that is able to operate within optimal temperature ranges without the need for continuous energy input for active cooling.

The performance of PCMs, when compared to traditional air and liquid cooling systems, in terms of efficiency and cost effectiveness need be assessed in the light of both thermal storage capabilities and operational conditions. Effective solutions that exploit strengths of both technologies include hybrid systems incorporating PCMs with other methods.

Significantly, more performance metrics are enhanced in hybrid PCM-liquid cooling systems than are afforded by using either method alone. Enabling better use of peak thermal loads and temperature fluctuations of batteries or other components, these systems combine high conductive liquids with the latent heat properties of PCMs. Not only does this enhance reliability, it also extends the life of components by dealing a blow to overheating risks, key considerations for high-density applications like EV batteries.

Furthermore, even with initially greater costs for such advanced materials, PCMs are long term cost effective, especially in hybrid configuration when integrated with nano enhanced phase change materials (NEPCMs). Conductive additives of carbon fibers or metal particles are used to address low thermal conductivity common with traditional paraffin-based PCMs, but improve conductivity overall.

In addition to this, passive nature of PCMs extracts it from the constant adjustment of coolant options that require the flow rates to continuously change, to be adjusted as per real time demands, making the operation easy to handle.

Though it is clear that incorporating PCMs in modern thermal management methods presents many benefits, there are also challenges such as the stability of the material through extended use time and potential volume changes based on phase transition that may require unconventional containment ideas.

As sustainability and environmental impact become more important, paraffin based or composite PCMs are an ideal solution in terms of being green in nature and are efficient in meeting energy needs, which is of the utmost importance given the impact that global warming is making on building consumption of energy.

Finally, though innovative phase change technologies are adopted, traditional coolants offer immediate results from continuous energy inputs and are a good example of adaptability and foresight for dealing with the demand of sophisticated battery management systems of the future. The latest PCBIM research is increasingly applicable to various application areas including industrial, automotive, residential, [2], [8], [13], [23], [28], [30], [31], and [32] that demonstrate that advancements in PCM research can drastically affect the designs of the next generation, which focus primarily on efficiency and sustainability in the thermoregulatory procedures.

Table 1: Existing BTMS technologies, [13].

Cooling Method	Advantages	Limitations
Air cooling	1. Relatively simple structure, low cost and lightweight.	1. Low heat conduction coefficient of the air, smaller that the heat capacity and weak temperature control capacity under high magnification. The battery pack temperature uniformity is not too good.
	2. The design is easy to realize and adaptable.	2. The active cooling method is capable of satisfying the heat management requirements, but the power consumption is greater, the space needed for the system is larger, and the energy density of the battery pack is in general lower.
		3. However, there is relatively small potential for improvement and there is economically low temperature control limit. Basically, it is suitable for battery packs with small energy density and low charging rates.
Liquid cooling (indirect)	1. Cooling is normally better for the same power consumption because liquids have a specific heat capacity and thermal conductivity normally higher than that of air.	1. It has more complex system structure, larger overall weight and higher cost.
	2. Coolant flow, channel design, and material properties help to improve coolant effectiveness very effectively. The amount of improvement is potentially high.	2. To prevent leakage and short circuit between the battery cell and coolant, the coolant must be in indirect contact with battery cell and increases the thermal resistance than that of the cooling effect.
	3. Usually, the ducts or cooling plates in contact with the cell side provide better temperature uniformity.	3. For this case, the thermal conductivity of the pipeline or the cooling plate is large, so that it is not conducive to suppressing the thermal runaway of the battery pack.
Liquid cooling (direct)	1. Simple and compact structure, lightweight and low cost.	1. Conductive media cannot penetrate into the system for higher sealing requirements of the battery pack.
	2. Greater convection heat transfer and further cooled effect are realized due to direct contact of the coolant with battery cells.	2. The coolant needs to be driven and the temperature of it reduced often with pumps and cooling systems.
	3. Short circuits can be avoided and	

	thermal runaway spread can be inhibited if the coolant is used as a medium.	
Phase change material (PCM) cooling	1. Without extra cooling system, PCM can absorb heat and reduce cooling down.	1. Increase in the potential for leakage is because the volume of the PCM usually changes greatly after a phase change.
	2. Both the shape of PCM is easy to change, the system arrangement is simple, and the temperature uniformity is better.	2. The thermal conductivity of most PCMs is low and they are insensitive to temperature changes.
	3. In PCM, insulation resistivity is usually good, and it can be used as insulation material to decrease the short circuit risk.	3. For the case of continuous circulation, cooling effect will be lowered, and an additional cooling system is required to take away the heat absorbed by the PCM.
Heat pipe cooling	1. Excellent thermal conductivity, a wide range of applications. Although sensitive to temperature changes, it is able to use temperature changes to control the temperature in real time.	1. Difficult to manufacture and complex system structure.
	2. Heat pipes do not require any additional operation and energy consumption.	2. High cost and risk of leakage and small thermal capacity.
		3. Small contact area with battery usually requiring additional cooling plates to account for non-uniform temperature.
Hybrid cooling	1. The hybrid thermal management system can enhance and compensate its merits and demerits to contribute to the improvement of the entire system performance.	1. Increased size and complexity of hybrid cooling system compared to single thermal management implementation with its associated cost of manufacturing and maintenance.
	2. To a certain extent, it can greatly reduce the system power consumption.	2. The greater control difficulty of hybrid cooling systems.

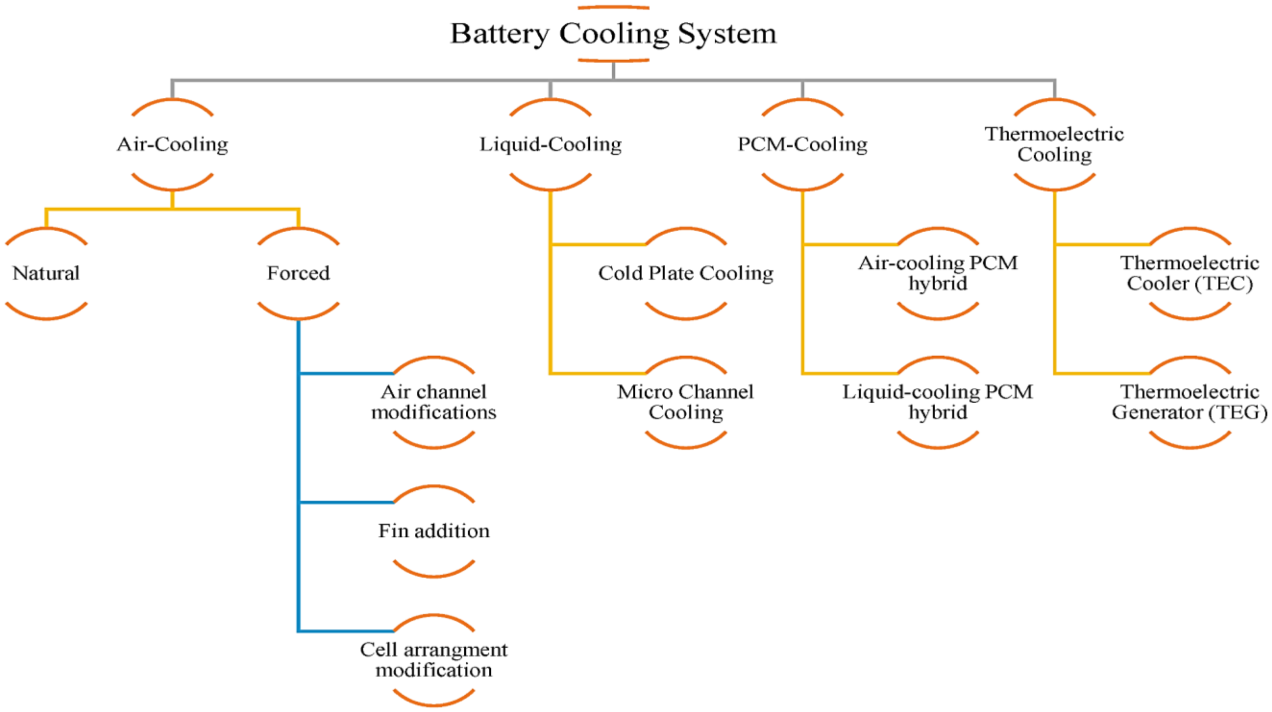

Figure 6: The battery pack cooling classification used in this study is based on the reviewed papers in this study, [28].

5. Performance Evaluation of PCM-Enhanced Cooling Systems

5.1. Efficiency Metrics: Energy Savings and Temperature Regulation

The Phase Change Materials (PCMs) give a superior enhancement to the cooling system in terms of improving the thermal management because of its specialty in keeping latent heat. Effective temperature can be regulated in these materials without continuous energy input through absorption, retention and release of large amounts of thermal energy during phase transitions. This capability is particularly important in conditions where it is critical to attain and sustain a stable operating temperature.

It is worth mentioning that the energy efficiency is one of the important factors in analyzing the performance of PCM-augmented cooling systems. Improvements to the energy consumption of cooling involving PCMs compares very favorably to approaches that are more traditional. Currently, it is shown that under some temperature ranges, these systems can be as much as 12% energy savings and up to 80% decrease in cooling loads respectively. Such large decreases are because PCMs are so good at managing heat flow better than other coolants, the need for active cooling solutions such as refrigeration or air conditioning can be greatly reduced.

Another important factor with which to consider functional performance of PCMs in cooling system is temperature control. PCMs have high latent heat capacities, resulting in almost constant temperatures at transitions, absorbing extra heat during peak thermal demands, and giving it back when conditions stabilize. This feature helps maintain the set temperatures even in the changing environmental conditions or under peak usages.

Both active and passive thermal management strategies can provide benefits from PCMs. In passive systems, PCMs can be encapsulated in building materials or battery assemblies and, as a result, will naturally absorb and dissipate thermal energy without the use of external power sources. One example of such usage is the use of PCMs in conjunction with lithium-ion batteries to stabilize the operating temperature and drastically improve both battery life and performance by eliminating the risk of overheating.

In essence, active PCM systems often run alongside mechanical components, pumps, fans etc to achieve better heat transfer rates. Hybrid solutions incorporate the reliable features of passive PCM management as well as the response capabilities of active cooling technologies to integrate an improved overall system efficiency. As a particular example, configurations that merge liquid cooling together with PCM storage elements are able to enhance rather than restrict largely rapid temperature modulation while capitalizing upon the long-term thermal stability available with PCMs.

Numerous case studies illustrate the success of PCM enhanced systems applications in various industries, more especially, in battery thermal management for electric vehicles (EVs), and solar thermal storage sectors, among others. Research has shown that in electric vehicles, PCMs can reduce maximum battery temperatures by as much as 55 percent by absorbing heat from charging cycle generated by excess heat. The reduction not only contributes to safer way of driving by reducing the number of cycles suffered by the cell, but also extends the lifetime of the battery as excessively cycled cells can wreck integrity of the cell over time.

As solar applications, PCMs are great because they store surplus thermal energy collected during peak sunlight hours for use at a later time when solar output decreases (for example, at night). The output temperature from stored heat is consistently maintained in these systems and this in turn enhances the overall efficiency in renewable energy.

Despite the obvious benefits offered by PCMs in cooling systems, research is still being conducted on new materials and configurations to determine whether we can continue to increase PCM efficiency. To address this, the use of innovative technique strives to develop composite PCMs with different material properties, chimeric organic and inorganic, that enhance not only the latent heat capacity but also the thermal conductivity. Such advancements may bring about next generation PCM solutions to efficiently control larger thermal load.

Utilizing phase change materials for thermal management not only offers an immediate return on energy but works towards fulfilling broader sustainability goals and environmental responsibility programs. The use of PCMs in optimization of heating and cooling processes of different applications such as waste heat recovery systems deployed in industry or smart fabrics that regulate human body temperature is a progressive thought for contemporary engineering.

Overall, these changes ultimately represent a shift in how we deal with heating and cooling control today, which been put on efficiency, and take advantage of state of the art directions from material science, [1], [10], [27], [28] and [33].

5.2. Case Studies Demonstrating PCM Performance Improvements

Many case studies have been undertaken with the aim of validating the efficacy of phase change materials (PCMs) in cooling application that show that PCMs are able to improve energy efficiency and thermal comfort in many different settings. Paraffin was one significant investigation of using it as a PCM in a thermal energy storage system designed to meet a building is cooling requirements. Nonetheless, it was demonstrated through this experimental investigation that room temperature fluctuations could be reduced by up to 50% with organic PCMs in compact thermal storage tanks. It stressed that the PCM's cooling performance is driven by changes in the operational parameters (such as temperature and flow rate of the inlet heat transfer fluid (HTF)). Notably, during the charging phase where cold water circulation causes the PCM to solidify, and the discharging phase when it is heated under heating loads, there were demonstrated significant improvements of performance.

In addition, another interesting case study was about PCM enhanced construction materials, especially gypsum boards. Reducing indoor temperature variability was achieved by incorporating paraffin based PCMs into wall panels. This advancement reduced dependence on conventional heating and heating and air conditioning systems, illustrating the potential transformation of PCMs in the energy management strategy of building designs. Not only did these materials have the effect of improving thermal comfort, they also helped save a major amount of energy in residential structures.

A new HVAC system with PCM-based heat exchangers was assessed comprising of various configuration using a simulation-based assessment in industrial applications. It was found that such systems could cut down on annual primary energy consumption by an amount up to 67 percent, primarily when augmented with free cooling mechanisms that rely on PCM technologies. Later studies had found that integrating tube structured thermal energy storage using calcium chloride hexahydrate as a PCM could increase the overall cooling capacity of air conditioning units by about 34 percent during peak summer period.

An active air-cooling using shell and tube latent heat storage system employing heptadecane as a phase change material was studied in an innovative way. The highest COP was achieved with an impressive performance with the findings that increasing inlet temperature reduced the efficiency without changing outlet temperatures, which indicates that sensible patterns in PCM systems can be optimized by appropriate design.

In addition, studies on the free cooling systems of various PCMs were carried out and optimal configurations were identified with C.O.P. values of greater than seven under special conditions that are suitable for ideal cooling. Researchers also showed how substantial progress can be made in optimizing output with respect to energy needs and maintaining comfortable environments by efficiently controlling airflow and plate thickness within these systems.

Concerted investigations on hybrid battery thermal management systems have demonstrated significant merit in using PCMs complimented by ordinary liquid cooling techniques. Advanced composite phase change materials were studied resulting in reductions in battery temperatures of more than 55%, from both an enhanced heat transfer coefficient as well as an enhanced thermal conductivity design. Furthermore, this approach enhances battery's life and improves overall reliability of the system at high temperatures.

A comprehensive review was provided for various passive wall systems incorporated with PCMs that effectively reduce temperature stratification in the rooms and shift heating and cooling loads over time. Building equipped with these technologies witnessed energy consumption decrease in the order of 20 to 30 percent that validates the role of integrated PCMs in modern construction techniques that look for greater sustainability.

Additionally, such studies showed promising results on the numerical analyses of plate type storage with PCMs; increasing the mass flow rates resulted in better cooling power capabilities. The results showed advanced heat transfer rates between air channels and PCM units with practical means to achieve greater efficiency.

It is evident that, beyond being supplementary components to an otherwise passive heat transfer system, phase change materials (PCMs) are not only needed but also critical to obtaining substantially better performance across many thermal management domains: residential, commercial HVAC, industrial processing, and battery management, [1], [6], [12] and [32].

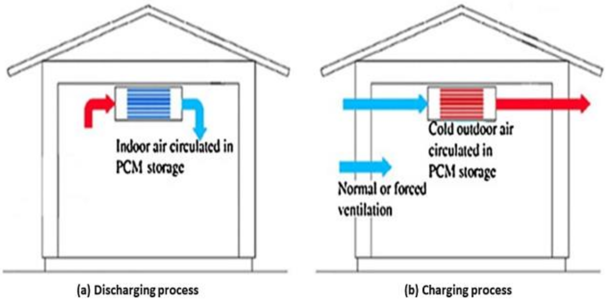

Figure 7: Concept of free-cooling PCM charging and discharging, reproduced with permission of, Elsevier, 2014, [6].

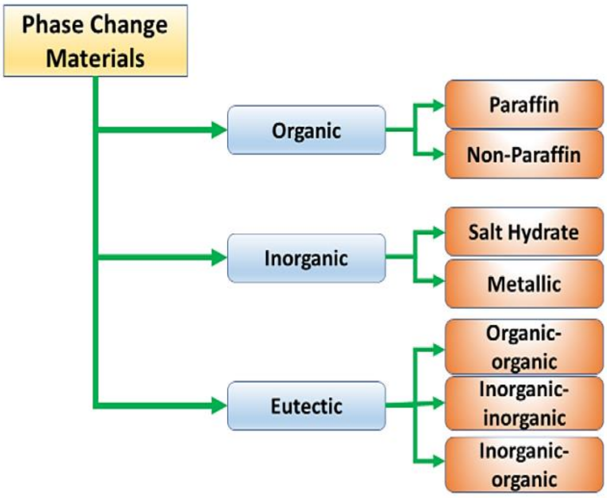

Figure 8: Types of PCMs, [6].

6. Challenges and Limitations of Using PCMs in Cooling Applications

6.1. Material Stability and Longevity Concerns

Durability and reliability of phase change materials (PCMs) are critical factors affecting its effectiveness in using several thermal management applications. Performance of the material over time is influenced by many factors including: composition of the material, environmental conditions, and operation stresses. A major consideration is thermal cycling stability that dictates a P.C.M.s capability to retain its thermal properties after a repeated phase change. If degradation occurs at these cycles, the efficiency of efficient storage and transfer of the energy will be reduced and hence the entire functionality of the cooling system will be decreased.

Depending on the type of change (physical or chemical) that PCMs experience, stability issues can develop. For example, some organic PCMs suffer degradation in air or moisture exposure over time and will change melting point and latent heat capacity for poor performance. However, for inorganic PCMs there are other challenges: they may separate in phase during cycling and cause components to segregate or crystallize unevenly. The physical changes adversely influence the material's ability to store energy well.

Supercooling also poses another concern where a PCM remains liquid (below its solidification temperature) but remains in the liquid state. It affects energy storage capabilities and complicates heat transfer processes largely. Additives such as gelling agents or nanoparticles have recently been introduced with an aim to increase the nucleation rates within PCMs. The addition of these improvements goes further to reduce the energy barrier required for crystallization, making these phases transition faster.

There is also a significant problem with corrosion in inorganic PCMs or any PCMs containing metal components, particularly. Some chemical compounds can have corrosive nature that can degrade the containment vessel as well as other system component making the vessel life and reliability short. Success in this will rely on finding materials for the containers that resist corrosion that are also cost effective.

It is necessary to study long-term performance of long types of PCMs to understand their resilience under the real world conditions. In addition to thermal properties, this research looks at how thermal management systems that contain these materials will evolve over time. All of this should lead experts to suggest a game plan for standardized testing to yield reliable data on PCM characteristics during their lifespan.

Although environmental conditions do not determine how long PCM will last, certain factors in an environment can accelerate such degradation. The encapsulation technique has proved to be an effective tool of stability enhancement by protecting PCM phases from external influences while maintaining thermal efficiency during phase changes.

Decisions involving PCM selection for specific cooling application are also impacted by the cost consideration. Advanced formulations with PCM in Nano form or with gelling agent are found to enhance the stability and performance however, its high cost of production may hinder its wider adoption by budget unconducive industries.

Consequently, in summary, complete strategies of chemical composition, environmental interactions and operational needs, along with economic feasibility are necessary to provide for material stability and longevity. Future advances should target developing improved PCM formulations through new techniques of encapsulation or additive integration as well as overcome inherent limitations of the PCM, such as supercooling and corrosion resistance, [1], [9], [10], [11], [15], [23], [34], [35] and [36].

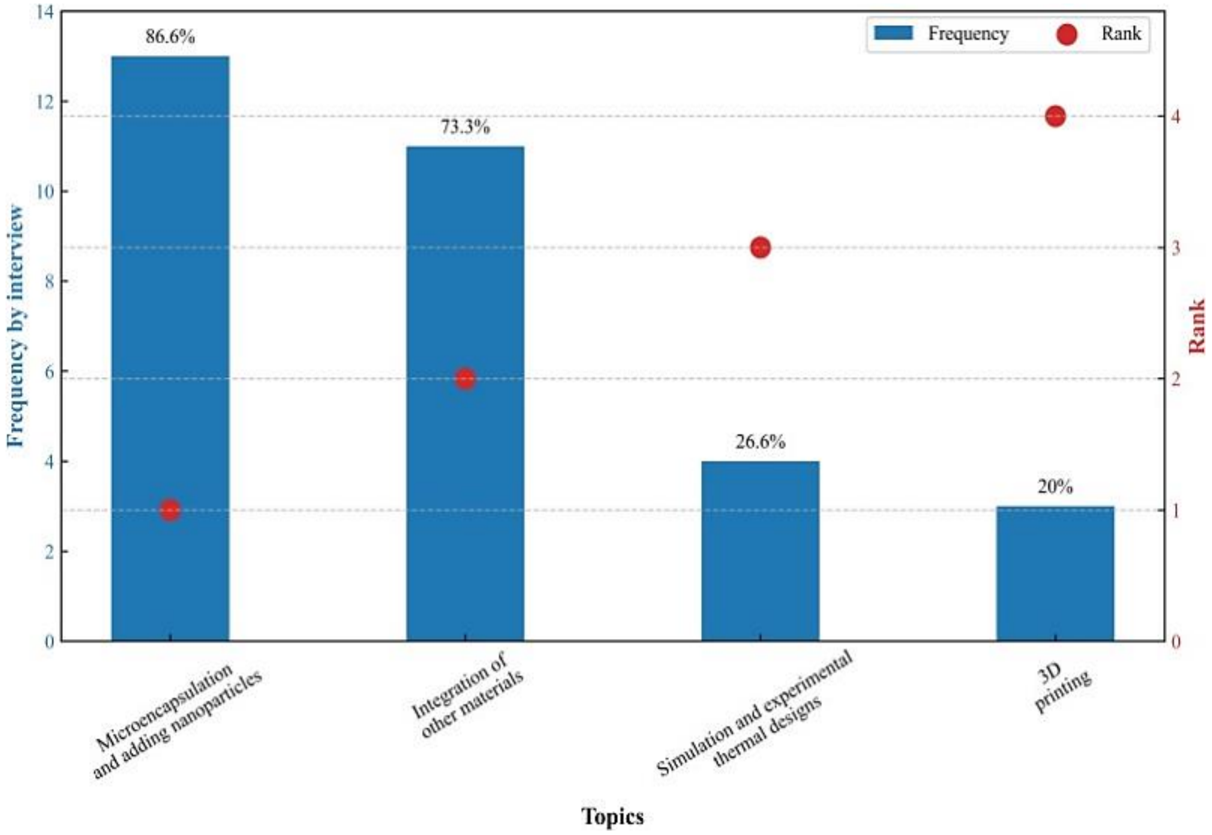

Figure 9: Approaches to mitigate drawbacks present in PCM battery applications, [10].

6.2. Cost Implications for Industrial Implementation

The unpredictable nature of phase change materials (PCMs) in industrial cooling mean that it is a complex financial situation, including initial investments, operational costs and if there is a chance for a sustained economic benefit. Nevertheless, PCMs provide a number of advantages, such as effective thermal energy storage and a perfecting temperature regulation, but integrating them into existing infrastructures make financial challenges.

There is a big consideration for adoption of PCM that is the initial cost. The price of PCMs differ dramatically from each other and can be relatively expensive compared to inorganic such as salt hydrates. Salt hydrates are cheaper is more practical since salt hydrate are cheaper to produce since on the other hand, organic materials may require specialised extraction methods which may be financially infeasible when an industry has a constrained budget.

In addition, the modification of current cooling systems to accept PCMs should also be evaluated from an expense standpoint. These materials are often integrated into existing thermal management systems where improvements are often made with a new PCM by changing or redesigning already existing components to be compatible. Or use more advanced materials that resist chemical interactions with PCMs. Mods can cause additional expenses that will keep the industries from investing in the solutions whether it is beneficial for them or not.

It is required to match particular applications with specific melting points and thermal properties. Because of the complexity and necessitates of custom PCM formulations tailored for exact specifications, production costs are driven up in industries when needed. Temperature or phase transition can be modified to improve thermal conductivity or adjust prices for end users with additives or nanoparticles.

Secondly, PCMs’ feasibility is lacking to some extent when considering the amount of operational costs. These materials however can help reduce energy consumption through reduced active cooling methods but total lifecycle costs must be taken into consideration when there is an economic analysis. Due to its dependence on external factors like ambient temperature fluctuations and operational pressure, the performance of a PCM can be affected and may require some additional monitoring or control systems to maintain optimal functioning.

The challenge in justifying PCM is between initial costs and potential long-term savings. A number of studies indicate that improved heat management could give rise to energy bill savings that can offset contributing cost, albeit the distinctions over how to quantify these benefits continues with industry stakeholders. Case studies show considerable success and failure of PCM integration, with some showing great energy savings resulting in quick return on investment, and others display operational inefficiencies that prevent achieving performance expectations.

Material selection and cost-effectiveness play crucial roles in this context. Maintenance needs or premature system failure can result if care is not taken to manage incompatibilities between some materials used with PCMs. However, this may require further investments in compatible materials or treatments to make stability, not to mention bring project costs out beyond estimated initial costs.

In addition, favorable market conditions also greatly affect the economic environment of PCM technologies. Most organic phase change materials are based on petroleum feedstocks and thus are sensitive to rate of oil, making them more/lower as fuel costs rise. It also makes it an uncertain environment for companies trying to determine whether PCM will be used as part of their thermal management strategies.

There are research gaps in the existing long-term performance assessment research pertinent to PCM implementation decision making related to financial consequences affecting different industries. In particular, many companies do not have enough data on how the durability is expected to behave under many different operating conditions.

Despite these costly financial consequences from PCMs deployments, such as employing them to manage battery temperatures—the advantages provided by strategic selection and engineering innovations make it worth investigating. However, continued research towards addressing these economic barriers appears promising, however, they need to conduct research with industry stakeholders where the information is transparent and the understanding is better about the affordability while addressing reliability and safety issues in a new set of technologies concerning future decisions, [10] and [35].

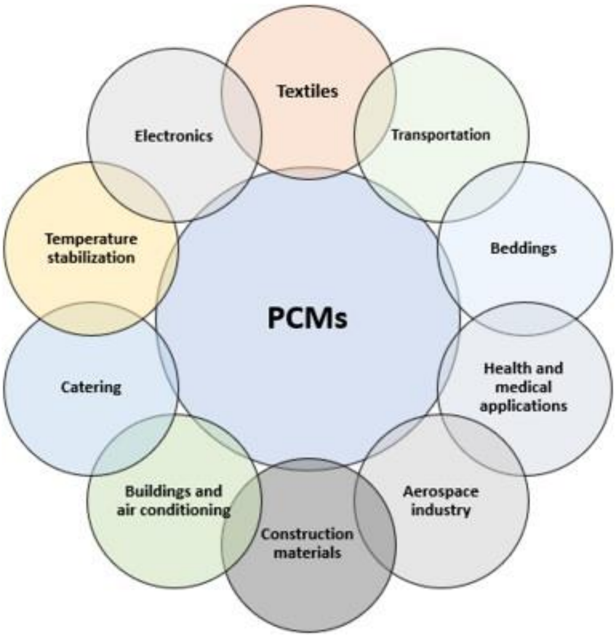

Figure 10: PCMs applications, [10].

7. Future Directions for PCM Research and Development in Thermal Management

7.1. Emerging Materials and Technologies for Enhanced Performance

Phase change materials (PCMs) are recent advanced technologies that have provided new opportunities for improving thermal management applications, especially in cooling systems. There were key advanced topics such as material improvements through the implementation of nanotechnology, composite manufacturing techniques, and the search of sustainable alternatives.

Incorporation of nanomaterials in PCMs as a significant breakthrough can enhance not only their thermal conductivity but also their stability. By integrating the carbon-based nanomaterials, metal foams or nanoparticles into conventional PCM structures, there have been remarkable improvements in heat transfer efficiency. For instance, it has been seen that aluminium oxide nanoparticles (Al2O3) mixed with paraffin wax raises the thermal conductivity without decreasing the latent heat storage capabilities. Such an improvement is crucial; enhanced thermal conductivity enables faster absorption and release of heat during phase transitions to improve system performance.

In another innovative approach to PCMs composite, PCMs are developed where different kinds of materials are combined to make full use of their own specific advantages. Typically, organics PCMs are blended with inorganic substances such as salt hydrates to create a composite system having high latent heat and good thermal conductivity. In addition to refining energy storage capabilities, this combination augments the operational temperature range that is appropriate for a large variety of applications.

The potential to reduce energy demand with bio-based and environmentally friendly PCMs from natural materials, such as fatty acids and plant derived waxes has broadened over the move towards sustainability. All these alternatives feature similar thermal properties to salt hydrate synthetic PCMs, and are at the same time biodegradable or non-toxic. Optimization of these ecofriendly options is an ongoing research to bring them close to or even beyond performance of the traditional materials.

Advanced characterization techniques are also important to the progress of PCM research alongside material advancement. Differential scanning calorimetry (DSC), thermogravimetric analysis (TGA) and scanning electron microscopy (SEM) provide the microstructure and phase behavior of these materials as well as improved design and optimization strategies.

Many industries are potential users of advanced PCMs. One example of construction products that are being developed to make them PCM enhanced in order to enhance their energy efficiency is drywall and insulation panels to effectively regulate indoor temperatures. In electronics cooling, or more specifically highly demanded efficient thermal management solutions, PCMs are being integrated into devices to absorb excessive heat that is produced during operation.

Another exciting development to come in this regard would be the integration of smart technology with PCM systems. Machine learning algorithms to optimize deplogenm of PCM can use the real time data regarding environmental conditions and real energy demand of the site. This dynamic monitoring is helpful in improving PCM system reliability and efficiency by reducing PCM charging and discharging cycles in accordance to the temperature variations.

Researchers are also studying PCMs that are multi-functional and can have or provide some electrical or magnetic functions in addition to their thermal duties, thus possibly enabling the development of advanced applications in the realms of electronics or energy generation through renewables.

PCM integration has great potential in the automotive industry because EVs can be effectively managed using their technology to manage battery temperatures. PCMs’ exceptional ability to maintain stable temperatures through charging cycles could extend battery longevity as well as address safety issues of overheating, an important metric for the adoption of EV tech.

However, limits remain in long-term stability of materials at different operating conditions, and in expense of producing high performance PCMs at scale. Major efforts in academic research" are focused on tackling these issues in order to get closer to greater commercial viability.

With these cutting edge technologies continuing to move into application at a practical level in various fields from HVAC optimization to renewable energy storage solutions (such as solar power plants) and smart textiles, the extension of how the enhanced phase change materials can be utilized to increase cooling efficiency begins to make great strides. Ensuring PCMs work reliably when loads increase while reducing costs will be needed in industries that are seeking more sustainable practices in an era when global energy needs are rising and a climate change challenge is being faced before it's too late, [1], [9], [10], [15] and [23].

7.2. Potential Applications beyond Conventional Cooling Systems

In addition to traditional cooling methods, the deployment of phase change materials (PCMs) goes far beyond, and innovative ways of application of PCs are found in almost all the sectors. In terms of energy efficient architecture, intelligent building materials that include PCMs are built into the thermal regulation of the building. PCM enhanced drywall and insulation boards absorb and release heat to maintain stable indoor climates minimizing reliance on conventional heating, ventilation and air conditioning (HVAC) systems. In addition, occupant comfort is improved, and this provides for lower energy consumption. In addition, smart thermal management systems with PCMs can adjust according to the real-time changes in temperature for improving energy efficiency.

As thermal reservoirs in renewable energy, PCMs are used as effective thermal storage of abundant heat during solar zenith hours for the time when solar production is decreasing. This feature increases the reliability of the solar energy systems and supplies a consistent amount of usable thermal energy independent of the weather variations. PCMs can stabilize temperature fluctuations within turbine components in wind energy generation to increase the system's efficiency and prolong the life's of such complex systems.

As well, advanced PCMs provide solutions to electronic cooling in the devices such as smartphones, laptops and data centers. Increasing pressures on making electronics smaller and physically smaller also increases pressures to prevent from overheating. The integration of PCMs can take the form of absorbs excess heat in high demand periods and dissipate more slowly during lighter periods.

PCM technology helps the medical field through usage of storing and shipping of temperature-sensitive medications. Pharmaceutical efficacy is ensured by avoiding deviance in drugs’ behaviour due to environmental fluctuations throughout transit or storage by using PCM technology that maintains drugs within safe temperature limits. Second, PCM integrated medical devices offer cooling with control for therapeutic purposes (e.g. post operation recovery, fever management).

Optimized PCMs are now being widely used in smart fabrics for textile industry. PCMs incorporated in garments provide a means for the garments to adaptively regulate heat based on body metabolic requirements, thereby improving comfort. One advantage of this feature is that, as sportswear and outdoor clothing exhibit dramatic temperature changes, it can be very useful.

Composite PCMs have been developed utilizing organic and inorganic components and help in improving performance. For example, paraffin wax composites with inorganic salts have shown higher latent heat storage and higher thermal conductivity, which are important for making a good fit in those previously mentioned sectors.

The potential for PCM implementation is expanding as emerging innovations are emerging. ML technologies help in the design of optimal PCM application. This enables researchers to improve system designs more effectively than using the traditional methods for PCM behavior predictive analysis under various conditions.

The other exciting development is self-adaptive radiative cooling technologies based on PCMs forming a dynamic response to ambient temperatures without additional energy for phase transition. The potential of these advancements was to change passive cooling strategies of buildings and vehicles, creating a path away from reliant mechanical cooling systems.

The integration of renewable sources such as geothermal or solar energy with district cooling infrastructures serves as an example in utilizing PCM for implementing sustainability goals of urban development by reducing resource use and allowing for a shift away from reliance on fossil fuel.

The potential for industrial applications is expanded as the work goes on researching novel material combinations. It covers solution for battery management of electric vehicles (EV), that lengthen battery life through temperature control, and smart grids that facilitate integration of renewables and efficiency on the demand side.

Phase change materials are deployed in different ways through such applications in order to help meet sustainability goals ranging from energy efficiency in the everyday to healthcare settings, [1], [9], [10], [14], [15], [16], [17], [23], [27], [28], [37] and [38] for greener alternatives for the future.

8. Conclusion and Summary of Findings on PCMs in Thermal Management Systems

Phase change materials (PCMs) incorporated into thermal management systems constitute a breakthrough in terms of energy efficiency and sustainability. PCMs are known for their ability to absorb or reject thermal energy at transition from solid to liquid state as well as retaining high quantity of latent heat and maintaining temperature stability. Its characteristic is particularly beneficial in cooling applications because it eliminates the need for relying on conventional refrigeration methods, consequently reducing energy consumption and lowering operational costs.

However, ability of PCMs in various applications was shown in the past works, including improving the cooling systems in buildings and thermal control the lithium ion batteries. PCMs make the cooling strategies passive by absorbing excess heat during peak demand and slowly releasing this energy during less demanding periods. An example of such an integration is to use PCMs to build construction materials that substantially increase, yet avoid greatly relying on, indoor temperature regulation by active HVAC systems, so as to increase occupant comfort while achieving large energy savings.

Second is to develop composite materials to enhance thermal efficiency. Aggressive studies have shown that in seeking to circumvent the issue of low thermal conductivity, PCM formulations can be improved by incorporating nanoparticles or foams. Latent heat storage capacity has also been extended by use of novel PCMs that include microencapsulation to extend the lifespan and to stabilize leakage.

Further research into yet unformed PCM formulations is underway that would work effectively over a wider temperature range. With the advancement of machine learning technologies, optimizing PCM application opportunities are made more exciting by better predictive model formulation and the development of more targeted control strategies to a specific environment or operational need.

Moreover, PCs can be integrated into renewable energy systems, like solar power installations, which have many advantages. Storing excess thermal energy generated during peak sunlight hours to use if the production falls short with fluctuating weather conditions results in higher energy capture efficiency.

However, challenges remain to be addressed for a broader adoption. In real world use, the materials are required to be stable over repeated heating and cooling cycles, so it is important to ensure this stability. For instance, the cost considerations are important as PCs provide long-term savings through diminished operating costs but the upfront expense may prohibit the adoption by industries with high sensitivity to it.

Given that policies aimed at promoting sustainability can spur uptake of PCMs in a variety of sectors, government incentives can help promote both investment in next generation thermal management solutions that make effective use of PCMs. In addition, such campaigns aimed at the public could help increase acceptance in the public and in businesses.

The exploration of potential PCM applications beyond their traditional uses holds great promise. Customized designs incorporating these materials could significantly reduce the cost, as well as offer effective solutions to modern computing needs where overheating is a serious risk to operations in sectors such as electronics cooling and more.

Overall, it is concluded that phase change materials offer great potential to transform thermal management solutions across a number of sectors. Urlencoded by their diverse applications from their use as critical components in battery management systems and building materials to optimize the indoor climates to their importance as essential contributors to global sustainability goals in terms of improved energy efficiency and reduction of dependence on fossil fuels through [1], [6], [8], [9], [13], [16], [28], [29], [30] and [40].

References

[1] "Phase Change Material (PCM)". Aug 2024. https://www.petronaftco.com/phase-change-material/.

[2] H. M. Ali. "Applications of combined/hybrid use of heat pipe and phase change materials in energy storage and cooling systems: A recent review". Jan 2019. https://www.sciencedirect.com/science/article/pii/S2352152X19306267.

[3] Ahmed H. N. Al-Mudhafar and A. L. Tarish. "A Recent update of phase change materials (PCM's) in cooling application". Jan 2022. https://eudl.eu/doi/10.4108/eai.7-9-2021.2314779.

[4] S. Koley. "Electrochemistry of Phase-Change Materials in Thermal Energy Storage Systems: A Critical Review of Green Transitions in Built Environments". Sep 2024. https://tis.wu.ac.th/index.php/tis/article/view/8538.

[5] A. Rahmani, M. Dibaj and M. Akrami. "Enhancing Heat Storage Cooling Systems via the Implementation of Honeycomb-Inspired Design: Investigating Efficiency and Performance". Jan 2024. https://www.mdpi.com/1996-1073/17/2/351.

[6] U. Masood, M. Haggag, A. Hassan and M. Laghari. "A Review of Phase Change Materials as a Heat Storage Medium for Cooling Applications in the Built Environment". Jun 2023. https://www.mdpi.com/2075-5309/13/7/1595.

[7] "Phase-change material". Jan 2025. https://en.wikipedia.org/wiki/Phase-change_material.

[8] N. Hamid, Sh. Shaddel Khalifelu, M. Mastani Joybari, Z. Rahimi-Ahar, A. Babapoor, B. Mirzayi and A. Rahbar. "Challenges in thermal management of lithium-ion batteries using phase change nanocomposite materials: A review". Oct 2024. https://www.sciencedirect.com/science/article/abs/pii/S2352152X24033176.

[9] S. Kumar, S. K. a. D. Banerjee and D. Banerjee. "A Review on Phase Change Materials for Sustainability Applications by Leveraging Machine Learning | IntechOpen". Apr 2024. https://www.intechopen.com/chapters/89235.

[10] Dylan D. Furszyfer Del Rio, D. A. Kez, Fadhli Wong B.M. Hasan Wong, A. Dolfi, G. Srinivasan and Aoife M. Foley. ""Encapsulating" experts' knowledge: An exploration of benefits, risks, barriers and

future opportunities of PCMs". Jan 2024. https://www.sciencedirect.com/science/article/pii/S221313882400376X.

[11] H. Jouhara, A. Żabnieńska-Góra, N. Khordehgah, D. Ahmad and T. Lipinski. "Latent thermal energy storage technologies and applications: A review". Jan 2020. https://www.sciencedirect.com/science/article/pii/S2666202720300264.

[12] U. Masood, M. Haggag, A. Hassan and M. Laghari. "Evaluation of Phase Change Materials for Pre-Cooling of Supply Air into Air Conditioning Systems in Extremely Hot Climates". Dec 2023. https://www.mdpi.com/2075-5309/14/1/95.

[13] R. Zhou, Y. Chen, J. Zhang and P. Guo. "Research progress in liquid cooling technologies to enhance the thermal management of LIBs". Feb 2023. https://pubs.rsc.org/en/content/articlehtml/2023/ma/d3ma00299c.

[14] L. Bertelsen. "Technological District Cooling Development in Asia | DBDH". Jan 2025. https://dbdh.dk/technological-district-cooling-development-trends-and-insights-from-malaysia-singapore-and-thailand/.

[15] S.S. Chandel and T. Agarwal. "Review of cooling techniques using phase change materials for enhancing efficiency of photovoltaic power systems". Jan 2017. https://www.sciencedirect.com/science/article/pii/S1364032117302058.

[16] Y. Zhou, S. Zheng and G. Zhang. "A review on cooling performance enhancement for phase change materials integrated systems-flexible design and smart control with machine learning applications". Jan 2020. https://www.sciencedirect.com/science/article/abs/pii/S036013232030144X.

[17] A. Liu, H. Xie, Z. Wu and Y. Wang. "Advances and outlook of TE-PCM system: a review". Dec 2022. https://link.springer.com/article/10.1007/s43979-022-00018-4.

[18] R. Zeinelabdein and S. Omer. "Free cooling using phase change material for buildings in hot-arid climate". Jan 2018. https://academic.oup.com/ijlct/article/13/4/327/5077507.

[19] "Phase Change Materials in Electric Vehicles: Trends and a Roadmap for the Future". Jan 2025. [Online]. Available: https://www.sae.org/webcasts.

[20] A. v. Aalst. "Unlocking the Power of PCM: 6 Key Benefits for a Sustainable Future". Nov 2023. https://plussat.eu/blog/2023/06/12/unlocking-the-power-of-pcm-6-key-benefits-for-a-sustainable-future/.

[21] A. I. Garivalis, D. Rossi, M. Seggiani and D. Testi. "Beyond water: Physical and heat transfer properties of phase change slurries for thermal energy storage". Apr 2024. https://www.sciencedirect.com/science/article/pii/S2666386424001413.

[22] A. Sevault. "What are Phase Change Materials? (Will they be the next big thing in Norway?)". Sep 2018. https://blog.sintef.com/energy/phase-change-materials-pcm/.

[23] G. Rasool, W. Xinhua, T. Sun and T. Hayat. "Recent advancements in battery thermal management system (BTMS): A review of performance enhancement techniques with an emphasis on nano-enhanced phase change materials". Aug 2024. https://pmc.ncbi.nlm.nih.gov/articles/PMC11403493/.

[24] V. N. Muppana, M. Samykano, W. A. W. Hamzah, K. Kadirgama and S. K. Suraparaju. "A Short Review of Recent Advancements in PCM-Air Hybrid Thermal Management for Batteries". Jan 2024. https://ikm.org.my/publications/malaysian-journal-of-chemistry/xcesfile.php?abs=J0050-31ee010

[25] P. Yan, W. Fan, Y. Han, H. Ding, C. Wen, Anas F.A. Elbarghthi and Y. Yang. "Leaf-vein bionic fin configurations for enhanced thermal energy storage performance of phase change materials in smart heating and cooling systems". Sep 2023. https://www.sciencedirect.com/science/article/pii/S030626192300716X.

[26] S. Caldwell. "Thermal Control - NASA". 7.0. Oct 2021. https://www.nasa.gov/smallsat-institute/sst-soa/thermal-control/.

[27] [25] K. Du, J. Calautit, Z. Wang, Y. Wu and H. Liu. "A Review of the Applications of Phase Change Materials in Cooling, Heating and Power Generation in Different Temperature Ranges". Apr 2018. https://www.researchgate.net/publication/324115722_A_review_of_the_applications_of_phase_change_materials_in_cooling_heating_and_power_generation_in_different_temperature_ranges.

[28] A. Rahmani, M. Dibaj and M. Akrami. "Recent Advancements in Battery Thermal Management Systems for Enhanced Performance of Li-Ion Batteries: A Comprehensive Review". Jul 2024. https://www.mdpi.com/2313-0105/10/8/265.

[29] K. Faraj, M. Khaled, J. Faraj, F. Hachem and C. Castelain. "Phase change material thermal energy storage systems for cooling applications in buildings: A review". Jan 2020. https://www.sciencedirect.com/science/article/pii/S1364032119307877.

[30] S. F. Ahmed, N. Rafa, T. Mehnaz, B. Ahmed, N. Islam, M. Mofijur, A. T. Hoang and G. Shafiullah. "Integration of phase change materials in improving the performance of heating, cooling, and clean energy storage systems: An overview". Jun 2022. https://www.researchgate.net/publication/361295067_Integration_of_phase_change_materials_in_improving_the_performance_of_heating_cooling_and_clean_energy_storage_systems_An_overview.

[31] G. A. Farulla, V. Palomba, D. Aloisio, G. Brunaccini, M. Ferraro, A. Frazzica and F. Sergi. "Optimal design of lithium ion battery thermal management systems based on phase change material at high current and high environmental temperature". Jan 2023. https://www.sciencedirect.com/science/article/pii/S2451904923002159.

[32] G. Dogkas, Maria K. Koukou, J. Konstantaras, C. Pagkalos, K. Lymperis, V. Stathopoulos, L. Coelho, A. Rebola and Michail Gr. Vrachopoulos. "Investigating the performance of a thermal energy storage unit with paraffin as phase change material, targeting buildings' cooling needs: an experimental approach". Jan 2020. https://www.sciencedirect.com/science/article/pii/S2666202720300148.

[33] N. Flaherty. "Phase change materials". Apr 2024. https://www.emobility-engineering.com/phase-change-materials/.

[34] S. Khanna and P. Prajapati. "Editorial: Phase change materials for energy conversion and storage". Jan 2023. https://www.sciencedirect.com/science/article/pii/S2666202723001799.

[35] Dylan D. Furszyfer Del Rio, D. A. Kez, F. Wong, B.M. Hasan Wong, A. Dolfi, G. Srinivasan and Aoife M. Foley. ""Encapsulating" experts' knowledge: an exploration of benefits, risks, barriers and future opportunities of PCMs". Nov 2024. https://pure.qub.ac.uk/en/publications/encapsulating-experts-knowledge-an-exploration-of-benefits-risks-.

[36] H. M. Ali. "Recent advancements in PV cooling and efficiency enhancement integrating phase change materials based systems - A comprehensive review". Jan 2020. https://www.sciencedirect.com/science/article/abs/pii/S0038092X19311752.

[37] D. Agonafer. "Agonafer, Damena | Department of Mechanical Engineering". (accessed Feb 06, 2025). https://enme.umd.edu/clark/faculty/1724/Damena-Agonafer.

[38] M. Ono, W. Li, K. Chen and S. Fan. "Self-adaptive radiative cooling based on phase change materials". Sep 2018. https://opg.optica.org/abstract.cfm?uri=oe-26-18-a777.

[39] K. Du, J. Calautit, Z. Wang, Y. Wu and H. Liu. "A review of the applications of phase change materials in cooling, heating and power generation in different temperature ranges". Jun 2018. https://www.sciencedirect.com/science/article/abs/pii/S0306261918303349.

[40] M. A. Sheik and M. K. Aravindan. "A comprehensive review on recent advancements in cooling of solar photovoltaic systems using phase change materials". Feb 2022. https://academic.oup.com/ijlct/article/doi/10.1093/ijlct/ctac053/6591516.