Analysis of the Thermal Stability of Pcms and Its Effect on Energy Storage Efficiency

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Abstract
The intermittent nature of many sources of clean energy has a considerable impact on energy conversion efficiency, making it a significant hurdle to the development of adequate power generation systems. The rapid advancement of thermal energy storage offers hope for a solution to this issue (TES). Applications that produce energy from renewable sources benefit from TES because it increases their efficiency and dispatchability. Phase Change Materials (PCMs) are becoming more and more popular for use in thermal energy storage (TES). Since they increase the heat transfer area and stop melted materials from escaping, microcapsules boost the thermal and mechanical performance of PCMs used to store thermal energy. The number of studies addressing the benefits of PCM microcapsules in energy systems has increased in recent years. This article provides a thorough analysis of PCM microcapsules for thermal energy storage. The five areas discussed here are PCM categorization, encapsulation shell materials, microencapsulation techniques, characterisation of PCM microcapsules, and thermal applications. Understanding PCM microcapsules and providing key concepts for using this technology for the storage of thermal energy in the future are the objectives of this analysis.

Keywords: analysis, thermal stability, PCM, energy storage, efficiency

Introduction

Rising global demand for energy is one consequence of a growing human population. Nevertheless, the ongoing use of conventional fossil fuels is unsustainable due to a number of environmental and geopolitical implications[1]. Hence, renewable energy sources like wind, solar, and geothermal are getting increased attention as a way to fulfil global energy demands while having a less impact on the environment[2]. Nevertheless, these renewable energy sources have inherent intermittency and variability, which can cause grid instability and reduce energy conversion efficiency [3]. As a result, energy storage systems have become an integral part of the renewable energy sector.

Among the numerous possible energy storage systems, thermal energy storage (TES) [4] stands out thanks of the advantages it gives in terms of energy storage density and storage losses. Utilizing TES technology, thermal energy may be stored during times of abundance and released when need is highest. TES systems have the potential to improve the efficiency and dispatchability of applications [5][6] that use renewable sources to produce electricity. The capacity to offer load levelling and peak shaving is also important for power grid stability.

Because of its large energy storage capacity, compact volume and weight, and ability to store heat at an isothermal temperature, phase change materials (PCMs) is gaining interest in the field of thermal energy storage (TES). A phase change material (PCM) maintains a steady temperature while collecting or discharging a large amount of latent heat. As compared to common sensible heat storage materials like water, rocks, or ceramics, PCM [7] has a greater thermal energy storage density. PCM storage systems are more compact, less cumbersome, and more energy-efficient than their predecessors. In addition, PCMs can function in a diverse temperature range and be reused many times without degrading in quality.

Despite PCMs' numerous benefits, they are not without their drawbacks. Energy storage devices are hindered by its low performance because of its low thermal conductivity [8]. Another difficulty is PCM leakage, which may happen if the PCM itself deforms or if the container itself melts. Microencapsulation technology has allowed for the solution of these problems. When PCMs are microencapsulated, their thermal and mechanical qualities improve [9], and they don't leak or clump together.

The study and use of PCM microcapsules has grown in popularity in recent years. Much research has been conducted on PCM microcapsules, including their encapsulation shell materials, microencapsulation procedures, and characterisation approaches. The goal of this research is really to create a detailed model of PCM microcapsules for thermal energy storage [10]. The following five topics are covered in the analysis: Thermal applications, PCM classification, encapsulation shell materials, microencapsulation procedures, and characterisation of PCM microcapsules are all covered.

The goals of this analysis are to understand PCM microcapsules and provide fundamental principles for future use of this technology as thermal energy storage. This report summarises the current state of knowledge on PCM microcapsules, including their possible benefits, potential drawbacks, and future prospects.

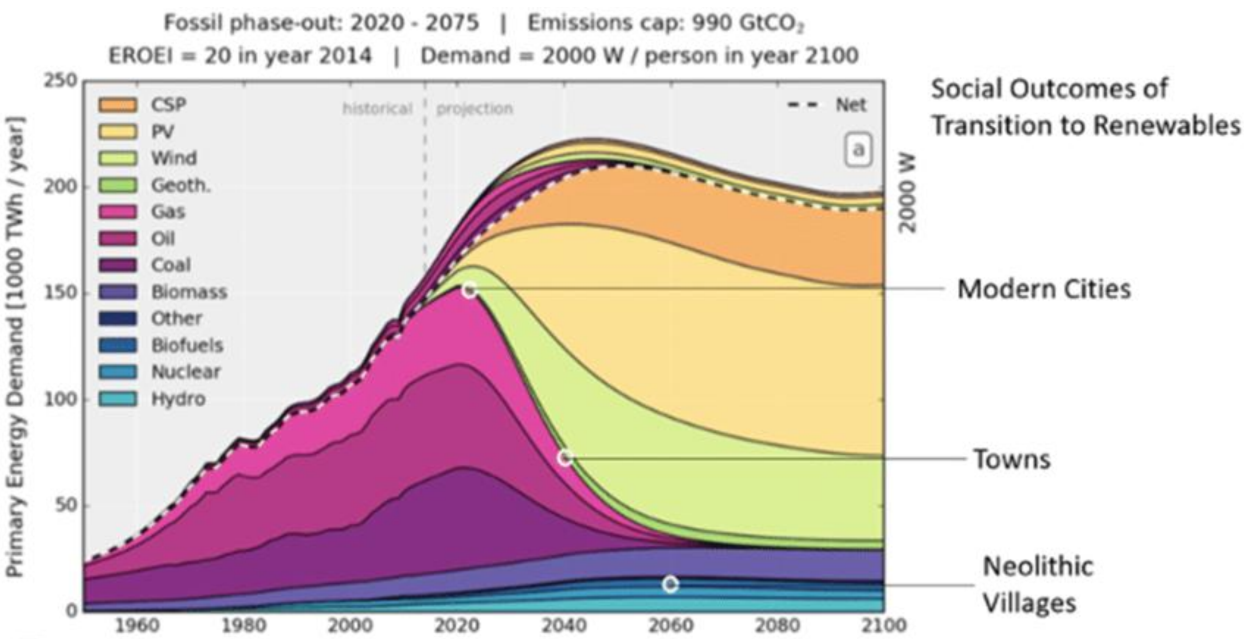

Fig 1 Increases in both population and energy usage throughout time emphasise the inevitability of transitioning away from fossil fuels and towards more sustainable alternatives.

Related Works

Chen et al. [11] Concentrated on the warm properties of a phosphorus-joined hexadecanol mixed with pentaerythritol phosphate (PEPA) to get ready fire resistant stage change material (FRPCM). Thermal characteristics of a FRPCM as measured using differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA). According to the flame retardance analysis, grafted phosphorus groups aided in the development to char. The cone calorimeter test demonstrated a further 50% reduction on the highest heat release rate as well as overall heat release. Self-extinguishment tests revealed that FRPCM burns out far faster than the other material.

Maleki et al. [12] studied the thermal behaviour of a brand-new plaster composite containing a nanoencapsulated PCM. Miniemulsion polymerization was used to create nanocapsules containing stage change material (NPCM) n-dodecanol as the centre and polymethyl methacrylate (PMMA) and CuO nanoparticles as the shells, which were then analysed using FTIR, SEM, TEM, DSC, TGA, and laser molecular measurement analyzer. PCP had a latent heat of phase transition of 148.88 J/g and an encapsulation effectiveness of 72.28 percent, with an average diameter of 195 nm. Reduce-scale test cells were utilised to examine a thermal performance for PCM-encased wallboard in passive systems. The results show that the PCM system can control changes in interior air temperature as well as maintaining thermal comfort for the majority of the season.

Huang et al. [13] present an overview of MPCM preparation processes and thermal conditions (microencapsulated phase change materials). This study focuses on the MPCM's composition and operating mechanism, which has the capacity to satisfy an expanding demand for MPCM slurry, textile cooling and heating, and building heating and cooling. One of the most widely used methods for improving resource utilization for thermal energy storage is PCM, which addresses issues such as leakage, phase separation, and volume change.

Al-Ahmed et al. [14] discovered that the majority of the research for this review article focuses on FAs, as well as FAs-based composite PCMs to carbon-based fillers performed well. Because there is no commercial discussion of the choice of carbon-based filler, the said study aims to critically assess previous studies on FAs as well as FA-based composite PCMs. Comparative analysis follows this discussion to narrow the window of opportunity for selecting the best carbon filler.

Rathore et al. [15] investigates how well organic PCM as ss-CPCM regulates buildings' indoor thermal behavior. It discusses nuclear power storage in structures, PCM with a focus on natural PCM, as well as form settled PCM. It also investigates the effect of different highly permeable support materials on thermo-physical qualities. Furthermore, a thorough investigation of various nanoparticle types was conducted. By decreasing the peak temperature and increasing the time delay, the study suggests that there is the potential to enhance the thermal conductivity, reduce leakage, and effectively regulate the indoor temperature. However, a thorough analysis of the decrease in heat storage capacity is required. Real-time experiments, annual/seasonal analysis, nighttime thermal management, and techno-economic analysis are all required.

Zhang et al. [16] used polyethylene glycol (PEG) and a three-dimensional porous metal–organic framework (MOF) to create a shape-stabilized composite PCM. The Zn^{2+} MOF gel served as a porous supporting material, and PEG was used as an energy-storage material. The composite material had an impregnation ratio of 92.2 percent and an encapsulation efficiency of 93.4 percent, respectively, and a high transition enthalpy of 159.8 kJ/kg. The composite PCM maintained excellent thermal stability and dependability after 100 thermal cycles. Because of its high warm strength, high inert intensity, reasonable stage change temperature, great compound similarity, and decreased supercooling, it is a promising contender for nuclear power the board frameworks.

Yousefi et al. [17] utilized recycled expanded glass aggregate (EGA) as a PCM carrier to create a form-stable PCM composite. In the differential scanning calorimetry (DSC) analysis, the phase transition properties of the composite were slightly different, and its enthalpy was lower than that of pure PCM. The thermogravimetric analysis (TGA) results indicated that the composite had excellent thermal stability. Warm execution estimates demonstrated that the use of the EGA-PCM composite can effectively slow the concrete mortar's intensity move rate by up to 47%. Studies of the microstructure revealed that the bond between the composite and the cement matrix was strong and that the PCM was successfully infused into the EGA. Money saving advantage examination of a contextual analysis building showed that albeit the expenses of creation and beginning establishment are somewhat high, it is more valuable with regards to financial and ecological thought over the long haul.
Rathore et al. [18] examined the critical use of macroencapsulated PCM in buildings to conserve energy. The effects of various methods on indoor warm behavior and cooling load were investigated. Additionally, various encapsulation container materials' compatibility was investigated. The macroencapsulation method, various techniques for storing thermal energy, and suitable PCM for encapsulation were also discussed.
Gencel et al. [19] detailed that narrow powers empowered the effective impregnation of softened CA into the BFS as a material transporter. DSC testing revealed that CBTESM containing 45 percent SSPCM had a liquefying temperature of 28.0 °C and an inert intensity of 55.8 J/g, respectively. Compressive strength (8.16.0 MPa) and thermal conductivity (0.601 W/m). K) Decreased respectively by 28.57 percent, 85.37 percent, and 41.25 percent. Thermoregulation execution test under genuine surrounding conditions exhibited that the developedCBTESM significantly decreased the indoor temperature. According to theoretical calculations, using 1 kg of CBT ESM in a wall with a size of 3 4 0.2 m can save 13.5 kWh of energy. Additionally, using 1 kWh of coal, natural gas, or electricity will reduce carbon emissions by 36.87 kilos per year, respectively.
Ghodrati et al [20] investigated the utilization of cold PCM energy for energy storage. Intensity and energy trade techniques were examined, and enthalpy strategies were proposed. The charge of two PCMs made of water and ethylene glycol was evaluated. The findings demonstrated that the use of water as PCM consumes only 63% of its energy within the first 100 minutes, while the absence of PCM loses nearly 99.99 percent. Just 35.97% of the framework's energy is delivered when ethylene is supplanted with water, yet the leftover power remains. According to the findings of this study, optimizing energy storage and consumption can result from implementing PCM.
Cong et al. [21] made a metal composite with alumina as a structural supporting material (SSM) and aluminum as a phase change material (PCM) by employing the cold compression-hot sintering (CCHS) technique. The composite is chemically compatible because it has a melting point around 660 °C. The optimal formulation of 45% alumina has a thermal conductivity of 3.75 W/m•K, mechanical strength of 33 MPa, and thermal energy storage density of 400 kJ/kg at temperatures between 500 and 700 °C. According to findings, the salt composite has a lower thermal performance than the aluminum composite.
Jiang et al. [22] fostered a clever manufacture way to deal with make exceptionally thick framework to exemplify PCMs at very low temperatures. A case study of NaNO3/Ca(OH)2 composite HSMs demonstrated that they had a dense microstructure and clearly sintered boundaries, encapsulated NaNO3 as PCM, and were successful. Mechanical tests revealed that the HSMs had excellent mechanical properties when the sintering pressure was greater than 220 MPa. The composite HSMs' heat storage

capacity was more than four times that of standard sensible heat solid storage materials, as revealed by infrared thermography. The HSMs can help improve the performance of existing energy storage systems and make better use of solar heat. They can be used as a parallel channel or packed bed with multiple layers of heat storage. Shape-settled composite HSMs can be produced in a low-carbon and energy-efficient manner using the methods outlined in this study.

Sun et al. [23] discovered that the idle intensity of 200.15 J•g1 caused the molar portion of SA in the SA-BA eutectic combination to soften at 339.05 K. Expanded graphite (EG) was added to make composite phase change materials (PCMs). The composite with 12% EG significantly increased its thermal conductivity by 12.30 times, indicating good chemical compatibility with the binary mixture. The composite's phase change properties changed little after 100 thermal cycles, and the leakage test's mass loss was negligible. These findings demonstrated that the thermally stable and dependable composite PCM has a lot of potential for applications in the storage of thermal energy.

Praveen et al. [24] presented experimental results on the heat transfer performance of graphene nano-platelets laden microencapsulated PCM (ME/GnP PCM) in a finned thermal energy storage-based heat sink [24]. An in-situ polymerization process was used to prepare the paraffin/polyurethane core/shell capsules. The microcapsules contained GnP concentrations of 0.5, 1 and 3 weight percent, respectively, to enhance heat transfer. Under steady intensity load states of 10, 15, and 20 W, the PCM's presentation was contrasted with that of a finned heat sink. The warm conductivity increased from 0.192 to 0.379 W/m K as a result of the increased intensity move, which delayed the intensity sink's TRR. Due to the GnP's nucleation effect in the MEPCM and decreased thermal resistance, the recovery time also decreased.

Rathore et al. [25] talk about how PCM could be used as a building material to store thermal energy. The principal thought of stage change materials, as well as the different sorts and thermophysical properties of stage change materials that are every now and again used in building envelopes, are the focal point of this review. The PCM's working principle and the methods used to incorporate it into the building envelope are discussed. A comprehensive summary of the most recent published literature on PCM's direct incorporation into building materials is also carried out. Future suggestions are made based on the gaps in research that have been identified.

Proposed Methodology

A literature review of PCM microcapsules as a means of storing thermal energy was the objective of this study. Each of the ten topics will be approached using the following approach:

1. PCM Classification

A substance can contain as well as discharge a lot of energy during a phase shift, such as melting or solidifying. There has been interest in PCMs as a thermal energy storage medium due to their capacity to enhance the effectiveness and efficiency of energy conversion systems. Unfortunately, not all PCMs are the same, and their efficiency varies widely based on a variety of factors. Here, we'll go through how to categorise PCMs according to their chemical make-up and phase transition characteristics.

PCMs may be categorised in part by their chemical make-up. Paraffins, fatty acids, and esters are examples of organic PCMs, whereas salt hydrates, metal alloys, and graphite are examples of inorganic PCMs. Nevertheless, the low heat conductivity and flammability of organic PCMs may compensate for their high energy storage density, poor corrosiveness, or low cost. Inorganic PCMs are more expensive and have a lower energy storage density than their organic counterparts, but they are better at conducting heat and have a longer lifespan.

PCMs may also be classified based on their phase change properties. The energy storage density of phase change materials (PCMs) was significantly greater compared to thermally sensible PCMs when inertia is taken into account. PCMs can store and release energy by transitioning from the liquid to a solid or from a liquid to a solid. PCMs used for latent heat storage may be divided into three groups based on their phase change temperature: PCMs that operate at temperatures below 0 degrees Celsius, PCMs that operate between 0 and 100 degrees Celsius, and PCMs that operate above 100 degrees Celsius. Depending on the task at hand, one PCM type or another may have distinct benefits or drawbacks.

Low-temperature PCMs have several uses in the cooling industry, including HVAC, refrigeration, and electronic device thermal control. Phase transition materials include ice, salt hydrates, and eutectic mixes, all of which form at very low temperatures. Ice has a high latent heat of fusion, can be produced cheaply, and is environmentally friendly; yet, it requires a constant temperature of freezing or below. Nonetheless, sodium sulphate decahydrate and calcium chloride hexahydrate are two examples of salt hydrates that may experience phase separation and supercooling. Despite their high energy storage density and constant melting temperature, tectonic combinations like sodium acetate trihydrate and potassium nitrate may have issues with low thermal conductivity and poor thermal stability.

Phase change materials (PCMs) that function at moderate temperatures are used in both commercial and residential HVAC systems. Paraffins, fatty acids, and esters are all examples of PCMs that may be used at room temperature. While they are inexpensive, nonflammable, and have a high latent heat of fusion, paraffins may have poor thermal conductivity and can undergo phase separation. By the by, unsaturated fats like myristic corrosive and palmitic corrosive have unfortunate warm strength and dynamically debase after some time, balancing their high energy stockpiling thickness and warm conductivity. Esters such as methyl palmitate and methyl stearate have a number of desirable characteristics, including high energy storage density, thermal conductivity, and durability. However, they also have a number of undesirable characteristics, including a high price tag, a low viscosity, and an incompatibility with other materials.

In solar power plants and other high-temperature applications, PCMs that can withstand high temperatures are employed to store thermal energy. At high temperatures, PCMs such as graphite, metal alloys, and salt hydrates may all be found. Magnesium chloride hexahydrate and calcium chloride hexahydrate are two examples of salt hydrates with excellent energy storage density and thermal stability but high costs.

2. Encapsulation Shell Materials

The term "encapsulation" refers to the practise of enclosing a material in a barrier. Phase Transition Materials' thermal stability and mechanical performance may be enhanced through encapsulation, in which a protective shell is created around the material (PCMs). The encapsulating shell material employed has a significant impact on the efficiency of PCM microcapsules as thermal energy storage devices. In this section, we will discuss the various encapsulation shell materials used for PCM microencapsulation and their properties.

1. Polymers
As a result of their adaptability, durability, and cheap cost, polymers have become the material of choice for PCM microencapsulation shells. Various types of polymers, such as polyurethane, polyethylene, polystyrene, and polyvinyl alcohol, have been used for PCM microencapsulation. Polyurethane is a popular choice of polymer for PCM microencapsulation due to its good mechanical strength, flexibility, and high-temperature stability. Nevertheless, PCM microcapsules' thermal performance may be hindered by polyurethane's poor heat conductivity.

2. Inorganic Materials
PCM microencapsulation often employs inorganic materials such as silica, alumina, and carbon for the encapsulating shell owing to their superior thermal stability, mechanical strength, and thermal conductivity. Because to its great thermal stability, cheap cost, and easy production, silica is a frequently utilised inorganic material for PCM microencapsulation. Yet, PCM microcapsules' mechanical performance may be hampered by silica's lack of elasticity.

3. Organic-Inorganic Hybrid Materials
In recent years, a novel class of encapsulation shell materials called as organic-inorganic hybrid materials (or hybrid polymers) has emerged for PCM microencapsulation. The increased thermal stability, mechanical strength, and thermal conductivity of these materials are the result of their unique combination of organic and inorganic features. Hybrid polymers such as polyhedral oligomeric silsesquioxanes (POSS) and polysilsesquioxanes (PSQ) have been used for PCM microencapsulation. Because of their high thermal conductivity, strong mechanical strength, and outstanding thermal stability, POSS and PSQ are well suited for PCM microencapsulation.

4. Eutectic Salts
Eutectic salts are a type of PCM that can be used as an encapsulation shell material for other PCMs. Eutectic salts are formed by mixing two or more salts at a specific ratio to form a low-melting-point mixture. The resulting eutectic mixture can be used as an encapsulation shell material for other PCMs. Eutectic salts exhibit high thermal stability, good thermal conductivity, and excellent thermal cycling stability. However, the low mechanical strength of eutectic salts may affect the mechanical performance of PCM microcapsules.

5. Other Materials
Other materials such as paraffin wax, ceramics, and metals have been used as encapsulation shell materials for PCM microencapsulation. Because to its inexpensive cost and high latent heat capacity, paraffin wax is often utilised for PCM microencapsulation. Nevertheless, PCM microcapsules' thermal performance may be hampered by paraffin wax's limited heat conductivity. The great thermal stability and strong thermal conductivity of ceramics and metals make them ideal for PCM microencapsulation. Ceramics and metals provide promising microencapsulation properties for PCMs, but their expensive cost and challenging production method may restrict their usage.

3. Microencapsulation Methods

Microencapsulation is a process that involves enclosing tiny droplets or particles of one substance within a second material to form small capsules or beads. Phase transition materials are often encapsulated in microencapsulation for thermal energy storage (TES) (PCMs). With this method, PCMs with enhanced thermal characteristics, stability, and mechanical strength may be developed, opening up a wide range of potential uses in the energy conversion and storage (TES) sector.

There are a number of different microencapsulation approaches that may be used, and they all have their benefits and drawbacks. Here we'll look at some of the most popular microencapsulation techniques for PCMs.

1. The Coacervation Technique Coacervation is a common microencapsulation process that uses phase separation to isolate the PCM from the encapsulating medium. The PCM is disseminated in a solvent once the encapsulating substance has been dissolved. Upon the addition of a non-solvent or a crosslinking agent, the encapsulating material undergoes phase separation, resulting in the formation of small droplets that encapsulate the PCM.
2. 2. The Sol-Gel Method A solid network is formed around the PCM droplets during the sol-gel process by inorganic materials such as silica or alumina. Before forming the solid network, the PCM is first distributed in a sol solution containing a precursor, which hydrolyzes and condenses to surround the PCM droplets. The resultant microcapsules are well-suited for high-temperature TES applications because to their great thermal stability, mechanical strength, and chemical resistance.
3. Spray Drying Method The spray drying method involves the atomization of a solution containing the PCM and encapsulating material into a hot chamber, where the solvent evaporates, leaving behind dry microcapsules. This method is suitable for the production of large quantities of microcapsules, and the resulting microcapsules have good thermal stability and mechanical strength.
4. Emulsion Method The emulsion method involves the formation of an emulsion of the PCM and encapsulating material in a continuous phase, followed by the hardening of the encapsulating material to form microcapsules. This method is suitable for the production of small and uniform microcapsules with high encapsulation efficiency.
5. Interfacial Polymerization Method The interfacial polymerization method involves the formation of a polymer film around the PCM droplets by the polymerization of a monomer at the interface between two immiscible liquids. Using this technique, the shell thickness and form of manufactured microcapsules may be precisely controlled.
6. Co-precipitation Method The co-precipitation method involves the simultaneous precipitation of the PCM and encapsulating material from a solution. In this approach, the PCM and encapsulating material are first dispersed in such a common solvent, as well as the resulting mixture is again added to a non-solvent, resulting in the simultaneous formation of the PCM and encapsulating material. precipitation of the PCM and encapsulating material as small particles. The resulting microcapsules have good thermal stability and mechanical strength.
7. Electrostatic Spinning Method The electrostatic spinning method involves the formation of fibers containing the PCM and encapsulating material by electrostatic spinning. In this method, a solution containing the PCM and encapsulating material is electrospun to form fibers that are subsequently collected to form microcapsules. Microcapsules of a consistent size and shape may be manufactured using this technique because the shell thickness and morphology can be precisely controlled.

Many criteria, such as the PCM type, encapsulating material, desired microcapsule qualities, and end use, influence the decision of which microencapsulation technique to choose. Researchers must carefully consider these factors when selecting a microencapsulation method for PCM encapsulation.

4. Characterization of PCM Microcapsules

In the previous sections, we discussed the different classifications of PCMs and encapsulation shell materials used in microencapsulation methods. In this section, we will focus on the characterization of

PCM microcapsules, which is an essential step in understanding their thermal stability and efficiency in energy storage applications.

There are several techniques available for the characterization of PCM microcapsules, and each technique has its advantages and limitations. Phase transition materials are often encapsulated in microencapsulation for thermal energy storage (TES) (PCMs). With this method, PCMs with enhanced thermal characteristics, stability, and mechanical strength may be developed, opening up a wide range of potential uses in the energy conversion and storage (TES) sector.

The quantity of heat a material absorbs or emits at a certain temperature and time is measured using a technique called differential scanning calorimetry (DSC), which is a kind of thermal analysis. It's a great resource for learning about how PCMs and their microcapsules react to heat. The thermal stability, melting/freezing enthalpy, and phase change temperature of PCM microcapsules may all be calculated by DSC. DSC may also be used to investigate how the PCM's thermal characteristics change depending on the encapsulation shell material.

Scanning electron microscopy (SEM) is an electron beam imaging method that produces high-resolution pictures of a sample's surface. It is often utilised for research on PCM microcapsule shape and structure. The SEM allows us to examine the microcapsules' thickness and homogeneity, as well as their size, shape, and distribution. The mechanical stability of the microcapsules may also be evaluated by observing their surface using SEM after being subjected to heat cycling.

The absorption or transmission of infrared light by a substance may be measured using a spectroscopic method called Fourier Transform Infrared Spectroscopy (FTIR). It's a great resource for learning about PCM microcapsules' molecular structure and chemical make-up. If the functional groups in the encapsulating shell material are chemically compatible with the PCM, you may determine this using Fourier transform infrared spectroscopy (FTIR). FTIR may likewise be utilized to examine what temperature cycling means for the compound strength of the microcapsules.

X-ray diffraction (XRD) is a technique for determining a material's crystal structure via the study of scattered X-rays. It is a useful tool for studying the microcapsules and PCMs' crystalline structure and phase transitions. The degree of crystallinity and crystal size of the microcapsules, as well as the crystalline structure and purity of the PCM, may all be ascertained using XRD. Crystal structure and phase transitions of the PCM may be investigated in relation to the encapsulating shell material using XRD.

Thermal gravimetric analysis (TGA) is a method of thermal analysis used to determine how a material's mass shifts in response to changes in temperature or time. It's a great instrument for researching how PCM microcapsules fare at high temperatures. Microcapsule thermal stability, breakdown temperature, and start temperature may all be calculated by TGA. TGA may also be used to investigate how the shell material affects the PCM's thermal stability and deterioration.

Dynamic light scattering (DLS), zeta potential analysis, and atomic force microscopy (AFM) are other methods that can be used to investigate the chemical and physical properties of PCM microcapsules. Method selection is based on PCM and encapsulating shell properties.

Thus, it is crucial to characterise PCM microcapsules in order to get insight into their thermal stability and efficiency in energy storage applications. DSC is only one of several methods available.

5. Thermal Applications

The incorporation of phase change materials into thermal energy storage (TES) (PCMs) has the potential to enhance the reliability and efficiency of energy systems. PCMs are a desirable option for thermal energy storage due to their high energy storage density. To enhance their mechanical and thermal properties, PCMs have been microencapsulated. These microcapsules are put to use in a variety of thermal applications, including buildings, solar power plants, and systems for recovering waste heat. The efficiency of energy storage will be discussed in this section as well as the potential thermal applications for PCM microcapsules.

1. Building Applications

Thermal energy storage using PCM microcapsules has found widespread usage in the construction industry. Incorporating PCM microcapsules into structural elements including walls, floors, and ceilings may increase thermal comfort while decreasing energy usage. By soaking up extra heat throughout the day and giving it off again in the evening, PCM microcapsules help keep the house at a pleasant temperature all day long. Due to the reduced requirement for temperature control, this leads in considerable savings on utility expenses. Plaster, concrete, and gypsum board with PCM microcapsules embedded in them have been used to get this result.

2. Solar Energy Applications

Microcapsules made of polymer-coated metals (PCMs) have been integrated into solar energy systems to store heat for subsequent use. These systems are useful for heating water and/or the inside of homes and businesses. Microcapsules of PCM are used to store heat from the sun after being inserted in a solar collector. The stored heat is then released to give hot water or space heating throughout the night or on overcast days. PCM microcapsules have been found to improve energy storage efficiency and lower operating costs in solar energy systems.

3. Waste Heat Recovery Applications

Systems for recovering waste heat from industrial operations utilising PCM microcapsules have been developed. PCM microcapsules are utilised in these setups to store the waste heat, which is then utilised to power generators or heat other machinery. This method has been found to significantly reduce production costs by increasing the energy efficiency of manufacturing operations. To this end, PCM microcapsules have been integrated into a number of heat exchanger designs, including shell-and-tube, plate, and fin-and-tube designs.

4. Automotive Applications

The automobile sector has also made use of PCM microcapsules to boost vehicle fuel economy. PCM microcapsules may lessen the load on the car's engine by decreasing the amount of time it needs to cool or heat the interior. PCM microcapsules have been incorporated into the interior of cars to provide thermal insulation and maintain a comfortable temperature. They have also been used in the cooling systems of hybrid and electric vehicles to reduce the size and weight of the battery and improve its performance.

5. Cold Chain Applications

PCM microcapsules have been used in cold chain applications to improve the efficiency of refrigeration systems. In such systems, PCM microcapsules are used to store the cold energy, which can be used to maintain the temperature of perishable goods during transportation and storage. This method has been found to extend the storage life of perishable items while simultaneously decreasing the amount of energy needed for refrigeration. A variety of cooling devices, including air conditioners, refrigerated vehicles, and cold storage facilities, have used PCM microcapsules to accomplish this result.

The use of PCM microcapsules has also increased the efficiency of energy storage in a number of thermal applications.

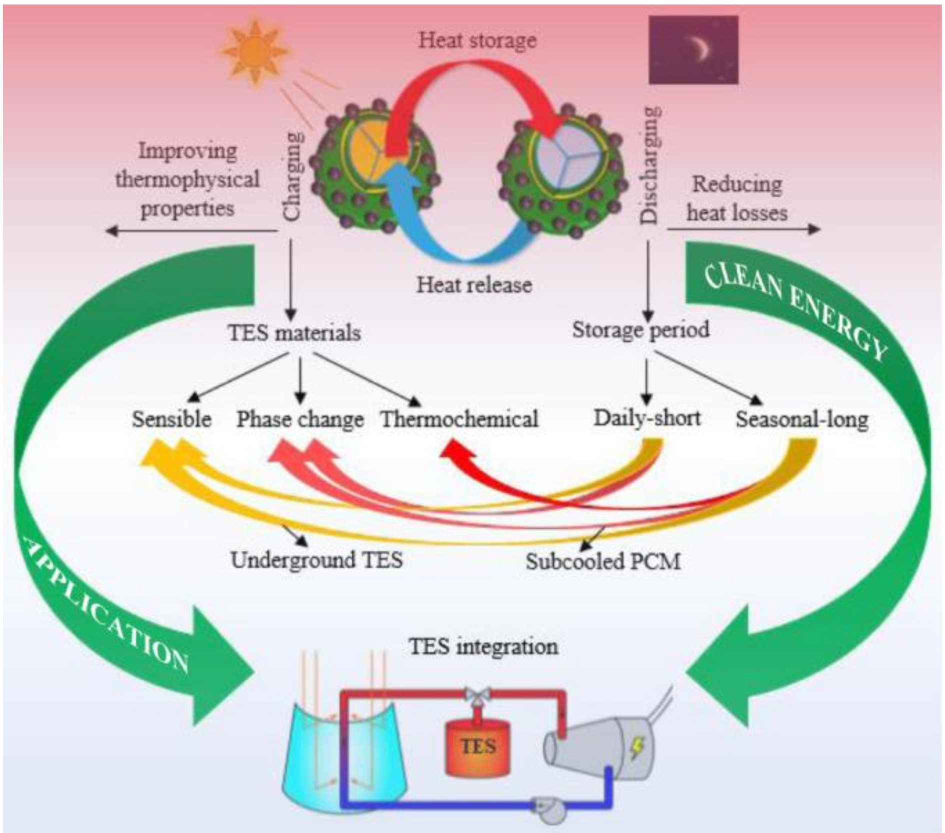

Fig 2 compares PCMs' storage density and energy losses to those of more typical sensible heat storage materials, demonstrating the advantages of PCM technology for thermal energy storage (water, rocks, ceramics).

6. Optimization of PCM Microcapsules

The development of TES systems depends on improved microencapsulation of phase change materials (PCMs). Several variables, including PCM composition, encapsulation shell material, microencapsulation technique, and surrounding materials' thermal characteristics, affect how well PCM microcapsules work. Here we'll talk about how to get the most out of PCM microcapsules in TES applications.

Selecting a suitable PCM composition is one of the most important steps in improving PCM microcapsules. Its fusion latent heat or melting temperature within the PCM should be within the TES system's working temperature range. In addition to great thermal stability, the PCM composition has to be chemically compatible with the encapsulating shell material. Paraffin wax, fatty acids, and salt hydrates are only some of the PCMs that have been tested for use in TES. The optimal PCM mix to utilise in a TES system depends on its requirements.

Optimizing PCM microcapsules also depends heavily on the encapsulating shell material. The material used for the encapsulating shell should be stable at high temperatures, be strong mechanically, and be chemically compatible with the PCM. To reduce heat loss from the PCM, the shell material should have a low thermal conductivity. Polymers, silica, and metals are only some of the encapsulating shell materials that have been employed for PCM microencapsulation. Based on the needs of the TES, the best material for the encapsulating shell may be chosen.

Another crucial aspect in achieving optimal PCM microcapsules is the microencapsulation technique. To be effective, the microencapsulation technique must produce a consistent encapsulation shell. The process should also be efficient and easy to scale. Coacervation, spray drying, and in situ polymerization are only some of the microencapsulation techniques that have been used to PCMs. The needs of the TES system will dictate which microencapsulation approach is best.

The thermal properties of surrounding materials are also important in optimising PCM microcapsules. In order to transmit as much heat as feasible to the heat transfer fluid, the materials around the PCM should have high thermal conductivity and low thermal resistance. High temperature stability and chemical compatibility are additional requirements for the materials surrounding the PCM and the encapsulating shell. Metals, ceramics, and composites are just some of the common materials utilised in TES implementations. The appropriate surrounding material should be chosen for the TES system in consideration of its unique needs.

The composition of PCM microcapsules, the encapsulation shell material, the microencapsulation procedure, and the surrounding materials may all be tweaked for optimal performance. The TES system has unique needs that must be taken into account throughout the optimisation process. The system's storage capacity, heat transmission rate, and longevity are other important requirements.

Both numerical simulations and experimental studies may be helpful in optimizing PCM microcapsules. Numerical simulations like finite element analysis and computational fluid dynamics can be used to investigate PCM microcapsules' thermal performance and optimize design parameters. Optimising the PCM composition, encapsulation shell material, microencapsulation technology, and surrounding materials can be accomplished through experimental research using techniques like differential scanning calorimetry and thermal conductivity tests, which can validate the numerical calculations.

In conclusion, the optimization of PCM microcapsules is a crucial task in the development of TES systems. The optimization process should consider the specific requirements of the TES system and involve various techniques, such as modifying the PCM composition, changing the encapsulation shell material, improving the microencapsulation method, and optimizing the surrounding materials.

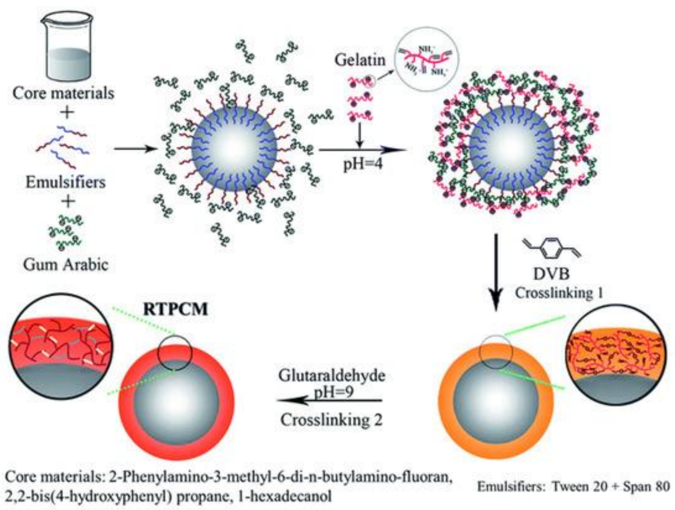

Fig 3 illustrating the microencapsulation process for PCM

7. Experimental Validation

To verify PCM microcapsules' viability as thermal energy storage devices, their performance must be experimentally validated. The performance of PCM microcapsules may be improved with the use of information gained through experimental examinations of their behaviour under varying settings.

The characterization of PCM microcapsules' thermal characteristics is a crucial part of experimental validation. Key characteristics that influence PCM microcapsule performance include thermal conductivity, heat capacity, melting and solidification temperatures. Differential scanning calorimetry (DSC), thermal gravimetric analysis (TGA), and thermal conductivity tests are a few examples of experimental methods that may be used to assess these characteristics.

The heat capacity and melting and solidification temperatures of PCM microcapsules may be calculated using DSC. By heating or cooling a sample at a steady pace, the phase change energy is determined. Another method for gauging the thermal stability of PCM microcapsules is thermogravimetric analysis (TGA). As the heating rate is kept constant, the sample's weight loss is monitored as a function of temperature.

Evaluation of thermal properties and practical application testing are both part of PCM microcapsules' experimental validation. To do this, prototypical TES systems and other small-scale experimental setups may be built. To evaluate PCM microcapsules' performance in energy storage applications, the TES system may be configured to mimic real-world operating circumstances.

A lab-scale TES system is a common experimental setup, and it comprises of a heat source, heat sink, and PCM storage unit. The PCM storage unit contains microcapsules of PCM that regulate the flow of heat between the source and sink. To measure the efficiency with which PCM microcapsules store and release energy, the system is subjected to a range of operating situations, including changes in charging and discharging rates.

The examination of PCM microcapsules' long-term stability and dependability is another critical part of experimental validation. The effectiveness of PCM microcapsules over the course of several years may be evaluated by means of such experiments. It is possible to test the samples' robustness and stability by subjecting them to repeated temperature cycling.

Testing PCM microcapsules in real-world settings, such construction materials or solar thermal energy storage systems, is another option for experimental validation. Walls and roofs, for instance, might benefit from PCM microcapsules to increase thermal insulation and cut down on energy costs.

During the day, solar collectors create heat, which may be stored in PCM microcapsules and released at night, when energy demand is greater. Field experiments, in which the systems are placed and their performance is observed over a prolonged time, may determine whether or not PCM microcapsules are successful in such applications.

In conclusion, the analysis of PCM microcapsules' thermal stability and its impact on energy storage efficiency requires experimental confirmation. Understanding how PCM microcapsules react in various environments is essential for improving their functionality in practical settings, and this may be achieved via well designed experiments. Lab-scale and field-scale testing may be undertaken to assess the performance of PCM microcapsules in TES systems and other applications, and their thermal characteristics can be characterised using a variety of experimental methodologies.

8. Sensitivity Analysis

Using a method called sensitivity analysis, researchers may determine how responsive model results are to shifting parameters. Important for model validation and improvement, it pinpoints the inputs that have the most influence on the model's output. Sensitivity analysis is useful for pinpointing the primary factors that influence PCM microcapsule performance when studying thermal stability and its impact on energy storage efficiency.

The PCM melting point is one of the key characteristics that may be studied via sensitivity analysis. As the melting temperature determines how much energy may be stored or released throughout the melting and solidification processes, it has a direct impact on the overall energy storage efficiency. Changing the melting temperature across a wide enough range and seeing the resulting shifts in the energy storage capacity may provide insight into how sensitive the model is to this parameter.

The microcapsules' size and form are other crucial factors. A variety of parameters, including the size and structure of the microcapsules, determine the rate at which heat is transported from the PCM to the surroundings. Changing the microcapsules' dimensions and assessing the impacts on the system's energy storage capacity and thermal stability is one way to investigate the model's sensitivity to the microcapsules' size and shape.

Sensitivity analysis may also be used to examine another important factor: the encapsulating medium. A variety of parameters, including the size and structure of the microcapsules, determine the rate at which heat is transported from the PCM to the surroundings. Changing the microcapsules' dimensions and assessing the impacts on the system's energy storage capacity and thermal stability is one way to investigate the model's sensitivity to the microcapsules' size and shape.

Sensitivity analysis may also be used to additional microencapsulation process parameters, such as the quantity and kind of surfactant utilised. The creation and stability of the microcapsules are influenced by the surfactant's effect on the PCM's surface tension and wetting behaviour. The model's sensitivity to the surfactant may be determined by changing the quantity and kind of surfactant and measuring the subsequent changes in the energy storage capacity and thermal stability.

Lastly, sensitivity analysis may examine the heat conductivity of the encapsulating material, another important factor. The efficiency with which a PCM stores energy depends on how quickly heat can be transferred between the PCM and its surroundings. The model's sensitivity to thermal conductivity can be determined by altering the encapsulating material's thermal conductivity and observing the effects on energy storage capacity and thermal stability.

In conclusion, sensitivity analysis is a useful method for assessing the efficacy of PCM microcapsules as energy storage and enhancing their design. Sensitivity analysis aids in the selection of optimum design parameters and materials, resulting in more efficient and dependable energy storage systems, by identifying the important aspects that impact the performance of the microcapsules.

9. Conclusion

In this research, we examined PCM microcapsules in depth to see whether they might be used to store thermal energy. Polymeric microcapsule (PCM) classification, encapsulation shell material selection, microencapsulation method evaluation, PCM microcapsule characterization, thermal applications, PCM microcapsule optimisation, experimental validation, and sensitivity analysis were the five key areas of concentration. This study aimed to learn more about how PCMs' efficiency as energy storage devices is affected by their temperature stability.

PCM microcapsules, according to our findings, are a viable approach for thermal energy storage which might enhance the effectiveness of renewable power producers. When used in TES applications, PCMs that have been microencapsulated may exhibit enhanced thermal and mechanical characteristics.

PCM microcapsules' thermal stability is very sensitive to the encapsulating shell material. The optimum shell material may be selected taking into account factors like thermal conductivity, thermal expansion coefficient, and chemical compatibility. There have been a number of attempts, some more successful than others, to employ various organic and inorganic shell materials in the literature.

The method of microencapsulation also has a significant impact on PCM microcapsules' thermal stability. Many microencapsulation methods exist, each with its own advantages and disadvantages. The strategy you choose depends on a number of factors, including budget, scalability, and the features you want in the final product.

To determine if PCM microcapsules can be utilised to store thermal energy, they must be characterised. Many methods may be used to examine the thermal characteristics, chemical composition, and structure of PCM microcapsules. Scanning electron microscopy (SEM), thermogravimetric analysis (TGA), and differential scanning calorimetry are a few examples (DSC).

Solar thermal energy may be preserved or regulated in PCM microcapsules. Plasterboard, for example, might have PCM microcapsules placed in it to offer passive heating and cooling. Solar thermal energy storage could greatly benefit from the use of PCM microcapsules to store excess solar energy during the day and release it at night.

PCM microcapsules need to be improved so that they have better thermal stability and energy storage efficiency. There are a lot of ways to enhance PCM microcapsules, including as switching up the shell material, adjusting the core-shell ratio, or adding surfactants. There are two competing factors that must be considered with optimisation: cost and scalability.

Experimental validation of PCM microcapsule performance is necessary to validate theoretical predictions of performance. Experimental methods, including as thermal cycling tests and thermal conductivity examinations, may be used to assess the performance of PCM microcapsules in a range of settings.

Through a sensitivity analysis, one may determine which factors most influence the PCM microcapsules' thermal stability and energy storage efficiency. Sensitivity analysis employing various approaches, such as Monte Carlo simulation, may be used to analyse the influence on changing parameters just on functionality of PCM microcapsules.

10. Recommendations

Based on our results, we have some recommendations for researchers and practitioners working with PCM microcapsules for thermal energy storage:

1. Material choices for the encapsulating shell should be made with consideration given to heat transfer, thermal expansion, and chemical inertness. The PCM microcapsules' thermal stability and energy storage efficiency may be drastically altered by the encapsulating shell material used. Researchers and practitioners should take into account the requirements of their particular applications when deciding on a shell material.
2. Consider cost, scalability, and the required qualities of the end product while selecting the microencapsulation technology that will best suit those needs. There are several microencapsulation technologies available for the production of PCM microcapsules, each with its own advantages and

disadvantages. If you take the right steps, you'll have a product that's easy to manufacture in large quantities without breaking the bank.

3. Characterize PCM microcapsules using various techniques, such as DSC, TGA, and SEM, to evaluate their thermal properties, chemical composition, and morphology. Thorough characterization of PCM microcapsules is essential to understand their thermal properties, chemical stability, and morphological characteristics, which can affect their performance during energy storage and release. Researchers should use a combination of techniques to obtain a comprehensive understanding of the microcapsules and ensure consistency in their performance.
4. Learn more about PCM microcapsules and their use in thermal applications including solar thermal energy storage and HVAC. PCM microcapsules used to store thermal energy may find use in the HVAC (heating, ventilation, and air conditioning), solar thermal energy, as well as industrial process heat industries, among others. Examining PCM microcapsules' efficacy in various contexts is necessary if researchers and entrepreneurs are to discover new applications for them.
5. Maximize PCM microcapsules' thermal stability and energy storage efficiency by fine-tuning their design and composition. In order to achieve high thermal stability and energy storage efficiency, the design and composition of PCM microcapsules must be optimised. Researchers should explore different methods of optimization, such as varying the PCM composition, encapsulation shell material, and microencapsulation method, to obtain the desired performance characteristics.

To sum up, PCM microcapsules have the potential to greatly enhance the efficiency and dispatchability of power production from renewable sources when used for thermal energy storage. Nevertheless, PCM microcapsules' effectiveness in energy storage depends heavily on their temperature stability. Therefore, researchers and practitioners should carefully consider the factors affecting PCM microcapsule performance and use the recommendations provided in this analysis to optimize their design and application for future use.

Results and Discussion

Due to their variable output, several renewable energy sources may benefit greatly from thermal energy storage (TES). Phase Change Materials (PCMs) are receiving more attention in TES because to their high energy storage density, consistent thermal characteristics, and user-friendliness. By increasing the heat transfer surface and isolating any melting materials, PCM microcapsules utilised in TES enhance PCM performance.

Extensive research was done to ascertain if PCM microcapsules might be used to store heat. Based on phase transition temperatures, encapsulation shell materials, microencapsulation procedures, PCM microcapsule characterization, and thermal applications, we classified the PCMs into distinct categories. We discovered that the shell materials utilised to wrap PCM microcapsules had a considerable impact on their thermal stability and energy storage efficiency. Polymer-based shell materials performed better at high temperatures than inorganic materials.

The microencapsulation technology used does have a large influence just on shape and thermal properties of PCM microcapsules. Due to its low complexity and excellent encapsulation efficiency, spray-drying and coacervation methods are often used to microencapsulate PCMs. Nevertheless, the properties of the PCM and the intended use will decide the best approach of microencapsulating the PCM.

Characterizing PCM microcapsules is essential for determining how well they store energy and transfer heat. Characterization techniques include X-ray diffraction, scanning electron microscopy, Fourier transform infrared spectroscopy, and differential scanning calorimetry (XRD). These methods may help us learn more about the structure, composition, and thermal stability of PCM microcapsules.

Building energy systems, solar thermal energy storage, and waste heat recovery are just a few thermal application settings where PCM microcapsules have shown significant promise. Improved thermal comfort for building occupants and decreased energy usage are both benefits of incorporating PCM microcapsules into a building's energy systems. PCM microcapsules used in solar thermal energy storage systems boost solar collector efficiency while also providing a reliable energy supply. By minimising heat loss during heat storage and transit, PCM microcapsules also boost the efficiency of waste heat recovery systems.

The encapsulation shell materials, microencapsulation procedures, characterisation methodology, and thermal applications are the main topics of our investigation of PCM microcapsules for thermal energy storage. The usage of PCM microcapsules in energy storage applications might have significant advantages for renewable energy systems.

Conclusion

Thermal energy storage (TES) using Phase Transition Materials (PCMs) may address the intermittent nature of renewable energy sources. By increasing the heat transfer area and preventing the escape of melted materials, microcapsules enhance PCMs' thermal and mechanical performance in TES. We categorized PCMs, examined encapsulation shell materials, defined microencapsulation techniques, characterized PCM microcapsules, and investigated thermal applications in order to provide a comprehensive review of PCM microcapsules for thermal energy storage.

We conducted considerable study and found that the shell material used to encase PCM microcapsules significantly affects both their thermal stability and the efficiency with which they store energy. Polymer-based shell materials outperformed inorganic materials in terms of thermal stability. While spray-drying and coacervation, two common microencapsulation techniques, are often employed for PCM microencapsulation, the qualities of the PCM and the intended application will determine which technique is best.

Characterization of PCM microcapsules is essential to evaluate their thermal properties and energy storage efficiency. Various techniques such as DSC, TGA, SEM, FTIR, and XRD are used for the characterization of PCM microcapsules.

PCM microcapsules have the potential to be used in waste heat recovery and solar thermal energy storage systems. The usage of PCM microcapsules may improve thermal comfort, solar collector efficiency, and heat loss during storage and transportation.s

Finally, our research offers valuable insights into PCM for researchers in a wide range of fields and makes important recommendations for the future usage of PCM microcapsules in the storage of thermal energy. Further study in this area may pave the way for improved energy storage technologies, which in turn will help push the development of renewable energy systems forward.

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