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Phase Changing Materials With A Special Focus On Recent Advancements-A Review

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Abstract
Phase-changing materials (PCMs) are utilized for energy storage by taking advantage of the quantity of heat absorbed or emitted in a process involving a phase transformation. They have found applications in a variety of fields such as heating, ventilation, and air conditioning systems, protective clothing, solar energy, and energy systems. This paper is a review of the most recent developments in phase-changing materials, including metallic eutectics and their composites, fatty acids, erythritol, fatty alcohols and their mixtures, water, and ionic liquids. It also places emphasis on rendering PCMs efficient, including using different approaches to enhance the thermal conductivity and suitable forms (micro, macro, and nano-capsules) to utilize in different applications. Progress on form-stable PCMs is also treated under a different section in this work. Finally, the paper outlines the recent techniques used to produce crystalline PCMs. Illustrations and tables have been used to enable readers to understand the work demonstrated in recent times. Lastly, industrial demand and future developments have also been outlined.

In this paper, an extensive review of the most recent advancements on PCMs is presented. This review is classified into various PCMs depending on their groups such as metallic eutectics and their composites, fatty acids and derivatives, alcohols, acids, water, ionic liquids, composite PCMs, form-stable PCMs, latent heat storage units, and crystalline PCMs. Besides providing advancements on the PCMs and their use, we essentially lay emphasis on rendering the PCMs efficient by providing a review on increasing thermal conductivity using different approaches, and the morphologies such as micro, macro, nano-capsules, etc., used in various practical applications. Management of PCMs, including preventing leakage, super cooling, and superheating, is detailed in this review. In addition, market demand for PCM applications has been provided to understand the application part.

Keywords: Phase change material; Renewable energy; Thermal energy storage; Property; Application.

1. INTRODUCTION

Modern societies rely heavily on low-cost energy sources to run day-to-day activities at their highest comfort levels for domestic, industrial, and commercial purposes. However, the excessive use of these non-renewable energy sources has resulted in a number of environmental issues (Zhang et al., 2024), (Usman et al., 2021). The newfound interest in renewable energy sources has led to the emergence of various alternative energy conservation technologies that are dispersed in nature with low adoption status. Phase Change Material (PCM) based system technology is one of the highest potential energy efficiency conservation technologies, attracting an increasing degree of global research interest (Faraj et al.2020), (Wang et al., 2022). The growing interest and investment in the field of PCM over the years is evidence of its potential as a green, environmentally friendly, and high-efficiency energy conservation technology, serving as a potential alternative. A modest overview of the evolution of PCM applications reveals their potential for domestic, industrial, and green technological applications. The focus of the present review is to systematically encapsulate and discuss PCM from various perspectives, including the past and present state of PCMs, recent advancements and their potential, a survey of novel applications, challenges, and a list of forces that limit their application, which is necessary to address to ensure the successful and complete design of PCM-based technologies (Cunha et al., 2023), (Hassan et al.2022). The ultimate PCM design strategy encourages the development of a new breed of intelligent green building materials that respond to their performance inefficiencies in use and are smart, adaptive, and controllable with additional capacities. In addition, this review focuses on developing a clear understanding of the physical and chemical transformations in PCMs and their behaviors through a range of relevant examples and reviews for the successful design of practical and operative PCMs while distributing basic PCMs (Junaid et al.2022), (Li et al., 2023).

2. FUNDAMENTALS OF PHASE CHANGING MATERIALS

Phase changing materials (PCMs) are a branch of the smart materials family and are of great interest because of the importance of the phenomenon that they can exhibit. Their direct phase change between solid and liquid phases or at a solid to a vapor/liquid–vapor phase transition, with appropriate changes in temperature or pressure respectively, allows the materials to absorb or release significant amounts of energy over a narrow temperature range (Shi et al., 2021). Made up of two (or more) materials, the most common PCMs are organics combined with an inorganic. Based on their chemical and physical properties, PCMs can be classified as organic PCMs, inorganic PCMs, and hybrid PCMs. In a more refined classification, PCMs may be classified as bio-materials, salt hydrates, paraffins and their mixtures, fatty acids, sugar alcohols, and blend products, utilizing a mixture of all or some of the above-mentioned categories (Yang et al.2022).

The graph of the energy transfer between the PCM and the environment is symbolized by a step curve, suitable for heat storage applications. The primary thermodynamic factor governing the effect of a PCM is the latent heat, measured in MJ/kg or Btu/lb. In general terms, when the heat required to change a material from one phase to another (i.e., a solid changing to a liquid) is higher, that material has a higher latent heat (Tamuli et al., 2021) (Ahmed et al.2022). Higher values signify heat stored or released, while a low latent heat value is appropriate for narrow-adjustment control applications. The primary performance criteria for the PCMs are the phase change transition temperature, the thickness needed to store energy, the energy storage density, and the thermal latency (Hou et al.2022).

3. DEFINITION AND TYPES AND CHARACTERISTICS OF PHASE CHANGING MATERIALS

Definition of Phase Changing Materials: In general, phase changing materials (PCMs) are used to store calorific or frigorific energy in the form of latent heat. Energy storage in the form of latent heat in materials occurs during the process of phase change. In latent heat storage, the temperature of the storage does not change during the melting of the solid to liquid or during the freezing of liquid to solid. PCMs can have various forms, such as inorganic PCMs, organic PCMs, and eutectic PCMs. However, it is possible to store the same amount of heat within a small temperature phase range or expand the phase change temperature difference depending on their chemical nature. Previous studies have shown an improvement in energy efficiency by increasing the thermal energy storage density of the PCM. Furthermore, the physical state of PCMs can be manipulated by varying the environmental temperature, providing a variable heat sink with the most basic PCM (Aftab et al.2021)(Hassan et al.2022).

Types of PCMs: The classification of PCMs shown in figure 1, can be executed from various aspects. Usually, PCMs can be divided into three main types depending on their origin and physical state, including inorganic PCMs, organic PCMs, and eutectic PCMs.

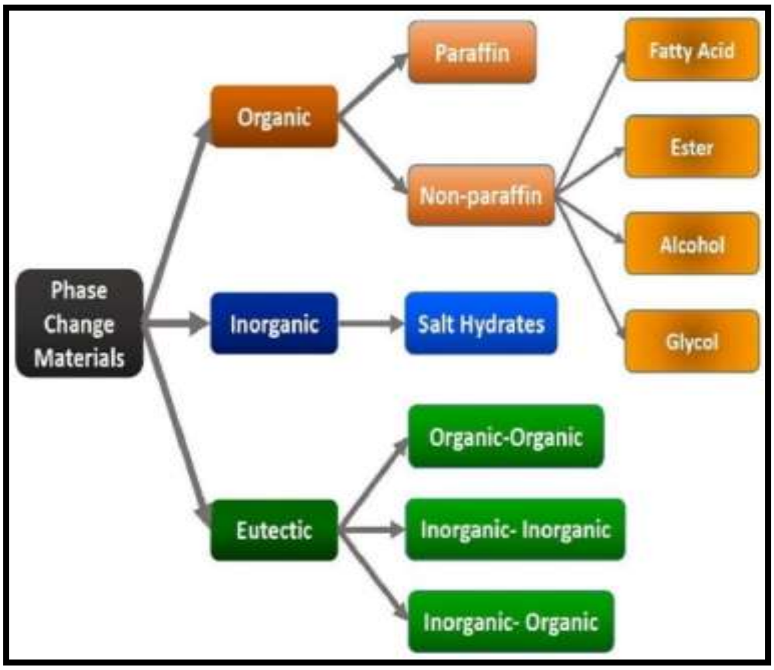

Figure 1: Classification of Phase Change Materials

Besides, they can also be classified on the basis of forms such as salt hydrates, fatty acids, paraffin waxes, metal alloys, and eutectic mixtures. Salt hydrates react physically with water, organic PCMs are mainly linear or slightly branched alkanes, and fatty acids are mainly composed of n-alkanes and have a flat molecular structure. Paraffin materials of organic PCMs can be derived from natural and synthetic raw material sources. Also, waxes have a more organized structure than other organic forms. Metal-resistant PCMs expanding the applications are composite PCMs. According to material particulate form, there are microencapsulated PCMs, conglomerated PCMs, and impregnated PCMs. Organic, inorganic, and eutectic PCMs also have microencapsulated, conglomerated, and impregnated forms because each material can contain these three states (Singh et al.2021)(Sun et al.2023)(Mehling, 2024).

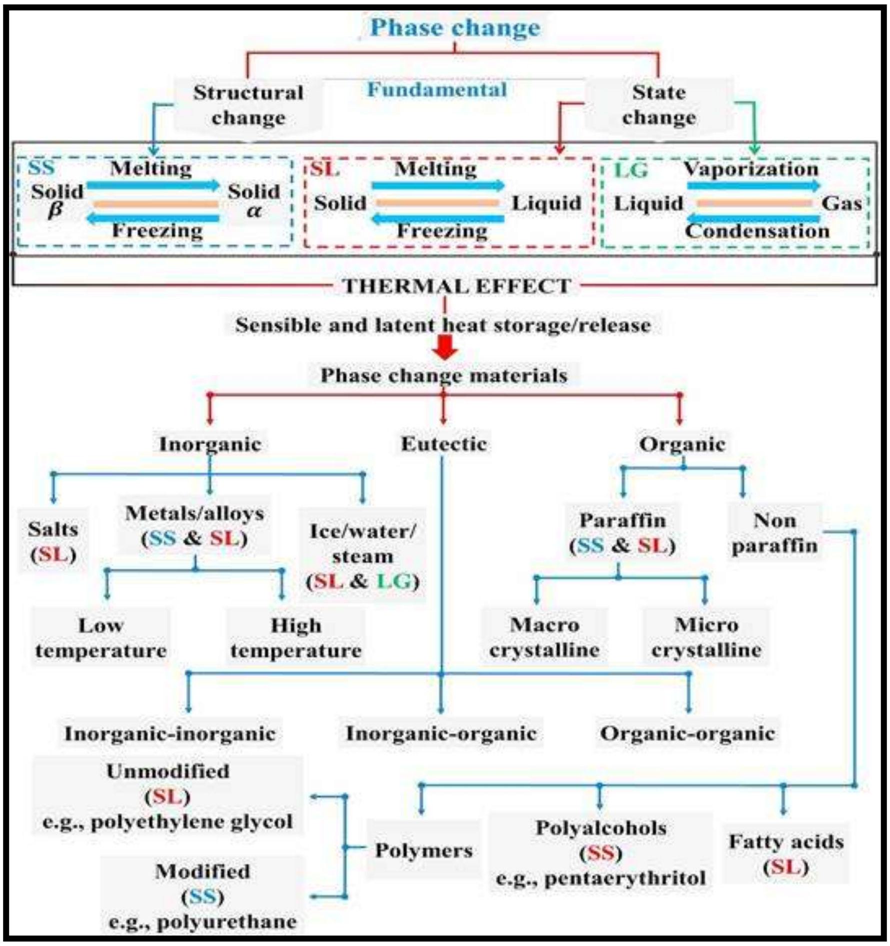

Figure 2: Phase Change dependent Classification of Materials
(Source: doi: 10.1016/j.apenergy.2019.01.114)

The brief classification of PCMs is provided as shown in figure 2, in the following:

- Organic PCM (Paraffin Waxes) Fatty acids, e.g., steric acid, lauric acid, or myristic acid. - Inorganic PCM Salt hydrates, e.g., alkali metals, earth metals. - Eutectic PCM Mixture of the organic PCMs and inorganic PCMs. - Salt Configuration Binary PCMs, multi-quaternary PCMs.

Characteristics of PCMs are shown in figure 3, Due to their thermal storage abilities, PCMs have the potential to reduce energy costs and enhance overall system efficiency. They offer many advantages, including a distinct high storage capacity and space saving, load leveling due to their smooth thermal storage capabilities, no risk of thermal runaway, and relatively low storage costs per unit of capacity. PCMs can serve as a storage facility for materials that, for a time, undercut the cooling process, resulting in reduced power consumption and the potential for capital and operating cost economies (Prabhakar et al., 2020)(Ahmed et al.2022). However, they also have some associated limitations, such as relatively low thermal conductivity that can limit overall heat transfer.

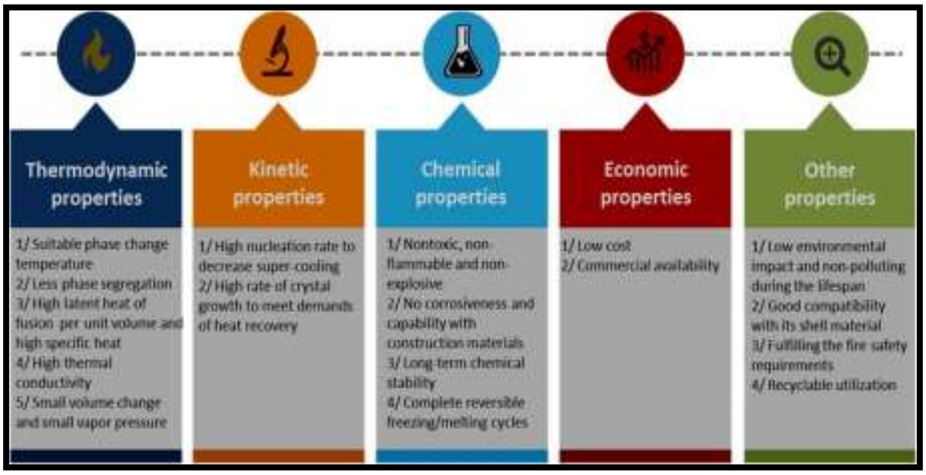

Figure 3: Characteristics of phase change materials (PCMs)
(Source: DOI: http://dx.doi.org/10.1002/est2.127)

The selection of the phase changing material used in a thermal energy storage system will significantly affect the system design, performance, and cost. In order to study and select the PCM or low temperature eutectic at first, the conditions of application need to be carefully examined. The choice of PCM depends on a number of factors, such as the desired storage temperature, storage density, cost, and material weight and volume changes during phase transition. To qualify PCMs, adequate factor selection and design is a significant concept (Nižetić et al., 2021) (Ali, 2020).

4. PRINCIPLES OF PHASE CHANGE BEHAVIOR

Figure 3 Shows the Principle of Phase change behaviour. Phase changing materials (PCMs) are capable of storing and releasing energy during reversible phase transitions. As a result, they absorb a large amount of energy at constant temperature to undergo a physical transformation from solid to liquid, known as fusion or melting, and during solidification (Yang et al., 2021). This additional energy made available at the temperature in the form of a plateau causes an abrupt increase in a temperature–time curve during melting or a rapid decrease in temperature during solidification. As a result of differences in melting points, freezing points, and specific heats of any two materials, the ease of heat transfer can be ascertained. To put it another way, a metal with a higher thermal conductivity transfers heat more efficiently due to a decrease in specific heat. The ideal PCMs have a phase change temperature range that is moderate and matches the requirements of the application regardless of the particular application area (Nie et al.2020), (Ismail et al.2022).

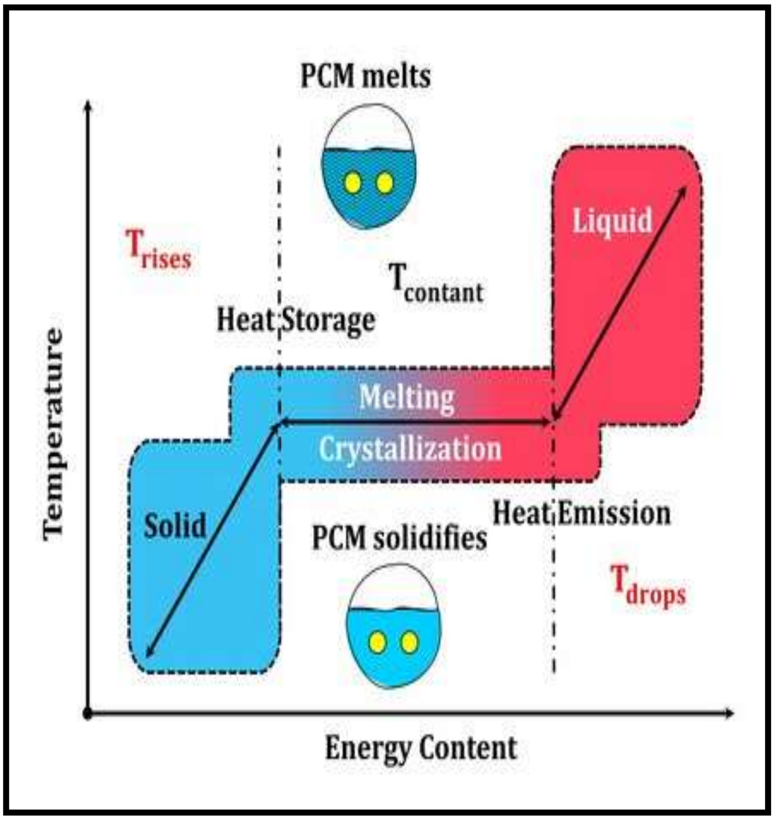

Figure 4: Principles of phase change behavior of PCM
(Source: DOI: 10.1016/j.est.2024.110945)

The transition temperature of a PCM indicates its reliability under given working conditions. The phase stability is specific to a substance; a temperature change will cause a phase transition. For all materials, the change of phase is determined by temperature and pressure. During a phase change in a medium, the temperature remains constant, but the substance undergoes atomic or molecular rearrangements (Jebasingh and Arasu, 2020) (Nafis et al.2020). There are two physical ways in which a PCM may undergo a phase change: (a) Evaporation and Condensation; and (b) Sublimation and Deposition. In solids and liquids, these atomic or molecular rearrangements producing a phase change take place at an interface known as the phase boundary. Moreover, the phase transitions are influenced by molecular or atomic behaviors and states of energy (Yancheshme et al.2020), (Kalidasan et al.2023).

5. APPLICATIONS OF PHASE CHANGING MATERIALS

Thermal Energy Storage: PCMs can store enormous amounts of mechanical energy and release it when required to perform industrial tasks according to demand. Because of this feature, PCMs are adopted in some thermal energy storage systems-such as solar-thermoelectric generator hybrid systems and "saving electricity cost" schemes-in which PCMs are charged by thermal collectors or waste heat at low temperatures during off-peak hours and are discharged during peak hours by utilizing the stored energy to generate electricity when its price is high. In many off-peak charging and peak discharging applications, integrating PCMs into thermoelectric generator systems could increase the electric power output and the round-trip efficiency (Samykano, 2022), (Malik et al.2022).

Building Materials: Developing appropriate advanced building materials can make a substantial contribution to improving the energy efficiency and thermal comfort of new buildings and existing constructions. A popular application of PCM-enhanced building materials is for the reduction of indoor temperature fluctuations. External building materials are prone to large temperature fluctuations in most climatic conditions, and therefore, storing thermal energy in PCMs would prevent the outdoor side of such building envelopes from becoming suddenly too hot or too cold, thus reducing the need for subsequent heating or cooling (Khdair et al., 2022)(Prabhakar et al., 2020), (Gholamibozanjani and Farid, 2021). The use of PCMs in building applications offers low initial costs, requires no controls, needs minimal maintenance, and is easy to install. Moreover, the approach is especially suitable for implementation in existing buildings, where the additional cost of an integrated active system would otherwise be prohibitive. The effectiveness of PCM-enhanced building materials for thermal load shifting has been demonstrated by testing in various commercial case studies and demonstration projects. It is expected that using PCMs would reduce the managed power of the site by shifting energy demand to off-peak times (Saffari et al., 2022), (Kishore et al.2022).

Electronics Cooling: Short-term electronic device failure can be caused by an overheating self-protecting system, and a reduced operational life or permanent damage of many devices is caused by heat buildup. Electronic devices, especially portable ones, such as mobile phones and laptops, but also others, experience a high degree of heat generation. The thermal performance of the chip can be locally modeled by embedding phase change material layers on the outside of the heat dissipating part of the chip, and this embedded PCM is found to be thermally more effective compared with the use of a fin array at the chip surface to improve heat transfer (Dmitruk et al.2020). Heat generated in the heat dissipating region of the system is initially stored in the PCM layer, and then part of the heat is transferred by conduction and convection to the relevant surface boundary. In recent years, PCMs have attracted relatively serious attention as potential cooling candidates for electronics systems.

5.1. Thermal Energy Storage

Thermal energy storage (TES) has been a well-considered and efficient way to manage and exploit the energy from the electricity grid and renewable energy sources (RES) to widen the time of use. Phase Change Materials (PCMs) have been frequently employed as storage mediums in order to store the excess thermal energy from electricity, the heat recovery system, or during off-peak hours. Using the stored thermal energy during peak hours brings another advantage of using PCMs: the ability to level load, namely to reduce simultaneous power demand and increase energy efficiency. In the field of solar energy, a number of researchers have hybridized PCM systems with other TES techniques such as latent heat storage, sensible heat storage, and thermo-chemical storage (Nie et al.2020), (Singh et al.2021).

Though the energy investment in TES equipment might increase up to 15–35% of the costs of the energy system without TES, cost-benefit analyses indicate that overall savings could be achieved up to 10 to 30%. The application of PCMs in TES can be found in various systems such as solar energy collectors, charge-air coolers, and storage tanks in which hot water, steam, or air is stored as a heat transfer fluid. As for shape-stabilized PCMs, applications include floor heaters, infrared heating panels, convective heaters, and other systems. The most direct solar energy applications are the solar flat-plate collector, solar air heater, solar cooker, solar dryer, and solar-assisted cooling (Chaturvedi et al., 2021), (Soares et al.2020).

5.2. Building Materials

By integrating PCMs directly into building materials or adding them as coatings, the behavior of envelopes or façades to temperature fluctuations could be significantly enhanced. Potential applications range from residential buildings to industrial processes such as cold storage units or food and dining services. The aim of this technology is to shift the peak temperatures resulting from easily entering sunlight from the warmer day into the cooler night, to reduce the internal energy consumption by operating the indoor temperature where the internal heat is predominantly resulting from people for a constant average value in the day (Čurpek and Čekon, 2020), (Zhan et al.2023).

One of the major criteria in selecting and designing PCM-enhanced building materials is their thermal performance. First and foremost, the latent heat of the PCM should be closely matched to a certain period of thermal comfort. The phase change temperature should be preferred as a phase transition temperature as close to the targets comfort temperature as possible, so that the comfort of the inhabitants is optimal. In addition, the freeze and melt points have to be selected properly, so that the range of the desired comfort temperature is encompassed. An increased specific heat storage capacity of around 1500 J/kgK, good volumetric heat storage properties, eutectic mixtures, a sharp change of the thermo-physical properties at the phase change temperature, a melting/solidification range of 5 to 8 K, and high thermal conductivity, density, and heat of fusion values can be useful in most cases. Another important property when choosing PCMs, particularly in building, is their durability. The PCMs should be stable on a macroscopic and microscopic scale, over long periods of time, and should not change their overall structural form even after thousands of phase change cycles (Arıcı et al., 2020), (Qu et al., 2021).

Therefore, during the period 2008–2019, a number of studies have been published on the impact of PCMs and phase change processes, but only a few focused on the majority of the aforementioned criteria which make a PCM of interest for a large target audience directly involved or close to the construction industry. Another limitation of most of these recent publications is that they focus more on the synthesized rather than on the commercially bound materials (Radomska et al., 2020), (Cárdenas-Ramírez et al., 2020). Natural materials and natural PCM composites, when carefully designed, can fulfill many, if not all, of the expected performances of a PCM and they are vastly available as raw materials at a low cost. Another weakness of PCM composite studies is that although thermal performance studies have been performed with good results and attempts to map these materials into the construction phase were done, no study has been done until now to map and to regularize their use in a practical manner, even though those composites showed significant improvement of the indoor quality for the occupants and can alleviate the energy consumption of the buildings (Zhan et al.2023).

5.3. Electronics Cooling

Modern electronic devices are capable of performing multiple intensive tasks during usage; the excessive heat generated as a result poses a significant problem. Inadequate thermal management can greatly reduce the lifespan and performance of an electronic system. Smart phones, laptops, desktop computers, and servers all suffer from massive heat generation as a result of electronic components like microprocessors, memory modules, and graphics cards, which are integrated into the devices. The excessive heat generation is due to the constant increase in power consumption and decreasing footprint of electronic components (Khan et al., 2020), (Mathew and Krishnan2022). With the increase in power density, effective and efficient thermal management becomes an imperative mechanism for electronic devices to maintain device reliability and performance. The high power density integrated device is a major bottleneck in the microelectronics industry. Developments in passive and active cooling mechanisms are impeded due to decreases in device sizes; this, in turn, results in a less efficient thermal management system solution for base station computers and data centers. As a result, different industries and research communities throughout the world are constantly looking for alternate, cost-effective, and efficient thermal management techniques (Mathew and Krishnan2022), (Kalbasi, 2021).

One of the most efficient and promising mechanisms for thermal management is integrating phase-changing materials with electronic devices. These materials have the capability of storing and releasing large amounts of latent heat during phase transition at a near-constant temperature. When they absorb heat, the phase transition occurs from solid to liquid, wherein the state changes from solid to slurry; when they release heat, the temperature rises to the point where the phase change process is complete. Thus, the heat generated by electronic components will be absorbed completely during the phase transition, and the final released temperature will be at a near-constant temperature. Several commercially available products have also been developed using these materials for heating and cooling applications (Ma et al.2022), (Bianco et al., 2022). The effect of embedding the material inside the heat sink and also externally on heat sink performance has been studied, showing the advantage of using these materials for heat sinks. A detailed review of passive techniques used in electronic cooling has also been conducted. Apart from the development of different cooling devices using these materials, some research has been initiated on functionalizing materials to enhance their thermal transport properties. In miniaturized cooling, phase change materials are implemented for their high latent heat, which can store maximum thermal energy within the material compared to conventional thermal management systems. However, characteristic performance was not optimized. There is a need to enhance the characteristics to achieve the desired temperature profile. In recent years, a variety of these materials have been developed for different application areas (Lokhande and Tiwari, 2023).

6. CHARACTERIZATION TECHNIQUES

Before assessing the properties and behavior of latent heat storage materials, it is imperative to carefully characterize these materials using various techniques in order to obtain accurate results in a short period of time. Reliability, accuracy, and repeatability are required for characterizing phase change materials to advance efforts in the field of PCM nanocomposites. Differential Scanning Calorimetry was used to calculate the latent heat while determining the melting and freezing points of the PCMs. In terms of practical applications, phase change temperatures and latent heat capacities are crucial for selecting PCMs. The application of DSC to the research and analysis of PCMs has resulted in significant productivity for plain and cold storage purposes (Fatahi et al., 2022).

Much effort has been made to study using a Thermo-gravimetric Analyzer to analyze changes in residual mass, conduct evaluations, and determine the decomposition patterns of latent heat storage materials. An understanding of the thermal stability offers important information about the role of latent heat storage materials in the applications. An examination of the microstructure of latent heat storage materials to understand their performance based on microstructure and phase transition enthalpies has been conducted using a microscopic method. Microscopic analysis allows the phase transition properties and microstructures to be examined. The use of characterization techniques can provide opportunities for potential research to combine new PCMs, address some disadvantages of organic and inorganic PCMs, or add new features to conventional PCMs in order to win both markets while solving environmental issues in the future (Tofani and Tiari, 2021).

6.1. Differential Scanning Calorimetry (DSC)

Differential Scanning Calorimetry (DSC) has become the most critical technique to characterize the phase transitions and structural changes in all kinds of phase-changing materials (PCMs). The basic principle of this technique is based on the measurement of the temperature difference between a reference sample and the sample, which is placed in the parallel pans of a special corundum crucible. A sinusoidal heat flow is provided, and the power required maintaining the zero temperature difference between the reference and the PCM sample is measured. DSC measures the heat flow in mW of a material versus temperature or versus time under controlled conditions to determine the relationship between heat and temperature. The temperature and heat flow values are specifically measured, checked, and calibrated (Fatahi et al., 2022). The phenomenon of thermal transitions in the samples is typically detected and characterized by the melting and crystallization temperatures and enthalpies, often used for the determination of the main thermal properties and reliability. Heating and cooling cycles are carried out under isothermal conditions with typical rates of 5–20 °C min−1 to make evident thermal effects such as phase change, crystallization, solid-solid transition, decomposition, and sublimation processes. It is deduced that DSC is the most classical technique to aid in defining the thermo-physical and calorimetric PCM properties in indirect flights (Nazari Sam et al., 2020).

6.2. Thermo-gravimetric Analysis (TGA)

Thermo-gravimetric Analysis (TGA) is one of the most definitive tools used for the precise and absolute thermo-physical characterization of materials. TGA is used not only in the investigation of phase-changing materials (PCMs) and other related materials, but also in characterizing a wide range of materials in other fields of chemistry, physics, and materials science. The TGA system can be operated either isothermally or dynamically to measure the weight of a sample against time or temperature as it is heated in air, inert, or reactive environments. TGA is mainly employed in the investigation of thermal stability, degradation patterns, estimation of phase change enthalpy, or theoretically the activation enthalpy of PCMs and their composites used in the field of energy storage in certain applications (Tyagi et al.2022), (Müller et al.2020). According to the TG curve, the degradation rate can be understood from the DTG curve and can be used in the design part to prevent undesirable reactions between the PCM materials and their substrates. Furthermore, many patents and academic papers have contributed to the application of TGA as a supporting technique for real-world applications.

Moreover, the presence of temperature gradients over the vicinity of a sample leads to internal convection phenomena denied by the primary TGA hypothesis. The available literature has underpinned several limits of the TGA test tool including (i) The lack of measurement of the external and internal thermal parameters unlike using an external sensor or through differential thermal analysis techniques; (ii) The TGA does not release information about the behavior of the sample during its cooling process; and (iii) the accessible quantity of sample to be used for the TGA test. Due to these conceptual and practical limitations, as compared to other commercially available tools and techniques, TGA data interpretation proves to be very difficult and significantly lacks accuracy (Emiola-Sadiq et al., 2021). Nevertheless, the TGA, with the continuous development of techniques and tools, remains an essential tool for rapid and effective comparative screening of materials before going through absolute characterization, thanks to its measurement simplicity and low cost.

6.3. Microscopy Techniques

The micro-structural characterization is considered to be of major importance, as the physicochemical properties of the materials, including PCMs, are influenced over the micro- and nanometer scales. For the

A-class PCMs, consisting of multiple phases, micro-structural changes, like grain growth and phase separation, will greatly affect the materials' behavior. With microscopy techniques, the evolution of micro-structural characteristics can be visualized, providing insights into the changes in the material's properties due to cycling, temperature changes, or any number of other influences. When characterizing a new PCM or a new set of PCM samples, microscopy can be used to provide visual confirmation of the macroscopically observed changes, like alteration of melting temperature or enthalpy due to impurities. Also, for characterizing multi-unit cell samples, microscopy can provide valuable information. Microscopy is being used for different purposes, both looking at grain size, shape, and distribution, and localization of impurity or alloying elements using backscattered SEM or energy dispersive X-ray spectroscopy (Wang et al., 2022), (Kim et al., 2020), (Hayat et al.2023). Optical microscopy or EDS-TEM is often used to determine the number of phases in a microstructure in order to determine the changes in phase fractions or composition. Special SEM techniques exist that can provide visual data on local changes. The big challenge is, of course, to correlate the observed data to macroscopic properties of the PCM. Most micro-quasi measurements are accompanied by thermal analysis, and since it is impossible to measure within a single grain, large test specimens must be made. The larger the specimen, the greater their measurement uncertainties (Ji et al., 2022), (Liritzis et al.2024).

7. RECENT ADVANCEMENTS IN PHASE CHANGING MATERIALS

Phase changing materials (PCMs) have a variety of applications, and novel advancements are being made constantly. In this section, recent developments related to PCMs are discussed. Nanotechnology has a significant share of the advancements that have been made in recent years. In PCMs, the use of nano-phase change materials (n-PCMs) has shown promise. In PCMs with nano-material additives, nano alterations such as doping, impregnation, and encapsulation enable them to surpass micrometer-scale enriched PCMs. The highest performing nano-material additives obtain higher loading levels, which can enhance thermal properties and reduce phase transformation and super-cooling limitations for PCMs. In recent years, environmentally favorable PCMs have drawn a great deal of attention (Talebian et. al.2021). These are known as bio-based phase change materials (bio-PCMs). The production of bio-PCMs does not produce any toxic waste, uses less energy, and provides social and environmental benefits. In the realm of heat transfer methods, various advancements have been established. The development of improved heat transfer systems that integrate with PCM is proof of this advancement. In multiple applications, such as heating, venting, air conditioning, and refrigeration, renewable energy solid-liquid PCMs have been used. Thermal comfort has greatly benefited from the use of PCMs in building structures with unpredictable environmental conditions. Additionally, the use of PCMs in thermal storage systems has added to the overall efficiency of thermal and power plants. Although PCMs are considered highly promising, only a small number of applications are using them today. Scaling up laboratory estimates to commercial levels involves entrusting a new material to a wider community to demonstrate its benefits and reliability. Moreover, the features and reliability of these materials must be considered under realistic operating circumstances (Yadav et. al. 2023), (Mehrizi et. al. 2023). Certain problems are particularly pressing, specifically concerning their capacity and long-term behavior, which is essential for large-scale applications.

7.1. Nanotechnology in PCM Development

Cooling and heating systems are largely one of the major aspects and requirements in today's era, which encouraged scientists to contribute time, energy, and finances to research for the development of phase-changing materials. Nanotechnology, at nanometer length scales, has become important for the enhancement of material properties. The reviewed literature suggests that by adding a small quantity of nanoparticles, the thermal performance of PCMs is significantly improved. Several methods have been used to incorporate a nano-particle into a PCM matrix rapidly. Nanocomposites of PCMs are considered the best mediums for increasing the heat transfer rate as well as the energy-storing capabilities. At the nanoscale level, metal oxides are discovered to be a superior class of nanoparticles to be deployed within PCMs in the preparation of nano-enhanced PCMs/nanocomposites (Choure et al., 2023), (Li et al., 2023). The use of metal oxides or carbon-based nanoparticles in the organic PCM has revealed improvements in the physical and thermal characteristics of the nanocomposites, making them considerably more reliable for various thermal applications.

Though the application of nanotechnology within the PCM is very effective, some difficulties such as cost, debasement of thermal properties, and the lack of back scattering can be significant challenges to the large-scale commercial use of NE-PCMs. The sophisticated approaches to nanoparticles are expensive for adding them into the polymers. At present, the high cost is counting against nano-PCMs, but as the search continues and in order to commercialize these innovative products, the price will be reduced. Three sets of case studies are also highlighted in the later part of this section as a representation of the innovative applications for these NE-PCMs. It can be inferred from the following discussion that substantial research has been carried out in the nano-PCMs domain to develop PCMs with improved properties. This technology presents a good opportunity for developing high-efficiency SM devices (Zhang et. al.2024), (Wong et. al.2023). This technique shows the way and can be employed in the future to provide cost-effective, easy fabrication, deployed in various shapes and sizes, as well as flexible nano-PCMs for many other numerous commercial applications as well as for individual residential applications.

7.2. Bio-based Phase Changing Materials

One of the challenging aspects in the recent research trend is the upsurge of green chemistry consciousness motivated by a greater awareness of environmental preservation and, on the other hand, the constant increase over time of interest and approval for alternative solutions to finite resources. It has been reported that, due to major technical progress, some researchers have already achieved affordable and convertible phase change materials and chemicals from renewable resources that could curb fossil-derived content. The use of renewable resources as phase change materials or ingredients could significantly boost their environmental footprint and reduce disposal costs through composting or even hazardous waste handling. Despite some investigative work from several researchers, the concept of bio-based phase change materials and chemicals is still mainly unaddressed and needs greater attention (Sun et. al., 2020), (Wang et. al.2023).

In some research, a promising and intriguing new sector for the development and use of phyto-molecules in consumer products can be found exemplified in the food, pharmaceutical, commodity, and other production areas. So far, most importantly, more than two-thirds of the top-scoring phase change material development has belonged to materials derived from renewable resources in response to environmentally and user-friendly sustainability. In some extensive reviews, information on bio-based phase change materials has been emphasized from natural oils and fats, characterized by short and long-chain fatty acids; semi-crystalline polyesters; proteins; and nucleobases (Hou, 2024), (Blanco, 2021). Dedicated analyses of these phase change materials, focusing on thermal properties and heat storage performance for most applications, encapsulated, as micro- to macro-sized and infiltrated forms are increasingly described compared to that of low- to mid-density polyethylene glycol and other non-renewable phase change material markets. In comparison with traditional and non-renewable ones, the effects of the type of bio-based phase change material precursor used, production processes, and impurities are not taken into account to the best of the knowledge of any researcher. Its regulatory regime and industrial application opportunities were also only reported briefly. In their most recent works, they did not focus on the main further options for the direct use of renewable compounds as long-chain hydrocarbons and/or technical hydrocarbons formulated with and without them (Jafaripour et. al. 2023).

7.3. Enhanced Heat Transfer Systems

In addition to using PCMs in green construction, researchers have also enhanced the existing systems to cater to advanced needs. These include, along with other applications, HVAC systems, thermal storage management systems, and the aerospace industry. One of the extensive uses of PCMs in advanced research is for the reduction of the cooling load in many heating, ventilating, and air conditioning systems. Recently, research in different PCM systems has also led to the proposal of PCMs as an augmentation for the electronic cooling systems housed in data centers. The PCMs could have the capability of storing the server heat that can be utilized over an off-peak period. In another study, the optimization of shape-stabilized PCM under different freezing conditions is reported. Moreover, the commercial and development process study of PCM-based heat sinks in electronics cooling applications has been reported (Liu et. al., 2020), (Yuan et. al.2021).

For a typical electronics coolant loop, the cooling unit comprises an air cooler with a thermal storage case and an outdoor back cooler, a compressor, a condenser, four electronic expansion valves, four PCMs, four water pumps, and the primary power source. The developed PCM has low cost and potential application value in air conditioning and water heater fields. However, in these PCM-embedded devices, the global warming potential and the ozone depletion potential, as well as the flammability issue of refrigerant, need to be considered. A two-stage PCM-based VCR water heater has been designed to realize the benefits of small size and large capacity. The feasibility of operating under VCR conditions has been validated with local parametric studies through the experimental approach. In general, several PCM-based prototypes can be found in the literature. These embedded designs are described here (Arumugam and Shaik2021), (Muzhanje et al., 2022).

8. CHALLENGES AND FUTURE DIRECTIONS

Today, PCMs are used in modern energy-harvesting or energy-saving technology and have their own toughness. They face several challenges, which are briefly discussed as follows: - Material stability and degradation - Scalability and cost-effectiveness - Integration with existing technologies - Market demand - Consumer attitudes and perceptions - Need for standardization - Regulatory and long-term market acceptance The study of these aspects will help the researcher strategize future research directions to encourage further development of the use of PCMs in today's energy and bio-energy technology. Cross-disciplinary activities and partnerships that include industry will further increase collaborations and stimulate innovation by pushing an approach. This concept brings society closer to embracing PCMs alongside the shift to other sustainable practices in the future. The most promising and challenging area of PCM research for future advancement is to investigate a new generation of PCMs called bio-based PCMs. Bio-PCMs can be sourced from natural resources such as PVCs, SCOs, FCOs, and hydrocarbons. Regarding the second-to-last classification, these are COs released by the bodies of organisms and made available for all PCMs. In further breakdown of the COs, PCMs are not as commercial as other classes. In PUFs, the PCMs considered are either a pure PCM or a mixture of more than one PCM. However, most tests were carried out in the lab, and field studies would be considered important to obtain actual results given the potential risks of chemical change by the addition of other substances.

9. CONCLUSION

Phase changing materials (PCMs) have acquired an upper edge in the contemporary world of technology in thermal storage for energy efficient buildings. In the existing era, energy management is probably one of the biggest relevant issues which have remotely dominated many application domains. Some of the relevant application domains include passive designs for energy efficient residential and commercial buildings, energy efficient heating, ventilation and air conditioning systems, electronics, clothing, automobiles, food, refrigeration, agriculture, solar systems, aerospace and dwelling design. PCMs are capable of storing thermal energy for a long time over a narrow temperature band, which ensures no inconvenient energy is exchanged while also minimizing unit storage volume. An increase in latent heat is now considered a priority because the thermal storage density increases disproportionately with respect to unit volume. This review takes a close look at the various types of organic and inorganic PCMs and highlights developments like nanotechnology advancement and the implications of bio based PCMs.

While the potential of PCMs in various industrial fields has been highlighted, this has also raised some interesting points. For example, what are the prospects, if bio-PCM becomes cost effective on a small scale? Similarly, the potential of bio char coated nano-composite PCM incorporated construction materials and waste materials for potential industrial field become a topic of interest. This review primarily summarizes various palms, peaches, paraffins, steric acid, fatty acid, industrial developed organic and inorganic PCMs. There may be some potential assisting parameters for feedstock selection as renewable PCMs. Additionally, the future pathways; gaps and needs in the field have been discussed. This review paper intends to be beneficial to researchers aspiring to get the knowledge for further improvement in this field. A PCM based textile has been given as an example and entry route in the industrial field. In order to fulfill the global future energy requirements and achieve the recommended target of global climate changes, it is now time for the manufacturer and industrialist to join forces with policymakers, researchers and builders in these fields to develop and future adapt, modern buildings, would be remembered.

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