

Materials Horizons: From Nature to Nanomaterials

Zafar Said

Adarsh Kumar Pandey *Editors*

Nano Enhanced Phase Change Materials

Preparation, Properties and
Applications

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Materials Horizons: From Nature to Nanomaterials

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Zafar Said · Adarsh Kumar Pandey
Editors

Nano Enhanced Phase Change Materials

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Editors

Zafar Said
Department of Sustainable and Renewable
Energy Engineering
University of Sharjah
Sharjah, United Arab Emirates

Adarsh Kumar Pandey
Research Centre for Nano-Materials
and Energy Technology (RCNMET)
Sunway University
Petaling Jaya, Selangor, Malaysia

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Chapter 1

Introduction to Nano-enhanced Phase Change Materials



Essam M. Abo-Zahhad, Zafar Said, Ali Radwan, and A. K. Pandey

1 Introduction

Recent research has focused on improving energy efficiency using renewable energy, managing energy demand, and reducing heating and cooling requirements. This increased emphasis on energy efficiency is driven by the significant rise in global energy demand resulting from the growth of the world's population and economy [1]. This has led to severe environmental consequences, prompting efforts to mitigate them. Over the last 20 years, the International Energy Agency (IEA) has reported a 49% increase in primary energy production and a 43% increase in CO₂ emissions. The building sector is the largest energy-consuming sector, accounting for 25–30% of final energy consumption on a global basis, and is also considered an essential

E. M. Abo-Zahhad · A. Radwan
Sustainable Energy and Power System Research Centre, Research Institute for Science and Engineering, University of Sharjah, Sharjah, United Arab Emirates
e-mail: emohamed@sharjah.ac.ae

A. Radwan
e-mail: Ali.Radwan@sharjah.ac.ae

E. M. Abo-Zahhad
Mechanical Power Engineering Department, Faculty of Energy Engineering, Aswan University, Aswan 81528, Egypt

Z. Said (✉) · A. Radwan
Sustainable and Renewable Energy Engineering Department, University of Sharjah, P.O. Box 27272, Sharjah, United Arab Emirates
e-mail: zsaid@sharjah.ac.ae

Z. Said
U.S.-Pakistan Center for Advanced Studies in Energy, National University of Sciences and Technology, Islamabad, Pakistan

Department of Industrial and Mechanical Engineering, Lebanese American University (LAU), Byblos, Lebanon

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source of CO₂ emissions [2]. The IEA warns that if energy efficiency improvements are not implemented in the building sector, energy consumption could increase by 50% by 2050 [3, 4]. The building sector globally accounts for approximately 40% of total energy usage [5, 6], with over 75% of the energy consumed in single and multifamily houses attributed to space heating and cooling demand, according to IEA Solar Heating and Cooling Program findings [7]. Unfortunately, the environmental crisis is still in its early stages, and it is expected that the energy demand in the building sector will rise by 50% by 2050, with space cooling demand tripling during the same period [8]. Hence, scientists are diligently searching for feasible solutions to enhance energy conservation and storage to mitigate global energy consumption [9].

The use of phase change materials, or “PCM,” is a widely recognized method for reducing energy demand while improving cooling and heating efficiency in the building sector. Over the past four decades, PCM has gained significant attention and is considered a unique solution for storing and releasing thermal energy. The capability of PCM to absorb and release large amounts of thermal energy contents during the melting and solidifying process makes them useful in a variety of applications [10]. Recently, PCM has been involved in many modern applications to absorb excess heat during the daytime and release it at night when temperatures are colder. The application of PCMs in the building sector is an excellent example of the function of PCMs, and it is one of the most common applications as PCM can save thermal loads during daytime and realize the access heat during the night, which smooths the building temperature control and energy saving measures.

The authors spot that PCMs have significant potential for use in many fields, including energy storage, building insulation, and electronic cooling. However, the traditional PCMs have limitations that can limit their effectiveness in some applications. By presenting nano-enhanced PCMs as a solution to these limitations, the authors aim to provide readers with a more comprehensive understanding of the potential of these new materials. This book delves into the most recent advancements and innovations in PCMs and explores how the integration of nanoparticles has improved them. Furthermore, broad topics that cover a wide range of issues related to nano-enhanced PCMs are included in the current book. With 12 chapters, the book covers various aspects of these materials, such as their synthesis, characterization, properties, and applications.

A. Radwan

Mechanical Power Engineering Department, Faculty of Engineering, Mansoura University,
Mansoura 35516, Egypt

A. K. Pandey

Research Center for Nano-materials and Energy Technology (RCNMET), School of Engineering
and Technology, Sunway University, No. 5, Jalan Universiti, Bandar Sunway, 47500 Petaling
Jaya, Selangor Darul Ehsan, Malaysia
e-mail: adarshp@sunway.edu.my

CoE for Energy and Eco-Sustainability Research, Uttaranchal University, Dehradun, India

In this book chapter, the authors will provide an overview of the importance of conventional PCM and nano-enhanced PCM, specifically in various fields such as energy storage, thermal management, and building sectors. The general concept of traditional PCM and nano-enhanced PCMs, their merits over conventional PCMs, and the need to explore their properties and applications are briefly covered in the following subsections of this introduction. Section 2 in this chapter focuses on nano-enhanced PCMs only in more detail. In scope is the last section of this chapter (Sect. 3), which outlines the topics and areas that will be covered throughout the book and a brief overview of its content, allowing readers to gain insights into the book's contents quickly.

1.1 Phase Change Materials Theory and Definition

This section provides a theoretical and definitional overview of conventional PCMs. These substances can store and release heat energy during a phase transition process. When a PCM is heated, it changes from a solid phase to a liquid phase, and during this phase change, it absorbs heat energy. When the PCM is cooled, it switches back to a solid phase, and during this phase change, it releases heat energy. During the operation process, PCM starts in its solid state, and as it absorbs heat energy, it begins to melt and change into a liquid form. The heat energy absorbed by PCM during this process is stored as latent heat within the material, and it continues to absorb heat energy until it reaches its melting point. As shown in the diagram in Fig. 1, PCM reaches its melting point and starts to change into a liquid state, but its temperature remains constant until all the material is in liquid form. This is known as the “melting” phase, and during this phase, PCM continues to absorb heat energy while maintaining a constant temperature.

After all the PCM has melted and turned into a liquid, it can continue to absorb heat energy and increase its temperature. Once the external heat source is removed, the PCM starts releasing the stored heat energy as it solidifies and returns to its original state. The solidification process is comparable to the melting process, but in reverse, and during this phase, the stored latent heat energy is released, which can be used for heating or other purposes. The temperature of the PCM remains constant during the solidification plateau phase until all the material has solidified.

Generally, PCMs are classified based on their phase transition temperature, the temperature range where the PCM changes its phase from solid to liquid or vice versa. The classification is based on low, medium, or high-temperature levels; each field has specific PCM applications. The use of PCM in various temperature ranges and modes has gained significant attention in the last four decades. The low-temperature content (-20 – 5 °C) is mainly used for cooling applications, such as domestic and commercial refrigeration. In the medium–low temperature range (5 – 40 °C), PCM is used for heating and cooling in building passive systems and for various cooling applications, including free cooling, solar absorption chillers, evaporative and radiative cooling, and air conditioning systems. The medium temperature range (40 – 80 °C) is suitable

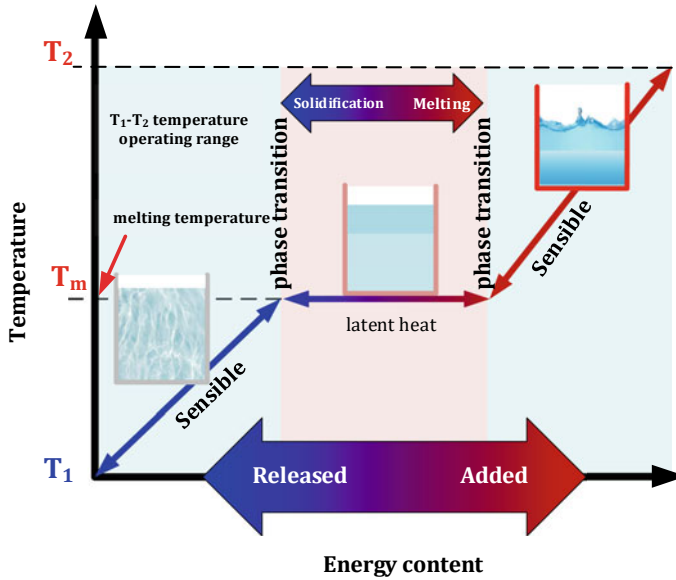


Fig. 1 Graphical representation of the temperature variation of a PCM during its heating and cooling process

for cooling electric devices and heating using solar air heaters, solar stills, and solar domestic hot water systems. In the high-temperature range (80–200 °C), PCM is used for cooling via solar absorption cooling, heating through on-site and off-site waste heat recovery, and power generation in solar-thermal electricity systems. Table 1 summarizes the classification of PCM and application based on the temperature range.

1.2 Conventional Phase Change Materials Limitations

The conventional PCMs have some limitations that confine their all-embracing use in various applications. One of these limitations is the low values of the traditional PCMs' thermal conductivity, which suppresses heat transfer between the PCM and the heat source or sink [12]. Consequently, the thermal response times can be prolonged, and the overall performance can be diminished. Another limitation of conventional PCMs is their low latent heat capacity, which limits the amount of energy that can be stored and released during the phase change process. This can make achieving the desired temperature control or thermal regulation in specific applications difficult.

Furthermore, conventional PCMs can suffer from issues such as subcooling and supercooling, which can lead to reduced performance or even failure [13]. Subcooling

Table 1 Classification of PCM applications based on the temperature range and the mode of operation [11]

Temperature range (°C)	Mode		Application
	Cooling	Heating	
Low −20–5	✓		Domestic refrigerator, commercial refrigeration
Low-medium 5–40	✓	✓	Building passive heating and cooling, free cooling, solar absorption chiller, evaporative and radiative cooling, and air conditioning system
Medium 40–80	✓		Electric device,
		✓	Solar air heater, solar stills, solar domestic hot water
High 80–200	✓		Solar absorption cooling
		✓	On-site and off-site waste heat recovery
		Power generation	Power generation solar-thermal electricity generation

occurs when the temperature of the PCM drops below its melting point without undergoing a phase change, while supercooling occurs when the temperature remains above the melting point even after applying sufficient heat. Finally, conventional PCMs can also experience stability and durability issues over time, reducing their effectiveness and lifespan [14, 15]. These limitations have led to the development of new approaches, such as the use of nanotechnology, to enhance the performance and overcome the limitations of conventional PCMs.

2 Nano-enhanced Phase Change Materials

Nano-enhanced PCMs are a promising class of PCMs that have gained increasing attention in recent years due to their potential to overcome the limitations of conventional ones [16]. In this section of the introduction chapter, we will discuss the significance and background of nano-enhanced PCMs and their potential applications in various fields.

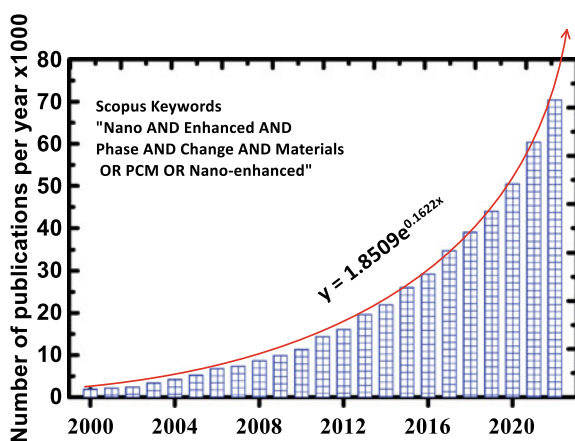
Nano-enhanced PCMs use nanoparticles, such as carbon nanotubes, graphene, and metal oxides, in conventional PCMs to improve their thermal properties and enhance their performance [17]. The integration of nanoparticles can increase the thermal conductivity and specific heat capacity of the PCMs, allowing for faster heating or cooling times and higher energy storage capacity. Additionally, nano-enhanced PCMs can also exhibit improved stability and durability over time, making them suitable for long-term use in various applications.

One way nanoparticles can increase the thermal conductivity of PCMs is by increasing the interfacial area between the nanoparticles and the PCM (similar to the nanofluid concept). The nanoparticles can create a network of thermal pathways that facilitates heat transfer, leading to an overall increase in thermal conductivity. Additionally, nanoparticles can increase the specific heat capacity of PCMs by providing additional energy storage sites. The nanoparticles act as nucleation sites for the PCM, which increases the number of phase change events and the amount of energy stored during each cycle [18]. In terms of stability and durability, nano-enhanced PCMs can exhibit improved performance over traditional PCMs. The nanoparticles can act as stabilizers and prevent phase segregation or degradation of the PCM. This is particularly important for long-term applications, such as building insulation or thermal energy storage, where the materials will be exposed to repeated thermal cycles and environmental factors [19].

Extensive research has been done in nano-enhanced PCM, indicating significant interest and activity in this study area. The following search query in the Scopus database to find relevant publications related to nano-enhanced PCM includes a combination of relevant keywords (Nano AND Enhanced AND Phase AND Change AND Materials OR PCM OR Nano-enhanced); over half a million results are relevant. No. of publication = $1.8509e^{0.1622x}$ year, suggests that the number of publications in this field has increased exponentially over time, as shown in Fig. 2.

It is worth noting that extensive research does not necessarily guarantee real and practical applications or commercialization of nano-enhanced PCMs. That is a critical point to keep in mind. While extensive research can provide valuable insights into the properties and potential applications of nano-enhanced PCMs, many factors can affect their commercialization and practical use. Some of these factors include the cost and scalability of producing nano-enhanced PCMs on a large scale, the safety and regulatory requirements for their service, and the market demand for products that incorporate these materials.

Fig. 2 Number of publications per year and cumulative publications on nano-enhanced PCMs 2020–2022



Additionally, even if the research shows promising results, there may still be challenges in translating those findings into practical applications in real-world settings. This can require additional research and development and collaboration between scientists, engineers, and industry partners. In a nutshell, nanotechnology research generally and nano-enhanced PCMs are essential for advancing our understanding of these materials. It is crucial to recognize that several challenges could be addressed before nano-enhanced PCMs can be utilized effectively and broadly in practical applications. This will be comprehensively covered and discussed in detail in this book, Chaps. 7–12.

3 Scope

In this section, the authors would like to clarify the book's scope and provide an overview of the main ideas presented in each chapter. The book will cover topics related to nano-enhanced phase change materials (PCMs), including:

- **Chapter 1: *Introduction to Nano-enhanced Phase Change Materials***
This chapter provides an overview of nano-enhanced PCMs, their importance, and the book's scope. It introduces the reader to the concept of phase change materials (PCMs) and the role of nanoparticles in enhancing their thermal properties.
- **Chapter 2: *Overview of PCMs***
Chapter 2 covers the basics of PCMs, including their classification, selection criteria, and ways to improve their thermal performance. It provides a comprehensive overview of PCM properties and their use in various applications.
- **Chapter 3: *Synthesis, Characterization, and Stability of Nano-enhanced PCM***
This chapter covers the synthesis, description, and stability of nano-enhanced PCMs. It discusses the different methods for preparing nano-enhanced PCM, how they are characterized, and the factors affecting their stability.
- **Chapter 4: *Influence of Nanoparticles on Thermophysical Properties of PCMs***
Chapter 4 explores how nanoparticles influence the thermophysical properties of PCMs, including their melting point, thermal conductivity, latent heat capacity, and more. It provides an in-depth analysis of how these properties change with the addition of nanoparticles.
- **Chapter 5: *Nanostructure-Based Colloidal Suspension for Thermal Enhancement for Nano-enhanced PCM***
This chapter covers using nanostructure-based colloidal suspensions for thermal enhancement in nano-enhanced PCM. It discusses the different types of colloidal suspensions, such as nanoparticle, nanotube, and nanofiber-based suspensions, and how they improve the thermal properties of nano-enhanced PCM.
- **Chapter 6: *Theoretical Analysis and Correlations for Predicting Properties and Evaluation Methods for Nano-enhanced PCM***
Chapter 6 discusses theoretical analysis and correlations for predicting proper-

ties and evaluation methods for nano-enhanced PCM. It covers various techniques used to indicate the thermal properties of NEPCMs and evaluate their performance.

- **Chapter 7:** *Application of Nano-enhanced PCMs in Solar Energy*

Chapter 7 focuses on applying nano-enhanced PCMs in solar energy, including solar water heaters, solar air heaters, solar thermal power exchangers, solar cookers, and solar collectors. It explores how NEPCMs can improve the efficiency of solar energy systems.

- **Chapter 8:** *Application of Nano-enhanced PCMs in Buildings*

Chapter 8 covers the application of nano-enhanced PCMs in buildings, including insulation, heating, and cooling systems. It discusses the potential benefits of using nano-enhanced PCM in buildings, such as reducing energy consumption and improving thermal comfort.

- **Chapter 9:** *Application of Nano-enhanced PCMs in Electronics Devices*

Chapter 9 explores nano-enhanced PCMs in electronic devices like batteries, sensors, and computer chips. It discusses the potential benefits of using nano-enhanced PCM in electronics, such as improving performance and reducing the risk of overheating.

- **Chapter 10:** *Application of Nano-enhanced PCMs in Textiles*

Chapter 10 covers the application of nano-enhanced PCMs in textiles, including clothing and bedding. It discusses how NEPCMs can regulate body temperature, improve comfort, and reduce energy consumption.

- **Chapter 11:** *Soft Computing Tool (Intelligent Techniques) for Nano-enhanced PCM*

Chapter 11 explores soft computing tools, such as artificial intelligence techniques, for nano-enhanced PCM. It discusses how these tools can predict the thermal properties of nano-enhanced PCM and evaluate their performance.

- **Chapter 12:** *Challenges and Difficulties in Developing Nano-Enhanced Phase Change Materials and Way forward*

Chapter 12 highlights the challenges and difficulties in developing nano-enhanced PCMs and presents a way forward. It covers various issues, such as stability, economic aspects, environmental impact, safety issues, cost, sonication effect, and original degradation.

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Chapter 2

Phase Change Materials (PCMs)



Imran Zahid, Muhammad Farooq, and Muhammad Farhan

1 Overview of PCMs

Some natural materials undergo phase shifts, and they are endowed with a high inherent heat storage capacity known as latent heat capacity. These materials exhibit this behavior due to the considerable amount of thermal energy needed to counteract molecular when a material transforms from a solid to a liquid or back to a solid. As a result, the melting process is very endothermic, while solidification is exothermic.

The inherent capability of phase change materials (PCMs) to take in and give off thermal energy during phase transformation. It also contributes to more effective thermal management of electronics since a significant quantity of heat gets absorbed by PCMs during the stage of melting and let out into the surrounding atmosphere after the process of solidification.

PCMs have a characteristic that allows them to become melted and consolidate at particular temperature extremes (0–100 °C) without consuming any excessive energy, which makes them an excellent choice for capturing significant thermal energy under transitory and continuous power loads. Then, in order to maintain a constant temperature and secure electrical circuitry, heat is released into the surroundings. Despite the fact that organic PCMs have several desirable qualities such as chemical long-term stability, latent heat capacity, noncorrosive, diffusion of thermal energy, and minimal pricing. Today, PCMs are employed in heating and air conditioning systems, battery packs made of lithium, solar thermal power systems, semiconductor chip cooling,

I. Zahid

Department of Mechanical Engineering and Technology, Government College University
Faisalabad, Faisalabad, Pakistan

M. Farooq (✉) · M. Farhan

Department of Mechanical Engineering, University of Engineering and Technology Lahore,
Lahore, Pakistan

e-mail: enr.farooq@uet.edu.pk

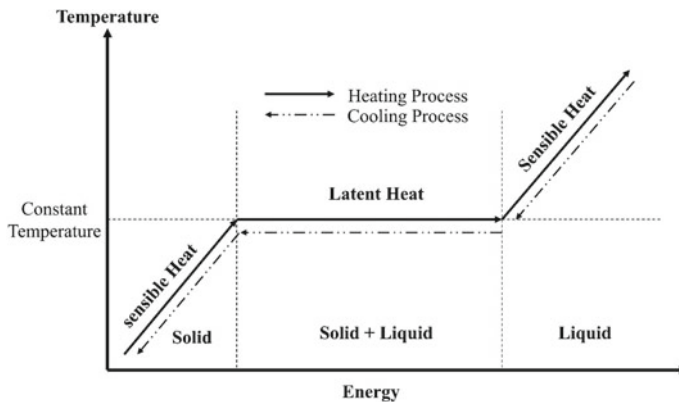


Fig. 1 Temperature changes in PCM during melting and freezing phases

textiles, refrigeration, heat pumps, and building thermal comfort. However, their performance in heat transfer applications is constrained by low thermal conductivity.

PCMs are particularly useful as latent heat storage systems because they can take extra peak energy loads during one run of the power cycle and release the heat at another, saving circuit element failure due to overheating. A PCM-based thermal management system is offered as a substitute cooling solution to reduce thermal resistance in the system and meet the requirements for safe operation of the electronic equipment. Because of PCM's high potential for the latent heat of fusion, relatively small amounts of material can capture enormous quantities of energy when it undergoes a phase shift without increasing in temperature. The latent heat storage device energy will be stored during melting as latent heat of fusion and recovers during later solidification of PCMs. The ability to predict such alternating melting-solidification heat transfer cycles (Fig. 1) is critical for the optimal formulation of a latent heat energy storage system.

Despite the importance of the system melting-solidification cycles, PCM's low thermal conductivity makes it challenging to utilize as alternate cooling management for electronic applications. Due to this, initiatives have been undertaken to elevate the rate of melting by applying various PCM thermal conductivity enhancement technologies. Pin-fin heat sinks, porous structures, and NPs in PCM-based HS offer efficient ways in boosting the thermal conductivity of PCMs.

2 PCM Characteristics

Researchers and scientists have gravitated to phase change materials (PCMs) as a consequence of their considerable heat-retaining ability, which enables them to take up more energy. PCMs can accumulate and discharge energy during their phase shift process at a constant process. If materials do not go through the transition phase, they

can't store a massive amount of energy. Thermal latent energy systems for energy storage dominate the sensible heat storage methods for energy owing to 5–14 times more high energy storage density. This is associated with the basic features of PCMs.

1. **High Energy Storage Capacity:** PCMs possess a great deal of heat capacity, which implies they are capable of holding huge amounts of heat energy without experiencing substantial temperature changes.
2. **Latent Heat:** PCMs gather or transfer heat energy without temperature fluctuations during a transition from one state to another, which is known as latent heat. Because of this feature, they are excellent for storing thermal energy applications.
3. **Selectable Melting Points:** Every PCM has a different freezing and melting point. These considerations are critical when selecting a PCM for a certain appliance.
4. **Heat Conductivity:** The heat conductivity of PCMs is a critical component influencing how well they perform. The ability to effectively transfer heat between the PCM and the surrounding environment is made possible by high thermal conductivity. “Thermal conductivity” refers to a material’s ability to conduct or transfer heat. With regard to PCMs, a high thermal conductivity indicates that heat can be effectively transferred through the substance, enabling quick heat transfer. Heat is either absorbed or emitted when a PCM experiences a phase shift, such as melting or solidification. Facilitating the flow of heat between the PCM and the environment is crucial for making the most of the PCM’s thermal energy storage potential. High heat conductivity is important in this situation.
5. **Degradation Stability:** To avoid degradation and sustain performance over time, PCMs ought to remain chemically stable.
6. **Non-toxicity:** Many PCMs are eco-friendly and non-hazardous, using them a more secure choice for thermal energy storage purposes.
7. **Compatibility:** PCMs are required to be compatible with the storage device’s materials as well as the rest of the substances with which they come into encounter over their lifespan.
8. **Cost:** For commercial uses, PCM prices are a crucial factor. Some PCMs can be pricey, which may prevent their use from being common.

Equation (1) illustrates the volume of stored energy during the latent heat storage system.

$$Q = \int_{T_i}^{T_m} m C_p \Delta T + m a_m H + \int_{T_m}^{T_f} m C_p \Delta T \quad (1)$$

Thermal and chemical stability, phase change temperature, cost, low volume expansion, and latent heat are the essential selection parameters of the PCMs. Moreover, its high energy storage phenomena make PCMs applicable in many engineering applications like batteries, refrigeration, desalination, textiles, solar thermal applications, thermal comfort in buildings, food packaging, heat pipes, and electronics cooling.

3 Classification of PCM

PCMs can be categorized into three groups: organic groups, inorganic groups, and eutectics groups. Organic PCMs can also be broken down into paraffin and non-paraffin subtypes. The detailed types of PCMs are summarized in Fig. 2.

The four types of phase transitions are solid to liquid, solid to gas, solid to solid, and liquid to gas. The most significant and typical conversion for latent heat storage PCM materials is from solid to liquid and likewise. During the heating phase, this type accumulates a lot of energy, and it releases energy during the solidification phase. Water–ice is the best example of a solidification phase at a constant temperature of 0 °C. Organic PCMs comprise all kinds of paraffin and non-paraffins. Inorganics include metallic and salt hydrates composites.

Carbon-based compounds are known as organic PCMs. They fall into two categories as paraffins or non-paraffins. Paraffin lies under the family of rich hydrocarbons whose chemical formula is C_nH_{2n+2} . Organic paraffin is extensively used in the cooling of electronic applications. The most commonly used organic PCMs due to their advantageous characteristics are non-reactive, degradation stability, and reuse ability after their service life. They have small volume expansion and subcooling properties. Organic phase change materials (PCMs) are particularly well-suited for building cooling applications due to their comparatively high latent heat of fusion. The quantity of thermal energy received or exhaled during the phase change process is referred to as the high latent heat of fusion. This implies that when a phase change occurs from a solid to a liquid or vice versa in an organic PCM, a sizable quantity of heat can be retained or released. This characteristic enables organic PCMs to effectively absorb heat from the environment during the day, keeping the indoor

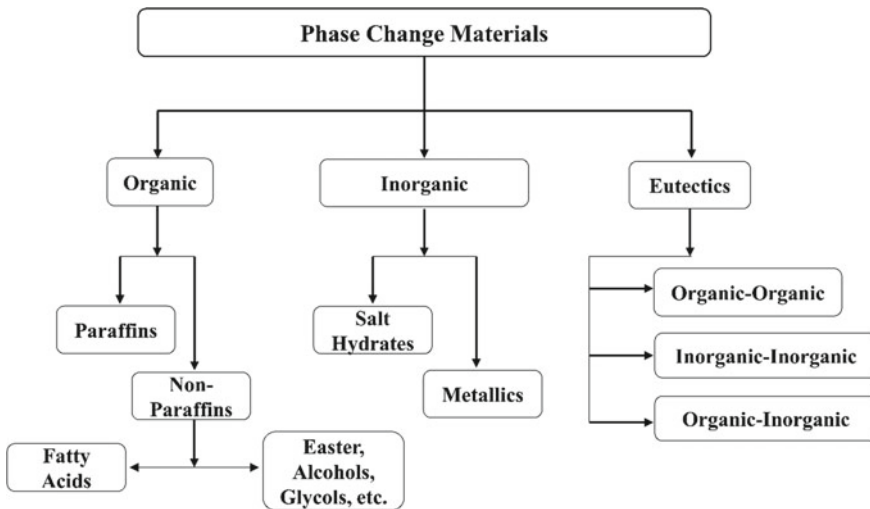


Fig. 2 Classification of PCMs

temperature lower. At night, when the temperature lowers, organic PCMs may then release the heat they have stored, aiding in cooling, and consuming less energy. At a certain temperature, organic PCMs having unique characteristics go through a phase shift from solid to liquid or the opposite. These substances are typically composed of organic substances including fatty acids, alcohols, and esters. Here are some examples of organic PCMs:

1. **Fatty acids:** These are organic substances with carboxylic acid groups attached to the ends of long-chain hydrocarbon tails. Stearic acid, palmitic acid, and lauric acid are a few examples of fatty acids. They melt at temperatures between 20 and 70 °C.
2. **Alcohols:** Compounds classified as organic are those that include a carbon atom bound to a hydroxyl group (–OH). The hydroxyl group, which is made up of an oxygen atom coupled to a hydrogen atom, and the covalently connected carbon atom make up this chemical structure. One-octadecanol, one-hexadecanol, and one-octanol are a few examples of alcohols. They melt temperatures between –10 and 60 °C.
3. **Esters:** Esters are organic compounds formed by the interaction of an alcohol with carboxylic acid. They have a wide range of characteristics, including methyl palmitate, butyl stearate, and ethyl oleate. Esters are extremely adaptable for a wide variety of applications due to their wide melting temperature range, which ranges from –20 to 100 °C. Esters are able to be used successfully across a variety of disciplines and sectors attributed to their wide range of melting temperatures.

Organic PCMs provide a number of benefits, including affordability, non-corrosivity, and low toxicity. They are frequently utilized in systems for thermal energy storage, building insulation, and controlling vehicle temperatures. They may also have drawbacks including poor thermal conductivity and probable flammability, which must be taken into account when choosing and using them.

Inorganic PCMs are substances that change a phase change at a specific temperature. These materials are typically composed of inorganic substances, which involve salt hydrates, metals, and their alloys. Here are some examples of inorganic PCMs:

1. **Salt hydrates:** These are inorganic substances that have crystal structures that include water molecules. Lithium nitrate trihydrate, sodium sulphate decahydrate, and calcium chloride hexahydrate are a few examples of salt hydrates. They melt at temperatures between 0 and 100 °C.
2. **Metals and their alloys:** These PCMs are inorganic, have high melting points, and are capable of holding a lot of thermal energy. A few instances of metal PCMs are copper, aluminum, and their alloys. They melt at temperatures greater than 100 °C.
3. **Eutectic mixtures:** These are inorganic PCMs that have a particular melting point and are produced by combining two or more inorganic substances. Potassium nitrate-sodium nitrate, calcium chloride-magnesium chloride, and sodium hydroxide-sodium acetate are several examples of eutectic mixtures. They melt down at temperatures between –25 and 150 °C.

High thermal conductivity, long-term stability, and high energy storage density are only a few benefits of inorganic PCMs. They are often frequently utilized in enhancing heat energy storage systems, building insulation to regulate indoor temperatures, and controlling vehicle temperature. However, they may additionally be expensive, caustic, and potentially hazardous, which must be taken into account while choosing and using them.

4 PCM Selection Criteria

In selecting PCM, several key selection properties/parameters are considered, such as physical, kinetic, chemical, thermal properties, thickness, cost, reliability, availability durability, safety and environmental impact, compatibility, and applications, as represented in Fig. 3.

The choice of a PCM is crucial since the quantity of thermal energy that a material is capable of retaining and releasing relies on its thermal characteristics. Some important thermal properties to consider when selecting a PCM include:

1. Chemical stability: To prevent deterioration or fragmentation that would lessen their usefulness, PCMs should be chemically stable over prolonged periods of time. To prevent corrosion or other compatibility problems, they may also be acceptable with the substances and fluids used in the energy preservation approaches.
2. Density: The density of the material affects how much energy can be stored in a PCM per unit volume.

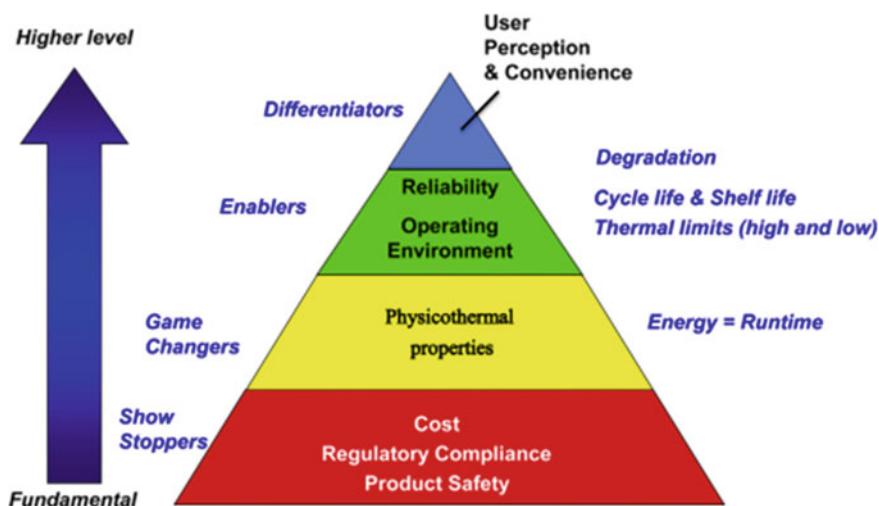


Fig. 3 PCM selection criteria [1]

3. **Density:** The quantity of thermal energy that can be kept within a specific measurement portion of a PCM depends on its density, which is another crucial factor. High-density PCMs have the capacity to store more thermal energy per unit volume, which might be useful in applications with constrained space.
4. **Melting temperature:** A PCM's melting temperature must be adequate for the purpose for which it is being used. For instance, a melting temperature above the maximum outside temperature would be preferable if the PCM was to be employed as building insulation.
5. **Heat of fusion:** The energy needed to change an ingredient from a solid to a flowing form is known as the latent heat of fusion. The quantity of thermal energy that may be saved or emitted during a phase shift is determined by this feature, which makes it crucial when choosing a PCM. A greater amount of energy can be held within a given amount of PCM by using materials with substantial latent heat of fusion.
6. **Thermal conductivity:** How quickly heat may be moved into or out of a PCM is dependent upon its thermal conductivity. For applications requiring quick thermal cycling, such as thermal energy storage systems, high thermal conductivity is preferred.
7. **Specific heat capacity:** A PCM's specific heat capacity specifies how much energy needs to be consumed to increase its temperature by a certain quantity. Because of its high specific heat capacity, the PCM may retain a substantial amount of energy per unit mass.
8. **Thermal stability:** The PCM ought to remain resilient across the required temperature zone and not deteriorate or disintegrate over time.
9. **Compatibility with other materials:** Other materials utilized in the application, such as containers or materials that transfer heat fluids, should be compatible with the PCM.
10. **Cost:** Finally, the cost of the PCM is a key factor to consider, especially for applications on a massive scale. To select a PCM that gives the needed performance at a reasonable cost, the cost should be assessed against the other parameters.

In summary, choosing the type of a PCM should be supported by careful examination of these parameters, as well as any application-specific requirements.

5 Thermal Performance Enhancement Techniques

It is a significant technical challenge that PCMs' low thermal conductivity lengthens the time needed to charge and discharge electrical appliances. To overcome this issue, various types of thermal conductivity-enhancing approaches are employed such as several types of use of metallic extended fins, porous foams structures, and smart materials. These performance enhancement approaches are explained in Fig. 4.

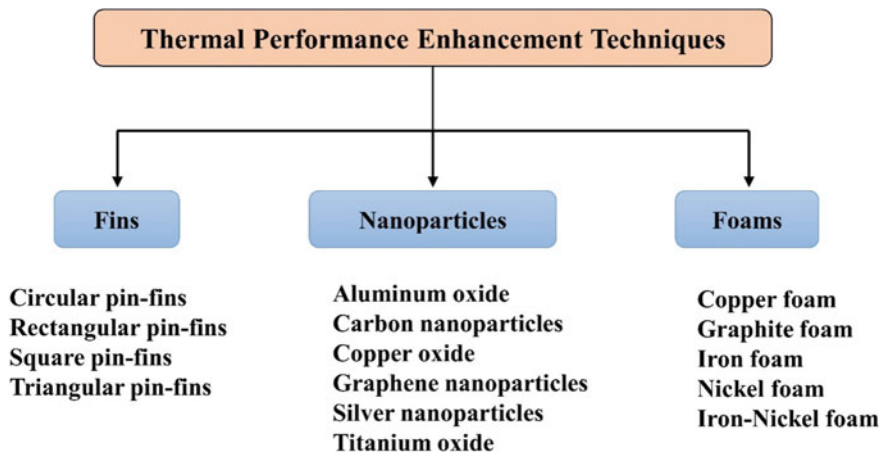


Fig. 4 Thermal conductivity enhancement techniques of PCM [2]

In order to boost thermal conductivity and place primary emphasis on the removal of excess heat from the system, these techniques are conjugated with PCMs. Here is some common technique introduction to promote thermal achievement of PCMs:

1. **Extended Fins structures:** The effective surface area of PCM vessels can be augmented by introducing finned structures or other extended surfaces, which will improve convective heat transmission.
2. **Composite formation:** By mixing PCMs with other substances (such as metals, ceramics, or polymers), composites can be made that have improved heat conductivity, strength, and structural stability.
3. **Nano structuring:** PCMs can have their thermal conductivity improved by adding nanosized particles (like multi-walled carbon nanotubes or graphene oxide) to speed up the rate of heat transfer during phase shift.
4. **Encapsulation:** In addition to preventing leakage, encasing PCMs in a shell material (such polymers or silica) can improve their durability, stability, and thermal conductivity.
5. **Thermal cycling:** Cycling PCMs through the melting-solidification process several times can assist to minimize supercooling and improve thermal conductivity.
6. **Phase change emulsions:** By dispersing PCMs in water to produce emulsions, it is feasible to boost their thermal conductivity while also making them simpler to handle and more stable.

The effectiveness of PCMs in a variety of applications, including thermal energy storage, maintaining comfortable temperature in buildings, and stabilizing temperature in vehicle cabin, can be greatly improved by using these strategies.

5.1 Thermal Performance Enhancement Using Pin–Fin Heat Sinks

Ali and Arshad [3] did experimental research to characterize the thermal performance of circular pin-fins heat sinks of different diameters and pin thickness incorporated with n-eicosane PCM. Unfinned, two, three, and four millimeters diameters of circular pin fins HSs were adopted to note the best thermal performance at varying heating loads. All of the circular pin fin heat sinks showed acceptable thermal performance compared to unfinned HS. Three-millimeter circular finned diameter-based HS showed the best thermal performance in lowering the HS base temperature and extending operating time at SPTs from 40 to 50 °C.

Usman et al. [4] focused their attention on three PCMs (RT-35, RT-44 and paraffin wax) at input powers ranging from 5 to 8 W, loaded in finless, triangular staggered, and inline fins configurations based HSs for efficient passive cooling of the processor. The experimental results revealed that triangular inline fins-based HS showed remarkable performance compared to triangular staggered fins-based HS for all PCMs. Furthermore, at 45 and 60 °C, when the performance of the HS is most important, the RT-44 PCM-filled triangular inline HS acted with superior performance. Avci and Yazici [5] conducted an experiment on the heating effectiveness of a flat-type HS to assess the influence of the inclination angle. The angle ranged from 0° to 90°. Imaging technology was adopted to see the behavior of the melting interface. Inclination angle showed remarkable thermal performance and increased working time to 5.5 times as the angle changed to 90°.

Hemati et al. [6] examined the performance and working time of the power supply using inorganic salt hydrate PCM ($\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$) with a fan. 15% volume fraction of fins was selected as TCE. 2100, 3300, and 4800 W/m² heat flux values and varying velocity of fan, from 1121.4 m/min to 1551 m/min, were two input parameters. The insertion of PCM in power supply assembly lessened the fan's power consumption. Pakrouh [7] numerically analyzed four-pin fins HSs filled with RT-44HC using the Taguchi method with simulation to get optimum results. Fins thickness, fins height variation, percentage of fins numbering, and thickness of the base of HS were four investigated parameters for optimization. The authors proposed a genetic algorithm (GA) method for the optimization of various HS configurations.

Leong et al. [8] executed experiments to inspect the efficiency of different HS configurations using paraffin wax and 1-hexadecanol at a heat input of 0.81 kW/m². When evaluated by comparing it to 1-hexadecanol, the outcome of HS with 16 fins as TCE stuffed with paraffin wax became more effective. Ali et al. [9] conducted extensive research on pin-fins HSs that were either circular, rectangular, or triangular in shape and inserted a variety of PCMs. At two distinct heat input powers, the use of-eicosane, RT-35HC, SP-31, and RT-44HC paraffin was utilized to achieve the best conceivable optimization. The heat transfer capabilities of the triangular pin-fins HS were exceptional, regardless of whether or not PCM was present. The subject HS also bolstered the working response time of the integrated circuit.

Arshaf et al. [10] studied round pin-fins HS at varying cross-sectional areas of pin fins with varying volume fractions of PCM. Maximum reduced baseline temperature and enhanced working time were observed for 3 mm pin fins HS. Dammak and Hami [11] numerically studied aluminum HS with 9% fixed volume fraction (72 fins) using paraffin wax for thermal consistency of electronic components. The kriging predictor model was adopted to note approximation with the original model. Cross-fins-based HS exhibited optimum thermal performance against reference setup. Optimal model HS reduced the base temperature by 30%.

Srikanth and Balaji [12] reported on 72 pin-fins HS performance filled with *n*-eicosane PCM at heat flux applied by four isolated heaters of equal area. The same performance of a single-plate heater and four discrete heaters was observed. The experimental investigation was carried out by Shang et al. [13] to examine the dependability and customer satisfaction of downhole electronics. Various active and passive cooling methods were applied. The authors claimed a passive cooling method for the thermal management of downhole electronics.

Kalbasi et al. [14] numerically studied finned PCM-based HS. ANOVA technique was chosen to check the behavior of the regression model. The findings indicate that a greater density of applied heat led to a higher optimal number of fins. Researchers have experimented with triangular, circular, and rectangular pin-finned heat sink geometries full with phase change material (PCM) at varying input powers. At 5 and 8 W of heating load, a triangular heat sink is recommended for use in heat transfer applications [9]. Table 1 shows the applications of PCMs for thermal management of electronics.

Table 1 Critical analysis of the published works on heat sink geometries with PCMs

PCM and melting point (°C)	Heat sink size (mm ³)	Heat sink type	Heat input (kW/m ²)/(W)	References
PCM-HS29P PCM-HS34 PCM-OM37P (29, 34, 37)	50 × 50 × 25	Simple, parallel, and crossed fins	3–5 W	[15]
Plastic paraffin (51.75)	51.5 × 25.5 × 16.5	Unfinned, Cu fins	4.7	[16]
<i>n</i> -Eicosane (35)	42 × 42 × 30	Plate and pin fins	4 and 8	[17]
Paraffin wax (56–58)	114 × 114 × 25	Simple and square pin fins	1.58–3.174	[18]
<i>n</i> -Eicosane (36.5)	80 × 62 × 25	Plate fins	0.99–2.78	[19]

5.2 Thermal Performance Enhancement Using Metallic Foams

The major setback of PCMs is that they have low thermal conductivity and numerous researchers have tried and are still attempting to find a solution to this issue. Metal foams have attracted a lot of attention as one of the most efficient ways to boost the thermal transfer capabilities of PCMs, and they are widely used in a variety of applications. This is because metal foams have a high thermal conductivity. Open cell and closed cells are two main types of metallic foams. In the open cell, fluid is poured into pores of metallic foam, while in the closed cell, metal foam is surrounded by other cells. In this study, the open-cell type of metallic foam is discussed. Pore size indicates porous materials are categorized into four types, as illustrated in Table 2.

The use of nickel and copper foam-based heat sinks extended the time period the heat sink was able to function effectively. A nickel foam-based heat sink filled with RT-44HC was the subject of research conducted by Rehan et al. [21] for the purpose of thermal management of electronic devices under varying heating loads. PCM and nickel foam insertion in the heat sink internal cavity positively enhanced heat transfer. Ali [22] investigated heat sink performance using porous metallic foam incorporated with PCM at various heat generations. The finding of the vacant heat sink were compared with those of a heat sink embedded with nickel foam and containing PCM in varying volume fractions (0.6, 0.7, and 0.8). According to the findings of the study, adding 0.8 fractions of PCM to a heat sink made of nickel foam increased the length of time the heat sink could do its job by four times while also lowering the temperature of the base by 24%. Hu and Gong [23] undertook an experimental study that investigated the thermal management of a heat sink integrated with porous material with various porosities (80, 85, 90, and 95%) fabricated by 3D printing. In every case, the enhancement ratio was highest for the heat sink that was integrated with the porous material having the lowest possible porosity. The increasing applied input power reduced in running time of the heat sink. Rehman and Ali [24] analyzed heat sink thermal performance using RT-54HC PCM integrated into metallic foams-based heat sink at 8, 16, and 24 W input powers. The experiment’s findings demonstrated that a heat sink integrated with copper foam was superior to a heat sink based on nickel foam in terms of lowering the base temperature by 26% when both were used with 0.8 volume fractions of PCM. Ferfera and Madani [25] researched the performance of heat exchangers embedded with metal foam and PCM. They numerically and

Table 2 Types of foams and their sizes [20]

Porous support	Porous size
Macro porous	>50
Mesoporous	2–50
Microporous	<2
Hierarchical	Ranging from macro to micro

experimentally tested five samples containing pure PCM and PCM/foam composites of variable porosity. When testing the thermal performance of heat exchangers for the purpose of thermal management of electronic components, one of the most important parameters was the porous morphology of the heat exchangers. COMSOL software was used for numeric investigation. They concluded that heat diffusion was improved four times more than pure PCM in the presence of metallic foams. The thermal behavior of PCM filled in low porosity metal foam was investigated by Hu et al. [26] using both numerical modelling and experimental research. For this investigation into the thermal performance of PCM, the Kelvin model was utilized. The numerical results exhibited a high degree of concordance with the experimental results. The PCM with 68% porosity foam showed a temperature reduction of 83.3% compared with pure paraffin wax.

Mahmoud et al. [15] experimentally studied the use of six heat sink geometries having fins and porous honeycomb material with PCM insertion at the heat input of 3–5 W. They concluded that the incorporation of honeycomb material could replace machined fins. Furthermore, PCM insertion with honeycomb material not only enhanced operating time but also shortened the uppermost temperature of the heat sink. Zhang et al. [27] conducted research with the objective of finding a solution to the problem of PCM's poor thermal conductivity. To achieve a higher level of thermal conductivity, they combined PCM with copper foam. They demonstrated that there is a significant non-equilibrium regarding the thermal conditions between PCM and copper foam. Veismoradi et al. [28] investigated battery cells bounded with metallic foam embedded with PCM-based paraffin wax to monitor cell heat transfer and phase change behavior. They concluded that the system efficiently performed with a combination of metallic foam and PCM at strong power pulses. The efficiency was increased seven times with a powerful heat pulse application. Zheng et al. [29] evaluated the melting characteristics of PCM with and without a copper foam containing 95% porosity in their research. The findings demonstrated that using copper foam/PCM reduced the length of time required for the melting process by 20.5%, which suggests that copper foam reduces the amount of thermal resistance within PCM.

5.3 Thermal Performance Enhancement Using Nanoparticles

By incorporating nanoparticles into PCMs, one can achieve the desired low thermal conductivity of these materials. The improvement in thermal performance is a direct result of the incorporation of all different types of NPs into the PCMs. Carbon-based NPs have a thermal conductivity in the range of 2000–6000 W/mK. Hence, they greatly enhance the thermal performance of PCM more than the metallic oxides NPs due to low thermal conductivity. Graphene NPs, also called “the mother of all graphitic forms of carbon,” are extensively used in PCM owing to their large surface

area to volume ratio, good thermal conductivity, easily synthesized, reduced erosion, and high heat transfer ability. The high cost is the major drawback of carbon-based NPs. Therefore, metallic oxide with the small addition of carbon NPs is also valuable for enhancing the thermal performance of PCMs.

6 Preparation of NePCM

The insertion and homogeneous mixing of NPs into molten PCM are called NePCM. There are two techniques for the preparation of NePCM and they are as follows

- (1) Single-step technique
- (2) Two-step technique

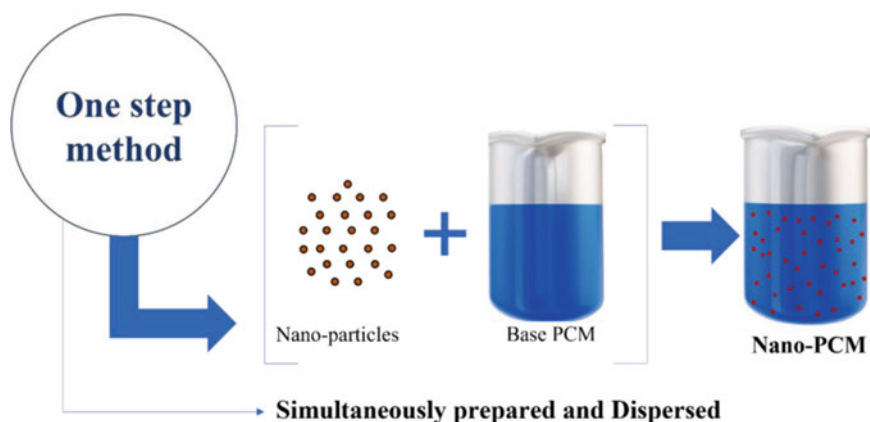
In order to improve the thermophysical properties of PCMs, specifically the enhancement of PCMs' thermal conductivity, researchers turn to these two methods/techniques. It is possible that increasing the thermal conductivity of PCM through the homogeneous mixing of NPs will be the solution. The NePCM mixture can be prepared using a variety of different methods, each of which has both advantages and drawbacks. But both techniques are used to upsurge heat transfer rate to overcome the deficiency of PCM. Two-step technique includes five different types of processes to ready homogenous mixture for PCMs composites with nanomaterials of various shapes and diameters. Centrifugal spinning, varnish layer, stirring and sonication, autoclave, and vacuum impregnation methods are all two-step methods for NePCM sample preparation. A review of the relevant literature concerning NePCM preparation methods is discussed in Table 3.

6.1 *Single-Step Method*

There has been a lot of interest in the one-step method for preparing NePCM. At the same time that the NPs are being synthesized, they are being suspended in the PCM base as shown in Fig. 5. The single-step method, which is also referred to as the one-step method, comprises chemical reduction, chemical vapor condensation, low-pressure droplets onto a running oil substrate, phase transfer technique, submerged arc NPs preparation system, chemical vapor deposition, and pulsed laser ablation. This technique reduces agglomeration because it doesn't require the shipping, dispersion, drying, storing, or blending of NPs. Oxidation can be also prevented using this method, but this method is expensive, pretty less final output quantity, and is only appropriate for certain types of materials under certain kinds of operating conditions. In addition, an incomplete interaction will result in the formation of leftover chemical reactions in the PCM base, thereby making it difficult to explain the effect of nano additions without also considering the effect of impurity. As a result, this strategy is not usually followed. Nano-PCM solutions were prepared using different types

Table 3 Literature review on NePCM preparation methods

Base PCM	Nanoparticles	NePCM preparation method	Surfactants	Sonication time (s)	References
Polyvinyl pyrrolidone	Ag nanowires	One-step			[30]
Cupric acid	CuO	Two-step		1800	[31]
Ethyl transcinamate	Ag-TiO ₂	Two-step	Ethanol	1800	[32]
Ethanol	Ag nanowires	Two-step	1-tetradecanol	4200	[33]
Paraffin wax	TiO ₂ , SiO ₂ , Al ₂ O ₃ and ZnO	Single-step		2400	[34]
Petroleum wax	α -nano alumina	Single-step		1800	[35]
Paraffin wax, oleic acid	Gr powder	Two-step		120	[36]
Palmitic acid	SiO ₂	Two-step	Sodium dodecyl sulphate	7200	[37]

**Fig. 5** One-step method for preparation of NePCM [38]

of NPs (SiO₂, TiO₂, Al₂O₃, and ZnO) using single-step method by Teng et al. [34]. The concoction was stirred for 40 min in order to achieve a smooth dispersion. In their experiments, Mohamed et al. [35] typically dissolved urea and Al(NO₃)₃·9H₂O in sterile water before microwaving the resulting mixture for three to five minutes. Following the addition of the petroleum wax to the solution, the resulting mixture was sonicated for a period of thirty minutes in order to get the composite alpha-nano alumina/petroleum wax.

6.2 Two-Step Method

The subject method, shown in Fig. 6, for the preparations of NePCM is most widely employed among scientists and researchers. First, the NPs are produced by the supplier or synthesized in dried powder form using microemulsion, sol–gel method, hydrothermal preparation, chemical reduction, and ball milling techniques. Then NPs are added to PCM to prepare NePCM mixture as shown in Fig. 7. After that, the solution is dispersed evenly utilizing a mechanical magnetic stirrer, ultrasonic bath, and high-shearing mixing methods. The key merit of this method is that NePCM is prepared on a large industrial scale. The demerit of this technique is the agglomeration of NPs, but it can be coped with using the addition of surfactants and homogeneous dispersion.

Surfactants act as the role of a barrier between NPs and base PCM to avoid the accumulation of NPs. It also minimizes the effect of surface tension. In addition, surfactants play a role in the stabilization of the nanofluid by contributing to the generation of ionic strength and repulsive forces. After blending CuO at a mass fraction of 0.5% in PCM (RT-24) at 60 °C and ultrasonifying the mixture for 1440 min, Sharma et al. [39] formed nano-PCM.

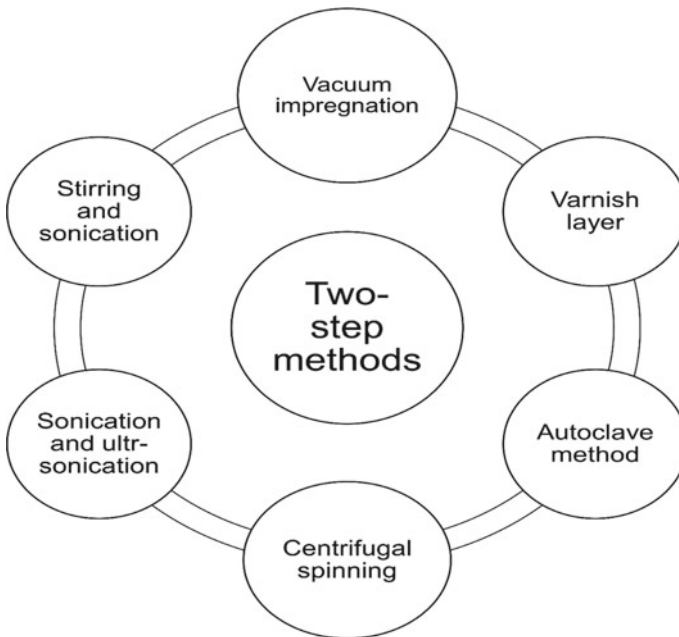


Fig. 6 Two-step methods for preparation of NePCM

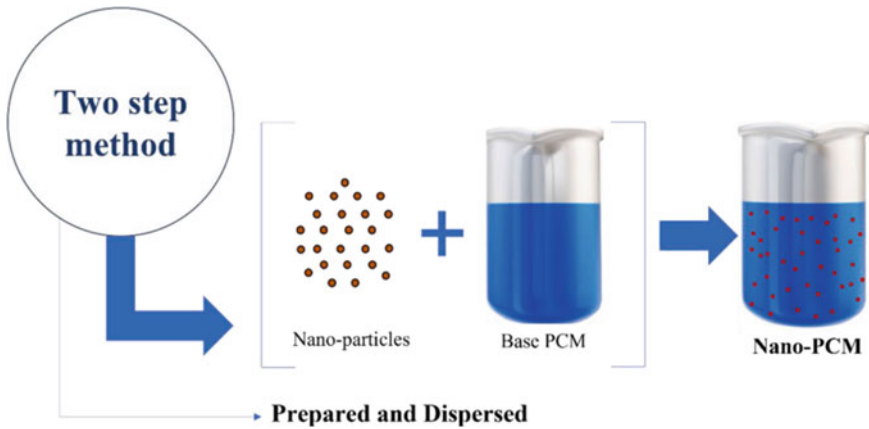


Fig. 7 Two-step method for preparation of NePCM [38]

7 Applications of NePCM

NePCM materials have a wide variety of applications in the technology that is used today as well as in a great number of engineering fields. However, the commercialization of PCM-NEPCM technologies is limited mainly by the high cost of NPs and the blurred cost expenses-benefit of the final outcome. PCMs and NePCMs, on the other hand, have a high thermal energy storage power and ability due to their excellent enthalpy for heat storage. They can be utilized in pharmaceuticals, waste heat recoveries, electronic cooling, lithium batteries, solar, textile fields, refrigeration, underfloor heating systems, milk, and food preservation.

7.1 Solar Thermal Applications

Solar water heating systems (SWHS) are commonly employed to supply hot water in-home applications. However, its industrial usage is limited due to its short operational time and performance. Applying PCM/NePCMs composites to SWHS could overcome both of these flaws. Many researchers published numerous works regarding subject integration. Kumar and Mylsamy [40] analyzed the performance of glass evacuated SWHS without PCM, with PCM and three mass percentages of CeO_2 in paraffin wax a standard-time solar media coverage (6.00 am–6.00 pm). The use of PCM- and CeO_2 -based NePCM SWHS improved the system's first and second law efficiencies. On days with abundant solar radiation, Kumar et al. [41] also studied the thermal performance of solar photovoltaic panels with SiO_2 in PCM. The findings indicated that the PV panel's surface temperature dropped, and its electrical efficiency went up. Wu et al. [42] experimentally analyzed SWHS to reduce the

effect of solar radiation fluctuation, improve its efficiency performance, heat accumulation for subject purposes, and shorten water heating time using PCM. The test rig of SWHS with main components such as heat pipe, solar collector, compressor, evaporator, water pump, thermostatic expansion valve, and water cooling condenser is shown in Fig. 8. Kumar et al. [43] looked into the common issue of PV panels of lower efficiency during peak hours by changing surface temperature. He installed two PV panels with no NePCM and one with a PCM made of TiO_2 on its back. They determined that by adding NePCM, the surface temperature of the PV panel was lowered by $13\text{ }^\circ\text{C}$, and the daily efficiency was raised by 2.1%. Furthermore, the results showed that electrical efficiency increased by 3.5% during the day's brightest hours.

Although conventional energy and tap water are readily available in more developed countries, solar stills have found widespread use in less developed countries. Yet, solar stills have several significant restrictions, including their heavy-weight and limited mobility. Usually, the small size of the absorber and glass cover for available domestic solar stills results in lower plant efficiency and freshwater production. South Africa, Saudi Arabia, and some other areas of the Middle East, are experiencing dry and hot weather conditions, which results in short of freshwater. So, it is

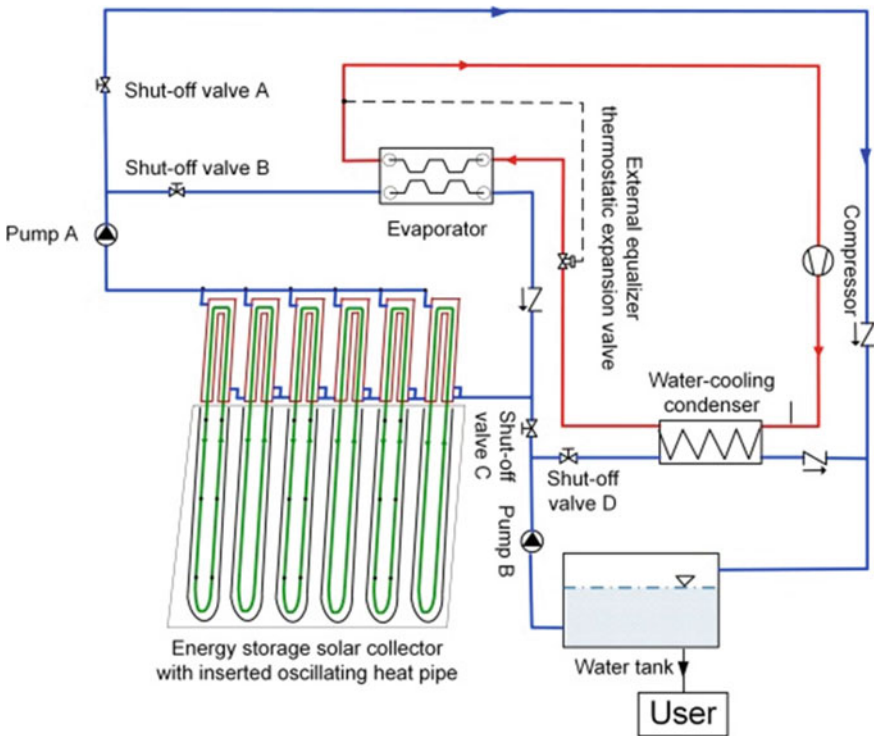


Fig. 8 The solar water heating system with major components [42]

necessary to make significant alterations in solar stills to improve efficiency and the water production rate. Sharshir et al. [44] established four solar still modifications to increase their production, as shown in Fig. 9. They were designed, manufactured, and experimentally performed using (1) flake graphite nanoparticles (FGN)/water, (2) FGN/water and encapsulating PCM, (3) FGN/water and film cooling, (4) FGM/water, encapsulating PCM and film cooling. FGN addition in water, PCM, and film cooling increased the heat transfer area. The enhancement in production for (1), (2), (3), and (4) 50.28, 65, 56.15, and 73.8% was observed, accordingly. In addition, the effect of water depth on the productivity boost was monitored. The findings show that a reduction in water depth from 2 to 0.5 cm results in a productivity boost of nearly 13%.

The peak-daytime output of a CuO-based NePCM solar still with a V-corrugated plate was experimentally studied by Behura and Gupta [45]. It was found that adding 0.1%, 0.2%, or 0.3% mass fraction of CuO to PCM increased solar still productivity by 440, 455, 510 ml/0.25 m² day⁻¹, respectively. A photovoltaic thermal (PV/T) hybrid system was designed by Al-waeli et al. [46] using nano-SiC particles in PCM and nanofluid to control higher thermal conductivities and thus improve efficiency. The experiment was carried out at the peak solar radiation time. The system brought the cell temperature down to 30 °C, increased the thermal efficiency to 72%, and increased the electrical efficiency to a maximum of 13.7%. Nada et al. [47] evaluated three PV, PV-PCM, and PV-NePCM integrated modules at the same location, time, and conditions to improve the module's thermal regulation and efficiency with PCM Al₂O₃-NePCM. The temperature was lowered to 8.1 °C, and 10.7 °C, respectively,

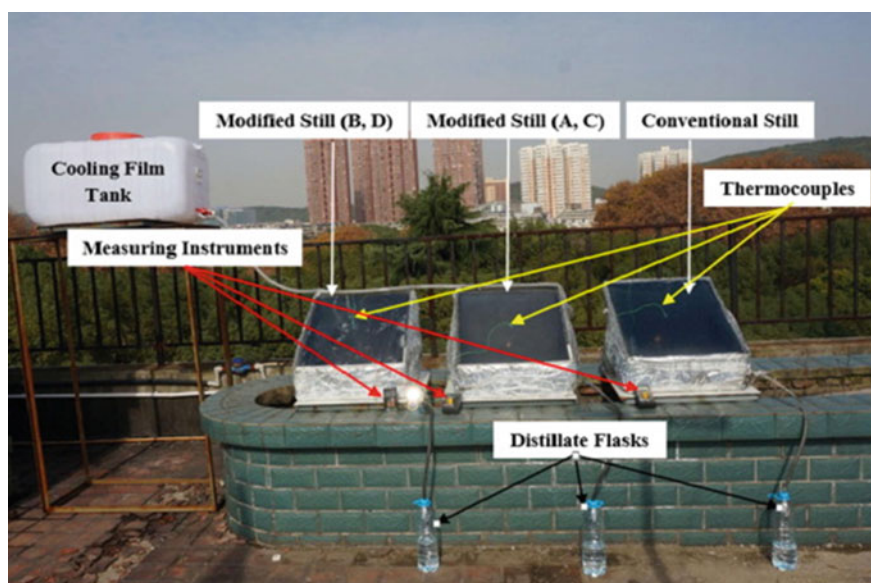


Fig. 9 The experimental solar still setup to increase water production rate [44]

for the integration of PCM and Al_2O_3 -NePCM to the backside of the PV module. Further, efficiency was enhanced by 5.7 and 13.2%. Experiments were carried out by Islam et al. [48] on five different types of solar systems, which are as follows: PV, PVT, PV/PCM, PVT/PCM, and PVT/NePCMPVT that were cooled by NePCM rather than PVT/PCM brought the temperature of the solar cell down by 4 °C. The water exit temperature of PVT/NePCM was more than 46 °C which is superior to PVT/PCM-based exit water. The maximum overall efficiency achieved by PVT/NePCM is 85.3%. A study was sought out by Hackem et al. [49] on the three prototype PV panels' electrical characteristics using pure and combined PCM. One PV panel is taken as a reference to monitor electrical energy efficiency and compare it with other PV panels. In the second panel, pure PCM is put into the rare face of the PV panel using an aluminum container. In order to improve the electrical performance of the PV panel that was being utilized in the third case, PCM was combined with copper and graphite nanoparticles (NPs). Different prototype PV panels used in the present study are depicted in Fig. 10. In comparison, the combined PCM increased the electrical outcome of the PV panel by 5.3%, whereas the pure PCM only boosted it by 3%.

Kumar et al. [50] worked on strengthening the thermal conductivity of PCM salt hydrate using Cu and CuO with six various concentrations (0.1, 0.5, 1.0, 2.0, 3.0, and 5.0%). Sodium dodecylbenzene sulfonate (SDBS) was, usually, employed as a surfactant in a mixture of NePCM to enhance the dispersion properties of NPs into PCM to avoid accumulation. The chemical behavior of CuO NPs in PCM was analyzed with the help of a technique called Fourier transform infrared (FT-IR) spectroscopy. At 3.0% of CuO into PCM showed an 87.39% enhancement in thermal

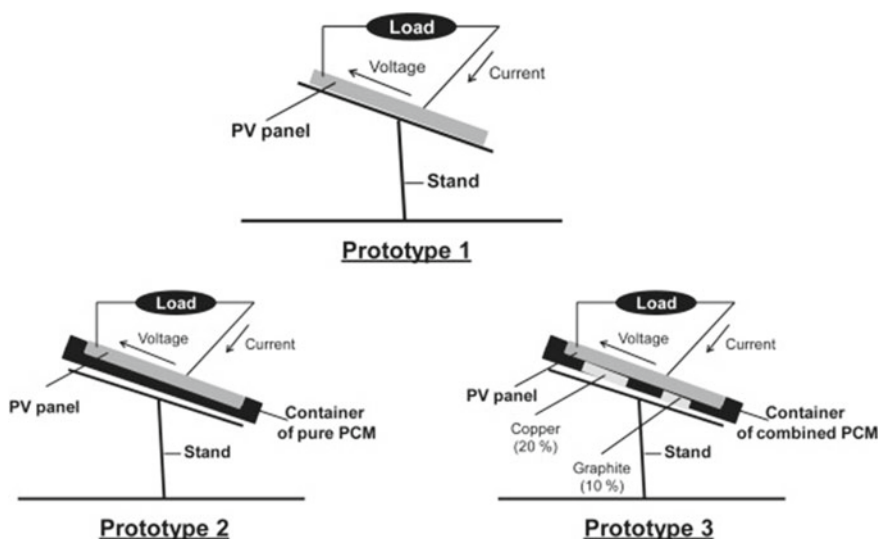


Fig. 10 The various prototype PV panels [49]

Table 4 Analyses of the performance of NePCM in various solar applications

Applications	PCM	NPs and wt%	Enhancement	References
Solar water heater	Paraffin wax	SiO ₂ (1%)	PCM's thermal conductivity was optimized by 22.78%. The energy efficiency increased by 74.79%	[41]
PVT system	Paraffin wax	MWCNT (0.1, 0.2 and 0.3)	Both the electrical and thermal performances were surpassed by 20% and 44%, respectively, at 0.2 wt% in PCM	[52]
PVT system/thermal battery	Paraffin wax	Ag	Both thermal and electrical efficiencies improved by 11.7% by comparing uncooled PVT system	[53]
Solar water heater	Paraffin wax	ZnO and CuO (5)	Improved supplied hot water period 6.2 and 5 h. There was a 26.7 and 45.7% increase in energy efficiency	[54]
Solar desalination	Paraffin wax	CuO (0.2)	The NePCM addition altered the heat transfer to environment	[55]

conductivity. Evacuated tube collectors, also known as ETCs, and flat plate collectors (FPCs) were both tested and evaluated by Olczak et al. [51]. During the winter months, when temperatures were lower, these collectors were put to use to heat the water in residential structures and swimming pools. During the experimental investigation, it was observed that ETCs performed much better steadier solar energy production than FPCs during a cold climatic period. Table 4 reflects the effect of NePCM in various solar applications. Table 4 shows nano-enhanced PCM: a solar application comparison.

7.2 Thermal Energy Storage Applications

PCMs possess high thermal energy capacity, which is one of the major reasons why they interest researchers. However, because they have a low thermal conductivity, their potential application in energy storage is restricted. There have been a number of different passive heat transfer augmentation methods developed to advance PCM thermal conductivity and make them more efficient without the use of any additional energy. Elbahjaoui et al. [56] predicted the heat transfer behavior of Cu NPs based *n*-octadecane PCM during the cooling process in numerical analysis. The two-dimensional numeric model was developed employing finite volume and enthalpy methods. During the investigation, the authors explored that Cu NPs played a positive role in heat transfer enhancement and enhanced storage performance. In an experimental study, Colla et al. [57] investigated two PCMs, i.e. RT20 and RT25, with alumina and carbon black nanomaterials of 1 wt%. The significance of the aforementioned nanomaterials on latent heat and thermal conductivity was investigated. Alumina NPs showed a 10% improvement in latent heat, while carbon black

showed more than 25% elevated in the thermal performance of PCMs. Kean and Sidik [58] experimentally and numerically investigated PCM with the addition of various volume fractions of NPs like Al_2O_3 , CuO, and ZnO in a square cavity. The impact of NPs concentration and the heating side of the wall was under observation. During the study of the computational investigation, the enthalpy porosity approach was utilized. At a low volume fraction of NPs addition in PCM, there was a notable enhancement in the heat transfer rate. Leong et al. [59] described some workable strategies for increasing the thermo-physical properties of PCMs through the incorporation of nanomaterials. When it involves the progression of thermal conductivity, the NPs' dimensions and shapes are of the utmost importance. They also explored that the mass concentration of NPs directly relates to PCM thermal conductivity enhancement and that repeated heat cycles significantly degrade the NePCM thermo-physical properties. In addition, they concluded that the thermal conductivity of NePCM may influence a role in determining how long it takes for the encapsulated PCM to charge and discharge.

Kibria et al. [60] investigated a wide variety of NPs in relation to energy storage for thermal systems. The authors reported on the behavior of paraffin and fatty acids-based PCMs that were incorporated with metal and metal oxide NPs, carbon nanofibers (CNFs), and carbon nanotubes (CNTs). Zeng et al. [61] investigated PCM with uniform addition of Ag nanostructure. A significant amount of phase change enthalpy is possessed by PCM composites. With the incorporation of Ag, there was a slight reduction in the phase change duration and substantial enlarge in the thermal conductivity. Kan et al. [62] mathematically explored the addition of various volume fractions of graphene NPs (1, 3, and 5%) in various types of PCMs (*n*-octadecane, $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$, and capric acid) filled in the square aluminum cavity to see the melting effect. According to the findings, the incorporation of graphene nanoparticles makes PCMs more thermally conductive, which, in turn, accelerates the rate at which they melt. As a method for storing latent heat, a combination of sugar alcohol-based PCM and graphene nano-plates, with or without the presence of fins, was subjected to a numerical investigation by Singh et al. [63]. Fins height was changed during the investigation for optimization of fins. The melting time was decreased by 11%, 39%, and 55%, respectively, when graphene NPs with volume proportions of 1%, 3%, and 5% were incorporated into PCM. The combination of NPs and fins speeds up the melting process by a factor of 68%.

Jiang et al. [64] investigated Al_2O_3 -based PCM to enhance phase change properties and heat transfer. He et al. [65] conducted an experiment in which they studied PCM ($\text{BaCl}_2 \cdot \text{H}_2\text{O}$) with a suspension of TiO_2 NPs in a system that stores energy at a low temperature. The authors reported that thermal conductivity was improved by 12.76%, while specific and latent heat was decreased by adding NPs. Marcos et al. [66] investigated the addition of Ag silver NPs in organic PCM (poly ethylene glycol) PEG400 for a new thermal energy storage solution. The effective addition of Ag NPs led to improvements in diffusivity as well as thermal conductivity, while also leading to a reduction in the effect of subcooling. Hossain et al. [67] conducted a computational investigation into the energy storage capabilities of cyclohexane PCM using aluminum foam and CuO NPs as the storage medium. They concluded that

the presence of NePCM and porous foam required a large amount of energy to melt PCM. Hari Krishnan and Kalaiselvam [68] focused on the thermophysical properties of PCM (Oleic acid) with CuO NPs addition. The performance of NePCM surpassed that of pure PCM. It was revealed that NPs based PCM saved solidification time by 10.71–27.67%.

7.3 *NePCM Applications in Heat Exchanger*

In a study by Khan et al. [69], 3-D computational models of 14 cases with varied extended surfaces and volume fractions of graphene NPs in PCM were under deep investigation. Within the vertical shell tube heat exchanger were utilized circular extended surfaces, longitudinally extended surfaces, and wire-wound extended surfaces. The extended fins had better charging rates and thermal distribution than NePCM. The novel design of fins with 1% NPs insertion in PCM provided the optimum solution for the thermal management of heat exchangers. Alqahtani et al. [70] experimentally analyzed the 2.5 kg of aluminum nano-enhanced PCM for thermal management of aluminum finned tube heat exchangers used for battery. The battery's charging process was enhanced by 30% with 1 wt% addition of nano-materials in PCM. Hajizadeh et al. [71] investigated the wavy channel using CuO NPs-based PCM to determine the solidification behavior of PCM. Working of PCM and charging surface of duct were two major parameters for improving the performance of the wavy channel. The addition of NPs helped to lower the solidification time. Mahdi et al. [72] investigated how adding alumina NPs to a triplex tube heat exchanger affected the amount of time required for PCM (RT-82) to become solid. As the volume fraction of NPs that were enriched in PCM increased, the level of heat transmission intensified as well. Time spent solidifying was cut down as a result of the improved heat circulation. With the aim to better manage the internal surface temperature of electronic gadgets, Krishna et al. [73] focused on heat pipes that made use of NePCM. It was observed that NePCM stored 30% energy at the evaporator, which resulted in the reduction of fan speed.

Ghalambaz et al. [74], graphene oxide NePCM was used in the outer shell to cool cupric acid in the inner tube. The inner tube is covered with a metallic foam layer and a mixture of NePCM. The nonuniformed shape metal layer and NePCM improved the rate of heat transfer. Furthermore, they examined that the porosity of foam, NPs concentrations, and eccentricity had minimum consequence on the thermal energy storage of the system but had a significant impact on melting time. Abidi et al. [75] study explored the boiling and releasing processes in a two-dimensional circular enclosure using graphene NPs in PCM ($\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$), as shown in Fig. 11. Twelve rectangular blades were placed in the inner circle of 7 mm diameter. The blade length varied from 0 to 1.5 mm in each case. The increasing blade length reduced the heating and releasing time of NePCM.

Masoumi et al. [76] mathematically and analytically investigated the melting and solidification performance of NePCM using longitudinal-fins-based shell and tube

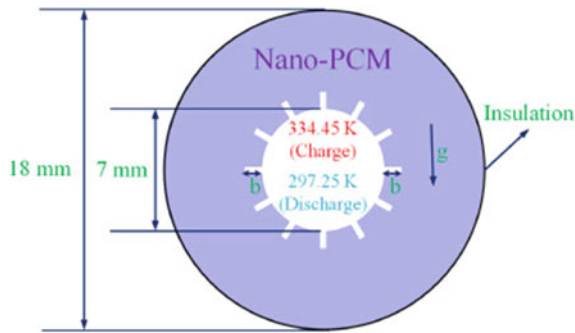


Fig. 11 The geometry of circular enclosure heat exchanger [75]

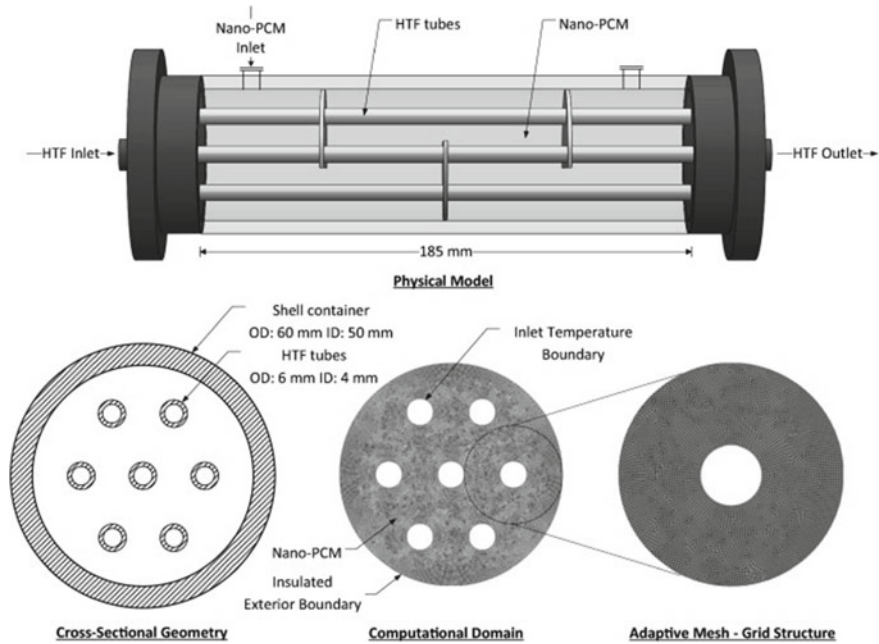


Fig. 12 Physical and computational configurations of heat exchanger [77]

heat exchanger. They used titanium oxide NPs in stearic acid PCM. They got to the conclusion that the addition of titanium oxide NPs has a beneficial effect on boosting the material’s thermal conductivity and rate of heat transfer. As can be seen in Fig. 12, Khan et al. [77] reported on the use of commercially available metal oxide NPs in the investigation of the heat transfer properties of PCM-based shell and tube heat exchangers. They utilized a computational approach known as the enthalpy porosity method. At the temperatures that were being controlled, the simulation was carried out so that the charging and releasing cycles for NePCM in the heat exchanger could

be examined. The thermal conductivity of PCM was also increased, which NPs did, as was the surface area available for the heat exchanger. SiO_2 -based PCM improved charging rates by 29.45 and 41.04% and enhanced melting rates by 21.09 and 30.08% with 1 and 5% addition of NPs. They identified that MgO , SiO_2 , TiO_2 , and Al_2O_3 NPs are preferable for domestic and commercial applications as nano additives due to good heat enhancement and relatively low cost.

In their study, Gorzin et al. [78] numerically analyzed the behavior of copper NPs to determine how to reduce the amount of time it takes for PCM to solidify in a multitube heat exchanger. In order to evaluate the process of discharging NePCM from the heat exchanger, several different NPs volume concentrations as well as Stephen's number were used as input parameters. The assessments suggested that the length of time needed for solidification was drastically cut down. In the research investigation on shell and tube heat exchanger by Noberga et al. [79] used homebuilt code to calculate and numeric estimate of finless and finned tubes submerged in PCM and NePCM. The increasing concentration of NPs enhances interface velocity and interphase position by 25% but reduces the time for phase change by 9.1%. Yadav et al. [80] examined a cylindrical thermal storage model using aluminum oxide NPs in stearic acid PCM to examine forced free convection during the cyclic analysis. The impact of the Fourier number, Nusselt number, Rayleigh number, total energy, and the rate of heat transfer was under observation throughout the research analysis. Investigators noticed that the melting durations of the PCM varied when nanoparticles (NPs) were added. In particular, they reported that applying 0.1% NPs caused the melting time to rise by 12%, 0.3% NPs allowed it to grow by 15%, and 0.5% NPs enabled it to raise by 16%. The NePCM-based thermal management was better performed than pure PCM. Khatibi et al. [81] numerically examined metal oxide NPs (ZnO , CuO , Al_2O_3 and SiO_2) mixed with PCM in the triplex tube with a volume fraction of NPs of 0–4%. The Taguchi method was adopted to find optimum solidification time. They examined lower solidification time with 4% CuO/PCM while higher solidification time with 2% $\text{Al}_2\text{O}_3\text{/PCM}$. Triplex tube reflects better thermal management while considering other shell and tube heat exchangers.

7.4 *NePCM Applications in Lithium Batteries*

Both pure electric vehicles and hybrids are seeing rapid growth in popularity in a variety of countries. In the face of escalating oil prices and worldwide global warming due to greenhouse gas emissions, these vehicles are seen as sustainable and environmentally friendly modes of transportation. It is important to note that the relevance of this technology is so great that certain governments in China, France, and the United Kingdom have announced plans to restrict the deal related to the sale of gasoline and diesel-powered automobiles in the coming year. This indicates the significance of this technological innovation's importance. In hybrid and electric cars, the primary source of energy is typically a battery pack that can be recharged. Batteries of variant types can store and supply electric energy to electric vehicle systems and consumer

devices. The most prevalent types of batteries are lead-acid, nickel–cadmium, nickel-metal hydride, and most modern Li-ions. The temperature significantly impacts the battery's reliability, safe operation, and lifecycle. In order to ensure performance, lifespan, safety, and security for lithium-ion batteries, heat generation, and thermal transport are crucial. The most significant deteriorating accelerator is raised battery temperature. A battery thermal management technique, also known as a BTM, is designed to maintain the batteries within the optimal temperature range for their operation while assuring that the temperature is evenly distributed throughout the pack and the cells. Enabling the stable and even temperature circulation at both the pack and cell levels is crucial because an uneven temperature supply causes non-uniform and rapid deterioration. Temperature management and control in a safe working range is an important parameter in the BTMS.

Air and liquid cooling techniques are commonly used in BTMS. However, researchers and scientists are getting more interest in computational and experimental investigation of the influence of NePCM in managing the temperature control of Li-ion batteries [82]. Ramanathan et al. [83] computationally analyzed battery thermal management using NePCM. MWCNT, CuO, and copper NPs in the base fluid of paraffin wax. In this parametric study, variation of NPs concentration and battery temperature were two input parameters. The findings showed that a higher concentration of NPs helps to lower battery temperature, hence improving heat transfer properties. Babapoor et al. [84] researched the thermodynamic efficiency of Li-ion batteries by mixing carbon fibers in PCM to reduce the amount of heat released into the atmosphere. Carbon fibers concentration and size were two variable parameters to improve heat transfer rate. Results revealed that mixing of carbon fibers of 0.46 mass percentage and 2 mm long reduced battery temperature up to 45%.

Jilte et al. [85] introduced a unique thermal cooling technique for the battery system using a multilayer of NePCM for an electric transport system to reduce dependence on fossil fuels, as shown in Fig. 13. The study proposed $m \times n \times p$ arrangements of battery cells and their thermal management system, which refers to battery cells, while n and p refer NePCM filled primary and secondary containers. The thermal management part of the study was performed at room temperatures between 30 and 40 °C. The study suggested that the multilayer NePCM arrangement improved the cooling performance of the battery.

Liu et al. [86] introduced a novel latent heat storage system for battery thermal management modules on a commercial scale. PCM was combined with expanded graphite powder to boost the heat transfer properties, polyethene octene co-elastomers to increase the material's flexibility, and ethylene-ethylene-butadiene-styrene block copolymers to serve as the material's support. The results showed that novel composite PCM reduced battery temperature and thermal resistance, which helped improve the battery's stability and safety. Thermal management of a Li-ion battery was the topic of research conducted by Rostami et al. [87], who used a spiral microchannel in a heat sink that was incorporated with nano-fluid and nano PCM. An increment in the Renold number causes a reduction in temperature.

Goli et al. [88] utilized blended PCM with graphene NPs to maintain rising the thermal cooling governance of Li-ion batteries and keep increasing their reliability.

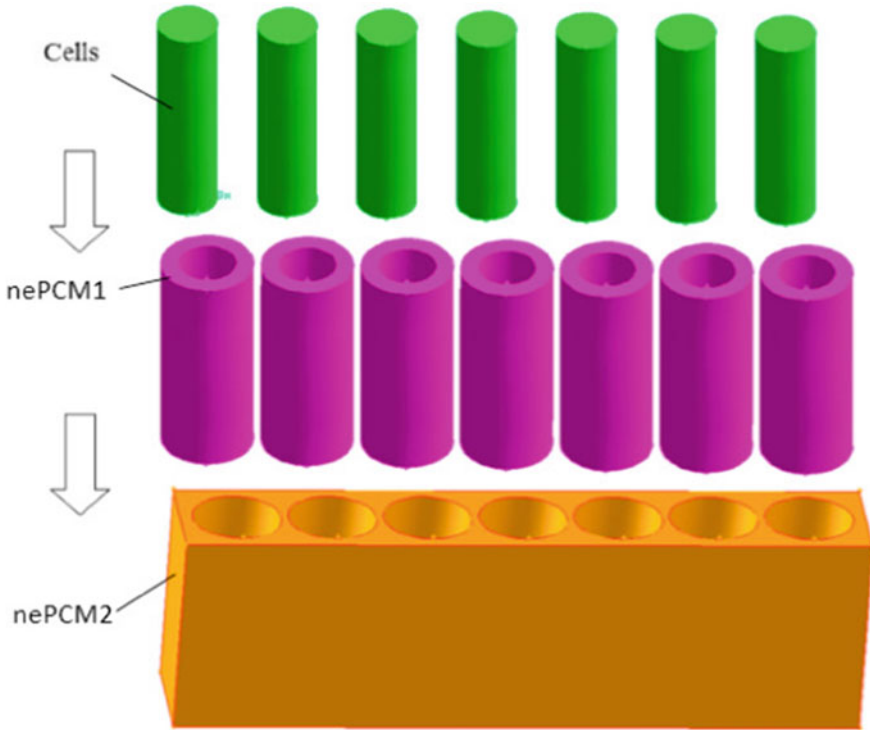


Fig. 13 Battery cells and NePCM arrangement [85]

They achieved this by incorporating graphene powder into the PCM, which expanded its thermal conductivity, reduced the battery inside temperature by improving the conduction process outside the battery, and preserved latent heat storage capacity to make the battery reliable for user satisfaction. Huang et al. [89] proposed stable, flexible-composite PCM integrated into battery packs to enhance thermal control performance and reduce thermal contact resistance.

Chuyuan et al. [90] described Copper NPs in PCM to develop a stable, anti-leakage, and high thermal conductivity battery thermal management system. They showed composites of PCM have a good cooling effect in the charging and discharging process. Experimental research was performed by Menale et al. [91] to enhance the thermal characteristics of Li-ion batteries being used in electric vehicles under both normal and hazardous conditions of operation.

7.5 NePCM Applications in Building Comforts

Any type of energy use significantly impacts energy security in any country’s economic development. Today, the sector’s demand has resulted in the construction of attractive and enormous structures worldwide. It’s worth noting that buildings will consume roughly 40% of all energy produced globally. There is a lack of understanding about the pricing of fossil energy, and there is an increase in information about environmental issues. Both of these factors have contributed to the serious consideration of a variety of alternative power solutions. In today’s buildings, the application of fossil fuels should be made more efficient through the implementation of thermal energy storage devices. Figure 14 depicts thermal energy storage devices in interior and industrial applications [92].

Kasaeian et al. [93] reviewed previous experimental studies on NePCM used in building applications, representing thermal storage as a critical matter in the building. An experimental investigation into the properties of a double layer of PCM composite that had been installed on the roof of a structure in India was carried out by Pasupathy et al. [94]. It was found that indoor temperature was reduced and enhanced thermal comfort level for humans. The generic NePCM uses in structures were examined by Ma et al. [95]. In addition to this, they carried out experimental research on RT-24 which had Cu NPs embedded in it and was installed in a ceiling ventilation unit. The NePCM excelled over the natural PCM, significantly improving both heat charge

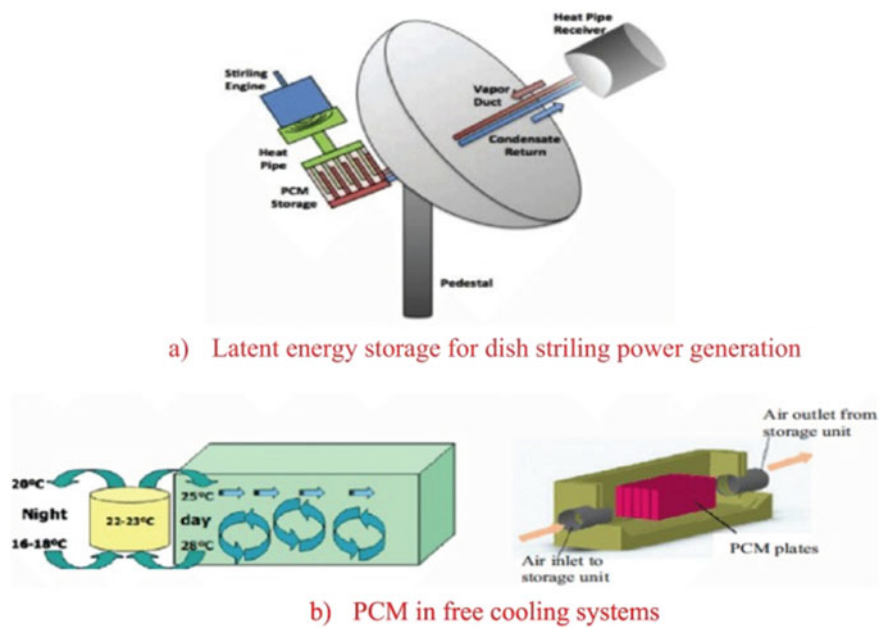


Fig. 14 The solar water heating system with major components [92]

and discharge rates. The heating rate went up by 8.3%, while the heat discharge rate grew by an extraordinary 25.1%.

It was studied NePCM containing eutectic fatty acid and graphite NPs filled in wall panels to improve thermal performance. According to their findings, a room with NePCM-based wall panels can cut heat transfer by 79%. In order to modify the interior wall temperature of the building and cut down on the amount of energy used, Li et al. [96] investigated the use of double-paned windows that were injected with NePCM. By carefully selecting the NPs concentration and diameter, the authors were able to reduce our overall energy consumption by 4% to the minimum level. They found that NPs diameter and volume fraction considerably affected energy consumption in the winter season. In order to lower residential and commercial energy consumption and improve building energy efficiency, Barreeneche et al. [97] examined two fatty palmitic and capric acid PCMs evenly distributed in cupric oxide NPs of varying mass concentrations (1.0, 1.5, and 3.0 wt%). During the study, they found high heat transfer and thermal stability for the NePCM mixture. Capric and palmitic acid showed 55 and 60% thermal conductivity with 3 wt% addition of CuO NPs. Yu et al. [98] focused on fatty acid PCM embedded with graphite nanoplatelets and carbon nanotubes. The heat-carrying power of PCM was ascended by 297 and 218% after NPs were added at a 3 wt%.

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Chapter 3

Enhancing Heat Transfer Performance with Nano Encapsulated Phase Change Materials: Synthesis and Characterization



L. Syam Sundar, Esam Jassim, and Faramarz Djavanroodi

1 Introduction

According to a statistical analysis of the global energy sector, fossil fuels provided 85% of the primary energy consumed globally in 2018 [1]. The need for energy is rising in tandem with population growth, which increases the use of fossil fuels. However, the utilization of renewable energy sources is now required due to environmental repercussions and the depletion of fossil fuels. Systems using renewable energy are crucial for creating clean energy and lowering greenhouse gas emissions. Solar energy is one promising renewable energy source that is currently available. Solar energy can be used all over the world due to its availability, abundance, and direct conversion into electricity.

The discontinuous behavior of solar energy, however, is the main drawback, because amount of energy that is accessible varies depending on the location, the time of day, and the weather [2]. By connecting solar collectors to energy storage systems, which continuously store and deliver electricity, this issue can be solved. Both the traditional energy-producing method and solar collectors can be linked with thermal energy storage (TES) systems. Charge, store, and discharge are the TES processes. Sensible heat storage and latent heat storage are other categories for TES [3].

The choice of PCM is influenced by the change in temperature, heat of latent, conductivity in thermal, heat of specific, density, and expansion thermal coefficient. The PCMs have various usages, but due to less conductivity in thermal, segregation, and larger cooling effect, they are only utilized in a few numbers of circumstances [4]. A number of scientists [5–10] advised the mixing of nanoparticles into PCM is a

L. Syam Sundar (✉) · E. Jassim · F. Djavanroodi

Department of Mechanical Engineering, College of Engineering, Prince Mohammad Bin Fahd University, Al-Khobar 31952, Saudi Arabia

e-mail: sslingala@gmail.com

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well-liked and successful method for dealing with the enhancement of conductivity in thermal. Although the presence of nanoparticles might rise in conductivity in thermal, other thermophysical properties including viscosity, latent heat, and melting point may suffer [11]. However, the proper analysis of how nanoparticles impact the thermo-physical properties, fluids stability, and performance in thermal is crucial.

Since the preparation of an analysis of utilization of nanoparticles in PCM, they are also covered along with the development of NEPCM and different tools/methods for acquiring physical parameters. The importance of larger properties of PCMs with NPs has been the subject of excellent review studies in the literature. The usage of NEPCMs for structures and collectors, the alteration in thermo-physical properties brought on by the inclusion of NPs, and the numerical simulation of NEPCM were all thoroughly covered subjects. There aren't many researches that compare the differences brought about by the various kinds of NPs, despite the fact that it has been shown that adding nanoparticles (NPs) to phase change materials (PCMs) affects these materials' thermo-physical properties.

Furthermore, little is known about the various methods that can be used to create and characterize nanoparticle-enhanced phase change materials (NEPCMs), stabilize NPs inside PCMs, and study the effects of heat and cool durations on physical properties of NEPCMs in 30–100 °C. In addition, there aren't many reviews papers and those that do exist are scarce that provide an overview of the necessary research that must be conducted before choosing suitable NPs for NEPCM applications.

As a result, the focus of the current review study is on the techniques for synthesis and characterization, changes in thermo-physical properties brought about by the use of NEPCMs, strategies for stabilizing scattered NPs in PCMs, and applications of NEPCMs. This information is especially important in light of the wide range of NEPCM applications that could be used in solar thermal energy systems [12–15], battery thermal management [16, 17], PV panels [18], and electronic components [19]. The preparation of nano-encapsulated phase transition materials and a discussion of their stability will be the main topics of this chapter.

2 Synthesis of Nano-encapsulated Phase Change Material

It is essential to ensure that the liquid–solid mixture is evenly and steadily suspended, with no particle agglomeration and no chemical changes, in order to produce a NEPCM that is effective. This is so that an effective NEPCM may be established, which these conditions must be. The two primary strategies used while trying to synthesize NEPCM are the one-step approach and the two-step method. The nanoparticles are produced and disseminated in the base PCM in one step when using the one-step technique. The nanoparticles are first created or purchased in the two-step technique, where they are then distributed in the basic PCM. The nanoparticles are created and dispersed in one step using the one-step process. Contrarily, the two-step approach is chosen by the vast majority of researchers, and it comprises techniques like vacuum impregnation, mixing and ultrasonication, simple mixing, the autoclave

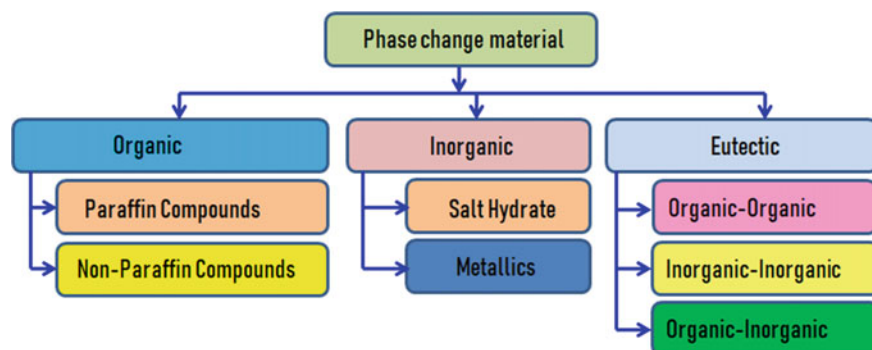


Fig. 1 Classification of phase change materials

method, the absorption method, the one-pot method, and the facial solution blend method.

Numerous investigations have found that the approach that combines mixing with ultrasonication is the most successful. It is feasible to discriminate between two modes when a PCM is coupled with particles that have high heat conductivity. In order to prevent the leakage effect, the first technique calls for the creation of a form-stable composite PCM, in which the PCM is absorbed into the supporting material's pores. This kind of PCM is referred to as a "passive composite."

The use of either three-dimensional or two-dimensional structural changes leads to the production of conducting heat structure in the core of composites to attain this level of thermal conductivity. The second technique involves adding a tiny amount of a material with a high level of thermal conductivity to PCM in order to increase its thermal conductivity.

The resulting combination could be regarded as an initiative composite PCM because it cannot stop liquid leaks from the PCM. This mode primarily establishes conduction in heat passage once PCM is mixed with additive 1-D or 0-D structures. It might of larger moment of free phonon to enhance the conductivity in thermal. The contaminants and gases in PCMs must be eliminated before NEPCM can be synthesized. Figure 1 indicates the classification of phase change materials.

3 Preparation of NEPCM-Based Nanofluids

Because it does not entail the direct inclusion of nanoparticles into the base PCM, the production of nano-enhanced phase change materials (NEPCMs) requires the employment of appropriate mixing and stabilizing processes. It is essential for the efficient operation of NEPCMs that these nanoparticles be dispersed in a uniform manner throughout the material. There are two basic approaches to the synthesis of NEPCMs, which are referred to as the one-step method and the two-step method

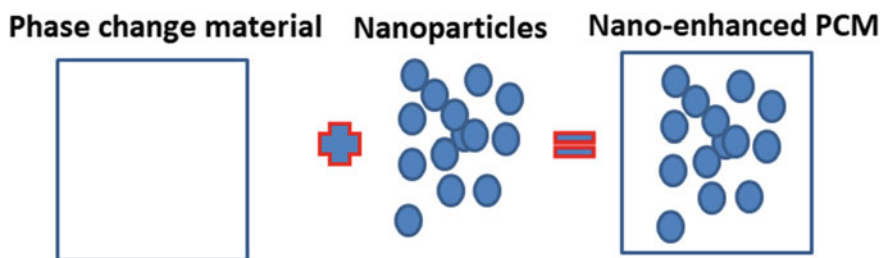


Fig. 2 Concept of nano-enhanced phase change material

respectively. The concept of the nano-encapsulated phase change material is shown in Fig. 2.

The production of nanomaterials and their subsequent dispersion both take place simultaneously in the primary phase of the PCM itself in a one-step process. The continuous procedure ensured by this approach makes it simpler to disperse nanoparticles uniformly. The two-step procedure, on the other hand, starts with the synthesis of nanomaterials and continues with their dispersion into the PCMs that act as the basis. This method, which generally results in reduced prices and has gained substantial uptake in recent years, is now being used to produce huge amounts of NEPCMs.

In order to achieve the objectives, they have set for themselves, both the one-step and two-step strategies employ a range of techniques. The one-step method, which ensures a continuous process and results in a mixture that is more evenly dispersed throughout, can manufacture nanoparticles locally. This could involve the application of techniques like chemical reduction, sol–gel synthesis, or electrochemical deposition, which all enable the production of nanoparticles while spreading them throughout the base PCM.

Even though the two-step method is more economical, it necessitates more effort to ensure that the pre-prepared nanoparticles are distributed properly. It is conceivable to employ techniques like ultrasonication, high-speed stirring, or ball milling to achieve this goal. These techniques support the uniform distribution of nanoparticles throughout the PCM base and the dissolution of nanoparticle agglomerates.

To ensure a uniform distribution of nanoparticles throughout the mixture, the stabilizing and mixing processes used in the production of NEPCMs must be exceedingly precise. While the two-step procedure is more efficient and is used most frequently to produce large numbers of NEPCMs, the one-step method offers a continuous approach to the fabrication and dispersion of nanoparticles. Both methods employ a variety of tactics to achieve their goals; the one chosen depends primarily on the specific application at hand as well as any relevant economic considerations.

3.1 One-Step Method

The production of NPs and their subsequent dilution both take place simultaneously in the one-step technique. With this method, there is no requirement for drying, storing, transporting, or mixing the nanoparticles (NPs) that are contained within the base PCM. As a consequence of this, it improves the NPs mixing within appropriate PCM and helps to alleviate the particle sedimentation. However, because of its greater expense in comparison to the two-step process, the one-step method is typically reserved for use in applications that are on a smaller scale. Figure 3 provides a diagrammatic illustration of the one-step procedure that can be followed.

Teng et al. [19] used the direct synthesis method to create NEPCMs. In their study, they combined paraffin wax with nanoparticles of Al_2O_3 , TiO_2 , SiO_2 , and ZnO at 1.0, 2.0, and 3.0 wt%. After another 40 min of stirring, the ingredients had been properly mixed.

Mohamed et al. [20] employed a different technique to create a —nano alumina/petroleum wax composite. They started by mixing distilled water with urea and $\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$, and then heating it in a microwave for 3–5 min. In order to create the necessary composite, this solution was then combined with petroleum wax and subjected to a 30-min sonication process.

The one-step procedure provides a more straightforward method for the concurrent creation and dispersion of nanoparticles. Because of this, the one-step technique leads to less particle agglomeration and improved nanoparticle distribution inside the PCM. Despite being more expensive than the approach that takes two phases, this method has been found to be effective in smaller-scale applications, according to studies conducted by Teng et al. [19] and Mohamed et al. [20].

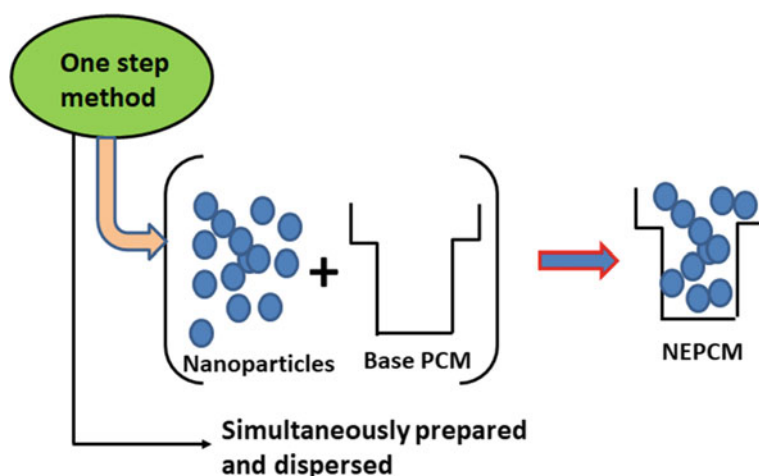


Fig. 3 One-step method of preparation of NEPCM nanofluid

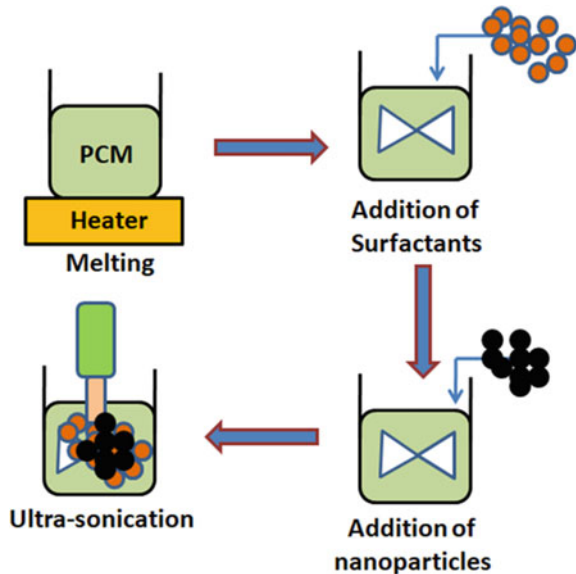
3.2 Two-Step Method

The two-step method is to create dry powdered nanoparticles utilizing a range of mechanical and chemical processes, including ball milling, chemical reduction, and sol–gel processing. The two-step process is then used to produce the nanoparticles. The nanoparticle powder is then added to the PCM base, and several techniques are utilized to ensure that the particles are equally spread throughout the base, high shear mixing, ultrasonic bathing, and magnetic stirring. Figure 4 shows a diagrammatic representation of two-step procedure. The main advantage of this approach is its suitability for large-scale industrial production of nanocomposites. However, it has the disadvantage of particle agglomeration, which encourages the use of techniques that only need one stage of preparation.

Surfactants, which are vital in preventing particle agglomeration, are used to create a barrier between base fluids and suspended particles as well as to reduce the surface tension between them. These surfactants produce zeta potential and repulsion forces, both of which help keep the solution stable. NEPCMs have been created using a variety of different surfactants, including Sodium Dodecyl Sulfate (SDS) [21], Sodium Dodecyl Benzene Sulfonate (SDBS) [22], Poly Vinyl Pyrrolidone-40 (PVP) [23], and Ethanol [23].

Basically, the two-step process involves producing nanoparticle powder first, and then mixing that powder into the primary carrier material (PCM) in order to achieve uniform dispersion using techniques like larger shear mixing, ultrasonic bathing, and magnetic stirring. Despite the fact that this approach is beneficial for mass production, the issue of particle agglomeration persists as a drawback, which may lead to the

Fig. 4 Two-step method of preparation of NEPCM nanofluid



preference for one-step preparation techniques. The use of surfactants like SDS, SDBS, PVP, and ethanol during the manufacture of NEPCMs helps to stabilize the solution and prevents the particles from aggregating.

By combining graphite nanosheets with capric acid (CA) and palmitic acid (PA), Sayyar et al. [24] created PCM nanocomposites. As a consequence, the composition was 92% PCM and 8% graphite. The combination was sonicated for an hour under the sonic bath, then it drops down to atmospheric temperature before analysis. Ramakrishnan et al. [25] first dispersed xGnP in acetone using an ultrasonic probe sonicator for about 30 min before creating an EP-xGnP composite. This specific composite had 1% xGnP, 49.5% paraffin, and 49.5% EP. The mixture was then combined with EP and continuously stirred with a magnetic stirrer for a total of 2 h.

Parameshwaran et al. [26] initially dispersed 1 g of TiO_2 in ethanol using a high-frequency sonicator for 0.5 h before producing the Ag- TiO_2 hybrid NEPCM. After that, silver nanoparticles that had been dispersed in water and then added to the precipitates of white TiO_2 nanoparticles. Throughout the hour-long addition of the silver nanoparticles drop by drop, the liquid was constantly stirred. After the addition of 0.06 g of ascorbic acid that had been dispersed in water, the hue of the solution became a mild shade of gray. Ag- TiO_2 nanoparticles were created as a result of the mixture being washed and dried. These nanoparticles were then ultrasonically disseminated in an organic ester that serves the PCM in order to construct the desired NEPCM.

Harikrishnan et al. [22] employed a PCM made of a mixture of lauric acid (SA) and stearic acid (SA) as a starting material in the synthesis of TiO_2 , CuO, and ZnO NEPCMs. Two steps were taken to integrate these nanoparticles into the PCM. Furthermore, sodium dodecylbenzene sulfonate (SDBS) was added as a capping agent at a concentration of 1.2 wt% to ensure that the nanoparticles were distributed uniformly throughout the PCM. The mixture was treated with ultrasonic waves for an hour in order to achieve stable dispersion of nanoparticles in the PCM base.

MWCNTs were incorporated into liquid paraffin by Zabalegui et al. [27], who subsequently sonicated the mixture using high-frequency impulse sonication at volumetric fractions of 0.2, 0.5, and 1.0%. The mixed materials were split into 12 distinct samples after being placed into an acrylic mold and allowed to set. Silver nanowires, tetradecanol, and ethanol were combined in test tubes for Zeng et al.'s experiment [28]. The mixture was subjected to 10 min of sonication at a temperature of 343 K before being allowed to cool to room temperature so that the ethanol may naturally evaporate. The mixtures were then processed with ultrasonics for 1 h at 343 K, let to cool to ambient temperature, vacuum dried for 24 h, and then ground.

NEPCM was created by Kumar et al. [29] by combining capric acid with a mass concentration of CuO nanoparticles equal to 0.8% and then sonicating the mixture for 30 min. By combining nanoparticles with RT20 and RT25 base PCMs that had a mass concentration of 1.0%, Colla et al. were able to create NEPCMs [30–32]. To achieve uniform dispersion, the mixtures were stirred in a probe sonicator for 20 min at a speed of 600 revolutions per minute (rpm).

Hussain et al.'s [33] method of mixing eutectic PCM with activated carbon nanosheets and sonicating the mixture for three to 4 h resulted in the effective production of nano-activated carbon eutectic PCM. The weight % of the activated carbon nanosheets ranged from 0.02 to 1 wt% in order to provide uniform dilution and avoid the occurrence of clusters.

Latibari et al. [21] used sodium dodecyl sulfate (SDS) as the surfactant, palmitic acid (PA) as the base PCM, and silicon dioxide (SiO_2) as the nanomaterial shell. After the SDS in distilled water had completely dissolved, PCM was added, and the mixture was agitated for 2 h at a constant speed of 1000 rpm. The mixer was diluted with PA emulsion drop by drop, and it is rotated at 500 rpm for 4 h. The whole mixture was then refrigerated to atmospheric temperature, cleaned with water, and centrifuged. The process created a white powder that was collected and allowed to dry for 10 h, and then toluene was used to remove any remaining PA that wasn't encapsulated.

Al-Waeli et al. [34] produced NEPCMs using the two-step procedure. Paraffin wax was initially mixed with SiC nanoparticles in a number of mass fractions, including 0, 0.5, 1, 2, 3, and 4%. The procedure of mixing was done in a 12 L ultrasonic shaker for about 60 min in order to ensure a constant and steady dispersion throughout the liquid. In a different study, Al-Waeli et al. [35] blended water with Al_2O_3 , CuO, and SiC nanoparticles using an ultrasonic shaker. For a total of 12 h, the bath was vibrated while the nanoparticles were supplied at regular intervals. A surfactant called cetyltrimethyl ammonium bromide (CTAB) was mixed to make sure that the water and the nanoparticles were thoroughly mixed. Volumetric concentrations of 0.5, 1, 2, 3, and 4% were used to create the NEPCMs, correspondingly.

In summary, many methods have been used to create NEPCMs using a variety of nanoparticles and main PCMs as the basic building blocks. To achieve uniform nanoparticle dispersion throughout the PCM base, both one-step and two-step procedures have been applied, coupled with a variety of sonication techniques and ultrasonic treatment times. These studies have demonstrated the flexibility of phase transition materials boosted by nanoparticles in a variety of applications, emphasizing the necessity of understanding the processes and conditions needed for efficient nanoparticle production and dispersion.

Due to their acceptable viscosity, nanofluids are frequently employed as heat transfer fluids, and many can also be utilized as PCM materials. For the aforementioned use, a variety of solutions are possible, with water-based nanofluids being the most popular. The impact of water NEPCM on the performance was covered by Altohamy et al. [36], Al_2O_3 nanoparticles were combined with water in volume fractions of 0.5, 1, 1.5, and 2.0%. Both the mixing frequency and the mixing device were non-specific. When hybrid nanofluids comprising TiO_2 nanotubes and nanoparticles were made with similar and varying total TiO_2 mass fractions (0.1, 0.2, and 0.3%), Shao et al. [37] studied the solidification behaviors.

The thermal radiative behaviors of an Al_2O_3 paraffin-based nanofluid were studied by Wang et al. [38]. 0.001, 0.005, and 0.01 vol% of Al_2O_3 nanoparticles are introduced to the liquid paraffin and diluted using 1.5 h of ultrasonication and 30 min of magnetic stirring. Other parameters, such as the used devices, were

not mentioned. Additionally, the CTAB surfactant was employed as a dispersant to prevent any nanoparticle aggregation. Inorganic hydrated salt PCMs (disodium hydrogen phosphate decahydrate $\text{Na}_2\text{HPO}_4 \cdot 2\text{H}_2\text{O}$) and sodium carbonate decahydrate ($\text{Na}_2\text{CO}_3 \cdot 10\text{H}_2\text{O}$) mixed with titanium-based nanoparticles were studied by Liu and Yang [39]. The TiO_2 nanoparticle mass fractions were 0.1, 0.3, and 0.5%, respectively.

Munyalo et al.'s [40] investigation into the latent heat in the fusing of phase transition materials based on nanofluids. Two nanofluids that contained two different kinds of nanomaterials were made using an aqueous solution of 24 wt% of $\text{BaCl}_2 \cdot 2\text{H}_2\text{O}$ as their foundation. Multi-walled carbon nanotubes and MgO nanoparticles with mass fractions of 0.2, 0.4, 0.6, 0.8, and 1.0% were added to the solution.

4 Characterization of NEPCM

4.1 X-Ray Diffraction

Researchers can obtain information through X-ray diffraction by diffracting X-rays and examining their diffraction patterns. A substance's composition or morphology of the atoms of material is discovered. In order to assess NEPCMs at various 20–28 and 27–31 °C, Tumirah et al. [41] performed an XRD test were investigated. The outcomes were shown in Fig. 5. It's crucial to remember that even while n-octadecane melted in St-MMA between 28 and 31 C, literally, the patterns of the substance in the encased shell material.

4.2 SEM Analysis

According to technical definitions, scanning electron microscopy (SEM) works by scan object with concentrated larger beam of electron that trigger a variety of data. The morphology of the sample is examined via receipt, amplification, and presentation of this information. Tungsten filament electron microscopes and FESEM are two types of SEM that are frequently utilized. Nanocapsules typically have a diameter of a few nanometers, hence a FESEM is more advised. Zhang et al. [42] use the SEM to obtain the morphology of NEPCMs with PEMA and PMMA and their image was provided in Fig. 6. The scans demonstrated that nanocapsules had a nearly flawless surface, a smooth and compact surface, and a regular spherical form. The figure of around 400 nm might be used to calculate the NEPCMs' diameter.

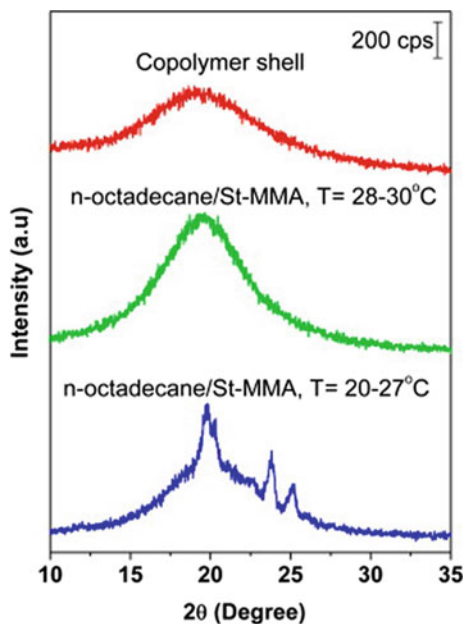


Fig. 5 XRD patterns of copolymer shell, n-octadecane/St-MMA nanoparticles of Sample A4 [41] (Reused with permission from Elsevier, under license number 5577711411307)

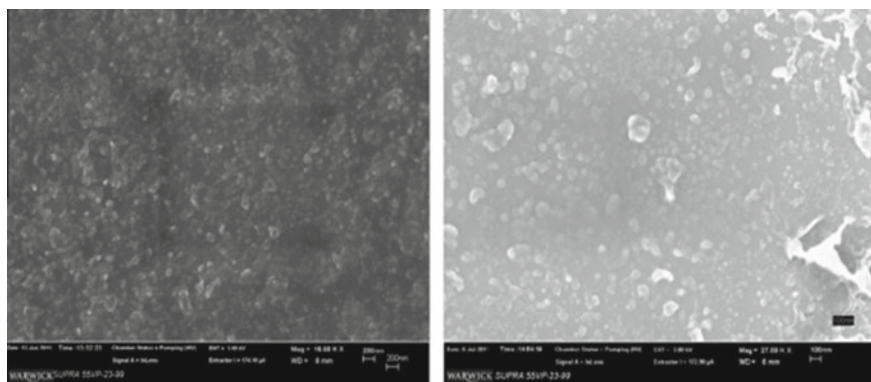


Fig. 6 SEM images of nanocapsules with PEMA shell (left) and PMMA shell (right) [42] (Reused with permission from Elsevier, under license number 5582640302229)

4.3 TEM Analysis

TEM requires more voltage and offers a higher resolution than SEM. The sample's interior structure may be seen because of the greater voltage's ability to allow electrons to pass through the sample. As a result, TEM is usually utilized to investigate

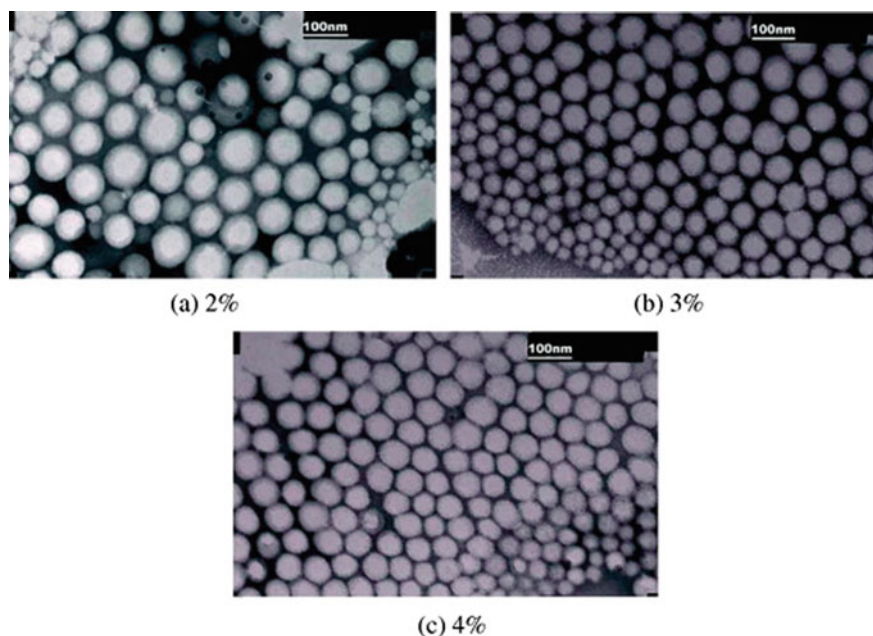


Fig. 7 TEM image of n-dodecanol developed: **a** 2%, **b** 3%, and **c** 4% [43] (Reused with permission from Elsevier, under license number 5582441079422)

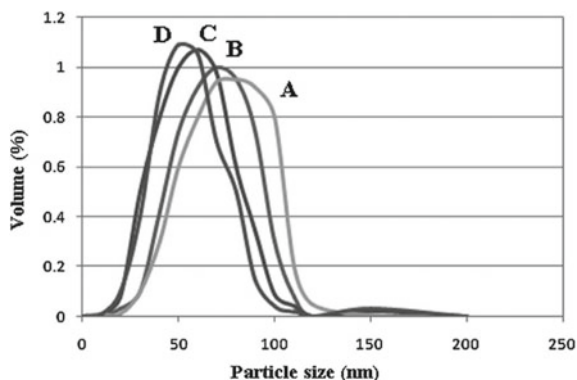
the inside crystal structure and vibration parameters, while SEM is always utilized to assess the surface appearance. The image (Fig. 7) from Chen et al.'s [43] TEM study of the morphological properties of NEPCMs demonstrated a complete spherical shape and a distinct core-shell structure.

4.4 Particle Size Distribution (PSD)

DLS is used to measure the diameter and particle size distribution (PSD) of NEPCMs, and the characterization is typically shown. It was said at the outset, one benefit of NEPCMs is the particle size. The PSD should be as narrow as possible and perfectly developed NEPCMs must be in nanosize range. When comparing four patterns in Fig. 8, Mohammadi et al. [44] discovered NEPCMs' encapsulation displayed the best distribution at an 800 rpm stirring rate.

Due to utilization of hybridized suspension, the NEPCMs' average diameter is 70 nm, and their PSD range is small (5–121 nm). Additionally, Wang et al. [45] examined PSD of nanocapsules at varying surfactant concentrations. It was discovered that as the surfactant concentration rose, the size of nanocapsules shrank. Because the oil phase is distributed more uniformly and nanocapsule sizes are smaller when there is a higher concentration of surfactant.

Fig. 8 Volume distribution curves of Nanocapsules with the use of hybridized suspension agents in different stirring rates (600, 800, 1000, and 1200 rpm) which refer to A, B, C and D curves, respectively [44] (Reused with permission from Elsevier, under license number 5582441437886)



4.5 FTIR Analysis

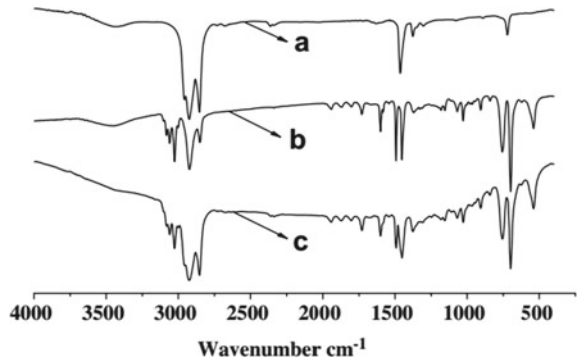
In order to determine the compositions of chemicals of NEPCMs, which involve bonds in chemicals, and groups of functional, Fourier Transformation Infrared (FTIR) Spectroscopy analysis is frequently used. For example, Fang et al.'s [46] in-situ polymerization of n-tetradecane with UF allowed for compositions of chemicals, which included bonds in chemicals and groups of functionals.

Figure 9 is the FT-IR spectra of n-octadecane, styrene, and the nanoencapsulated PCM. It can be seen from Fig. 9a, the multiple absorption peaks at $2916\text{--}2848\text{ cm}^{-1}$ were indicative of the aliphatic C–H stretching vibration, the peak at 1464 cm^{-1} was related to the C–H bending vibration and the peak at 721 cm^{-1} was attributed to the CH_2 group's in-plane rocking vibration. From Fig. 9b it can be seen that the absorption peaks at $3060, 3026\text{ cm}^{-1}$ were associated with the aromatic C–H stretching vibration, the absorption peak at 2923 cm^{-1} was associated with the aliphatic C–H stretching vibration, the absorption peaks at $1601, 1490\text{ cm}^{-1}$ were associated with benzene ring C@C stretching vibration, and the absorption peaks at $756\text{--}700\text{ cm}^{-1}$ were benzene ring deformation vibration. The absorption peaks at 3060 and 3026 cm^{-1} were connected to the aromatic C–H stretching vibration, the absorption peak at 2923 cm^{-1} was connected to the aliphatic C–H stretching vibration, the absorption peaks at 1601 and 1490 cm^{-1} were connected to the benzene ring C@C stretching vibration, and the absorption peaks at $756\text{--}700\text{ cm}^{-1}$ were connected to the benzene ring deformation vibration, as shown in Fig. 9b. In the FT-IR spectra of the nanoencapsulated PCM (Fig. 3c), all the aforementioned typical peaks of n-octadecane and styrene were visible, and no new peak was found.

4.6 Energy-Dispersive X-Ray Spectroscopy

The energy-dispersive X-ray spectroscopy (EDS) particular type of device that activates the distinctive X-ray of the elements by bombarding the sample surface with

Fig. 9 FT-IR spectra of n-octadecane (a) polystyrene (b) the nanoencapsulated PCM (c) [46] (Reused with permission from Elsevier, under license number 5582650348691)



a concentrated electron beam. To perform a micro area component analysis, energy and intensity of distinctive X-rays were then noted and examined. An add-on to SEM called EDS can handle the demands of the trinity examination of chemical composition, microstructure, and micro area morphology.

Yuan et al. [47] used EDS to characterize the samples and establish their chemical makeup; the results are displayed in Fig. 10. Combining the FIIR and SEM findings, discovered the LA core was enclosed in a SiO₂. Latibari et al. [21] use the same characterization technique. The EDS result assisted in determining that the sample only included the core and shell material and no extraneous impurities. (4) XPS, or X-ray photoelectron spectroscopy A type of photoelectron spectroscopy known as electron spectroscopy (ESCA) that uses X-rays as the excitation light source is known as X-ray photoelectron spectroscopy (XPS). For further chemical research, it can also provide information on the content and elements composition in addition to data of molecule structures and valence states of atoms.

Zhu et al. [48] created a brand-new class silver covered NEPCMs for large conductivity in thermal. Further, XPS analysis of the nanocapsules' elemental composition is

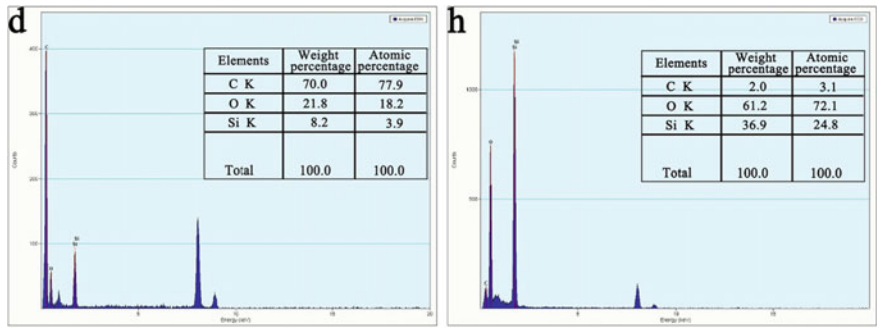


Fig. 10 EDS of synthesized sample under pH 10.4 (d) and pH 12.4 (h) [47] (Reused with permission from Elsevier, under license number 5582450393236)

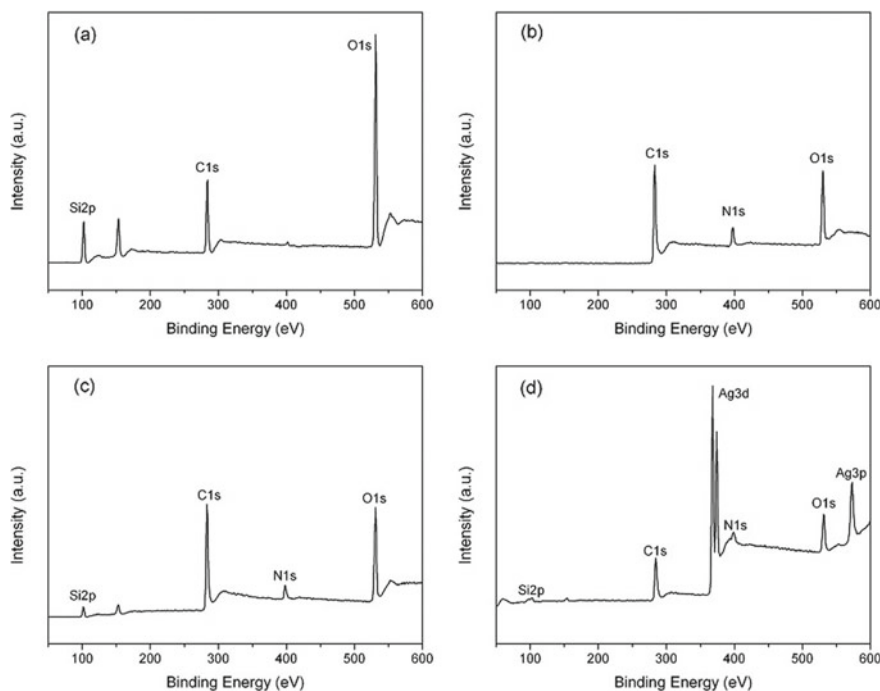


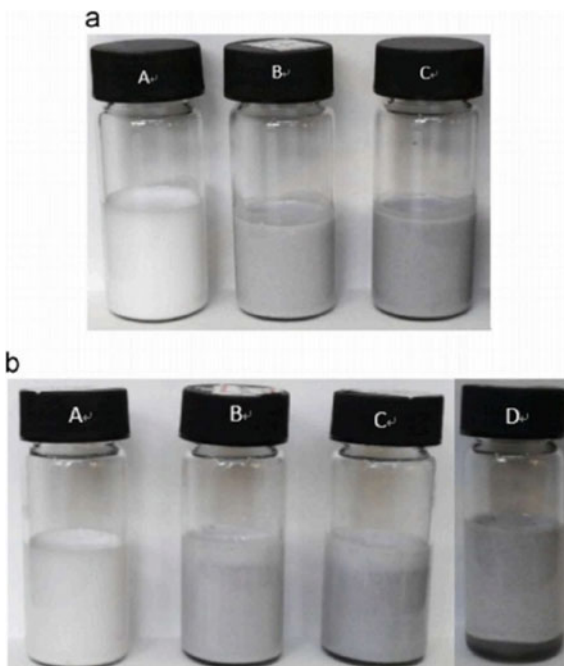
Fig. 11 EDS of synthesized sample at pH 10.4 (d) and pH 12.4 (h) [48] (Reused with permission from Elsevier, under license number 5582450588283)

depicted in Fig. 11. The figure contained the distinctive peaks of all the major components. The characterization outcome proved that the fabrication of the silver-coated NEPCMs was successful.

5 Thermo-Physical Properties of NEPCM Nanofluids

This section discusses the thermo-physical characteristics of NEPCM, including their density, viscosity, thermal conductivity, and latent heat capacity. Different studies have looked into the thermo-physical characteristics of PCMs nanofluids enhanced by nanotechnology. The emulsion before 7 days of storage is shown in Fig. 12a, and the emulsion 7 days later of storage (D-after 3000 heating/cooling cycles) is shown in Fig. 12b [49].

Fig. 12 **a** Emulsion before 7 days of storage and **b** emulsions after 7 days of storage (D-after 3000 heating/cooling cycles) [49] (Reused with permission from Elsevier, under license number 5582450888026)



5.1 Thermal Conductivity

The creation of tiny particles is now possible because of advancements in nanotechnology (10–9). Metal, metal oxide, carbon nanotubes (single-walled and multi-walled), graphene, and graphite are some of the nanoparticles that make up this mixture.

Due to their high surface area to volume ratio, nanoparticles are claimed to exhibit unique properties when compared to bulk solid. When compared to single-layer graphene, MWCNT has a thermal conductivity that is higher by 3000 W/m K. Nanoparticles often have a higher thermal conductivity than phase-change materials. Paraffin, for example, has a thermal conductivity of 0.305 W/m K at melting temperatures between 60 and 62 °C [50]. Thus, it is anticipated that the PCM's heat transfer process will be larger by dilution of these highly thermal conductive nanoparticles.

According to a recent study by Rufuss et al. [51], adding 3 wt% of TiO₂, CuO, and GO increased paraffin's thermal conductivity by, respectively, 25.1, 28.9, and 101.3%. Elgafy and Lafdi [52] discovered that adding carbon nanofiber increased paraffin wax's thermal conductivity from 0 to 4 wt% at ambient temperature. The conductivity in thermal raised 0.2757–0.765 W/mK for 5 wt% of silver nanoparticle mixed with organic ester PCM was found by Parameshwaran et al. [53]. Only physical interactions between the nanoparticles and PCM were seen during their examination.

The results of FTIR were examined between clean Palmitic acid and 0.8 mass% of CuO mixed Palmitic acid by Suresh Kumar and Kalaiselvam [54] and found no differences in the results. They also concluded that when utilizing CuO/Palmitic acid solid PCM, the conductivity rises linearly with the quantity of nanoparticles. For a 0.8 mass% sample, a 57% increase in thermal conductivity relative to pure PCM is seen. In addition, a recent study by Chen et al. [55] found that there was no chemical reaction or creation of a new molecule during the contact between MWCNT and stearic acid PCM.

Mohamed et al. [20], suggested that the γ -Al₂O₃ in paraffin wax solid form exhibits an increase in heat conductivity within the range of 25–50 °C, this is lower the melting point. Whereas, it demonstrates conductivity in thermal of paraffin wax has been treated TiO₂ diminishes as temperature rises [56]. The various kinds of paraffin wax utilized by the two researchers could be the cause of the contradictory conclusions drawn from both investigations. The increase in temperature caused the two pure paraffin wax samples to exhibit different characteristics. The PCM with nano-enhancements just maintains its original PCM characteristics.

Expanded graphite (EG)-erythritol has a better thermal conductivity than MWCNT-erythritol, according to Guo et al.'s [57] research, which they attribute to the faster phonon transport in the EG network and the higher interfacial thermal resistance of MWCNT. Saeed et al. [58] investigated the thermal conductivity of eutectic PCM (methyl palmitate, MP + lauric acid, LA) embedded with graphene platelets in both the solid and liquid phases. This work uses the thickening and gelling ingredient 2-hydroxypropyl ether cellulose (HPEC). At a 10% concentration of graphene platelets, the heat conductivity of eutectic PCM in both solid and liquid (melted) forms dramatically enhanced.

Under the temperature of 30 °C at solid state and 70 °C at liquid state, Harikrishnan et al. [59] investigated conductivity in thermal of SiO₂-myristic acid PCM. The number of nanoparticles in nano-enhanced PCM improves thermal conductivity in both the solid and liquid states, according to the study. Liquids have lower heat conductivity than solids because of the shift from an organized microstructure (solid) to a disorderly liquid structure [60].

According to Warzoha et al. [61], the amount of herringbone graphite nanofibers (HGNF) (2–100 nm) reduces the latent heat in a fusion of organic paraffin (T_m = 56 °C). In contrast to the NEPCM containing 11.4 vol% of graphite nanofibers, which had a latent heat of fusion of 242.7 J/g, the pure paraffin PCM had a latent heat of fusion of 271.6 J/g.

5.2 Density

According to a straightforward mixing model, as the concentration of nanoparticles rises, so should density of nano-enhanced. High density PCM, the optimum option when the volume of the PCM storage system is constrained since it can produce more mass transfer during the phase change process. However, the density of NEPCM is

the subject of very few works. According to Warzoha et al. [62], the density of paraffin increased by up to 1.48% when 8 wt% of graphite nanofibers were added. Additionally, when 20 vol% of nanoparticles are introduced, the density of NEPCM (graphene, MWCNT, Al, and TiO_2) is larger than the paraffin. Saeed et al.'s experimental work [58] has demonstrated that the mixing of graphene platelets increases eutectic PCM density.

5.3 Viscosity

The property of viscosity describes how fluids resist flowing. Larger pumping power is needed to forward the fluid when viscosity is high. However, even in liquid form, the application of PCM does not necessitate that it moves from one location to another. When solidifying or melting, the majority of the PCM is kept in dedicated storage. The stability of spherical particles in the liquid may be affected by the viscosity of the liquid phase change material. The Stokes law states that while using highly viscous fluid, the particle sedimentation velocity drops. Simply said, if the liquid has low viscosity, nanoparticles have a larger inclination to migrate downward due to gravity pull.

The liquid phase viscosity of phase transition material will undoubtedly rise by mixing of nanoparticles. The availability of nanoparticles in a liquid will cause it to flow improperly. For instance, He et al. [63] discovered that the particle volume percentage affects the viscosity of TiO_2 mixed barium chloride aqueous PCM solution nanofluid. This conclusion was also supported by Bahiraei et al. [23]. They claim that as operating temperatures rise under 91 °C, the viscosity of carbon-MEPCM reduces. Because there is more friction and interaction between the nanoparticles, viscosity increases as particle loading increases. Additionally, as the temperature rises, the Van der Waal forces between nanoparticles lessen, resulting in a decrease in fluid viscosity.

5.4 Latent Heat Capacity

Latent and sensible heats are two types of energy (heat) that must be considered while heating or cooling a substance. Latent heat is employed to avoid intermolecular interactions of a PCM in the melting process since it will not get the temperature moment in heat absorption or dissipation. Under solidification, heat is dissipated, allowing molecules to be rearranged in a systematic order. Sensible heat, on the other hand, modifies the material's temperature. Both fusion latent heat and vaporization latent heat are subcategories of latent heat.

Due to the fact that applications of conventional or NEPCM are typically only limited to solid and liquid states, researchers are primarily interested in the latent heat of fusion. The high latent heat of phase change materials is its most promising

property. It is suggested that thermal conductive nanoparticles be included in phase transition material because of its low thermal conductivity. However, no “foreign substance” should be added if it could endanger the phase transition material’s latent heat. As a result, in addition to thermal conductivity, researchers are now concentrating on latent heat of NEPCM.

For low particle concentration, i.e., from 0 to 1.0 wt%, a trend toward reduction is seen. While some of the decrease is minimal, others are greater than 5%. For instance, MWCNT up to 2.0 wt% is mixed, the heat in latent paraffin-wax drops to 0.9% [60]. According to Harikrishnan et al. [59], myristic acid combined with SiO₂ (1.0 wt%) had a melting and solidification latent heat that was lower than that of pure myristic acid by 1.09 and 0.59%, respectively. Researchers have noticed a significant reduction in latent heat [54, 64].

When copper is added to paraffin wax in the amount of 2.0 wt%, Lin and Al-Kayiem [64] discovered a 14.5% decrease in heat of latent (melting), 13.3% less latent heat of solidification was measured for the same nanoparticle dosage. The organic methyl ester reduced the heat of latent, similarly when copper-titanium hybrid nanoparticles were added. Researchers have also discovered the mixing of NPs to enhance the PCM’s latent heat.

According to Shaikh et al. [65], the latent heat (melting) of nano-enhanced paraffin wax based on SWCNT, MWCNT, and carbon nanofiller (CNF) raises drastically as loadings higher to 1.0%. For SWCNT, MWCNT, and CNF, the increases are 12.98, 10.08, and 6.80%, respectively. According to a recent study by Mohamed et al. [55] at 2 wt% of Al₂O₃/paraffin wax and micro-crystalline wax latent heat of NEPCM is superior to pure PCM. To fully understand the driving forces behind the variable PCM latent heat signature, more in-depth research is required.

6 Heat Transfer of NEPCM

The downsizing of magnetic devices and electronic components has resulted in a rise in heat production. PCMs can also be utilized as small-scale energy storage media [66]. Conventional heating methods like air cooling or cooling with heat sinks are frequently insufficient. Therefore, experts are constantly looking for workable solutions to these cooling demands in technology. The micro-channel and mini-channel heat sinks have demonstrated their high performance among the different suggested ways [67]. Using a working fluid with superior properties, nanofluids [68] or hybrid nanofluids [69], could enhance the heat transfer rates.

Previous research has focused on Micro-Encapsulated Phase Change Materials (MEPCMs), which have the potential to be used as heat transfer fluids. The microparticles in MEPCM slurries go through a phase change, which affects the heat transfer. The PCMs, which melt or solidify at fusion temperatures and store or release heat to environment in accordance with latent heat, are the fundamental component of MEPCMs. In-depth studies by Delgado et al. [70] and Chen et al. [71] have reviewed MEPCM slurries and mixers as well as its thermal properties.

Wang et al. [72] looked into transfer of heat of MEPCM flows in a micro-channel with goal of using them as channel heatsinks. By using a computational 3D model, Sabbah et al. [73] evaluated heat transport and performance of thermal of MEPCM-dispersed micro-channel theoretically and employing a detailed model. Liu et al. [74] investigated the heat transmission behavior of MEPCM slurries in microchannel and found that employing 20% of the mass of microcapsules caused the Nusselt number to grow by 190%.

A patent application for MEPCM micro-channel heat exchangers for cooling process was made by Farid and Al-Hallaj [75]. Another patent for MEPCM liquids for car cooling battery application was first introduced by Wang [76]. Ho et al. [77]'s investigation on the benefits of diverging minichannel designs in heat sinks for small channels showed that they might increase heat transfer rates and decrease pressure drops.

In addition, the pressure drops and convective heat transfer of n-eicosane MEPCM-suspensions in divergent mini-channel heat sinks were investigated by Ho et al. in their study [78]. Additionally, they investigated thermal efficiency of suspension at divergent angles of 1.36° and 2.06° and contrasted their observations to the parallel channel. The NEPCMs suspensions were a new class of encapsulated PCM that have just recently been presented, and Liu et al. [79] have studied the benefits of these materials for heat transmission. Researchers can create a stable mixing of NEPCM thanks to the microscopic size of nanocapsules. The NEPCM-dilutions are a sophisticated class of hybrid nanofluids as a result, and they hold promise for a variety of transfer of heat applications [80]. Because of the latent and sensible heat of fusion, diluted in PCNP can travel in liquids and aid in heat transfer.

A 3D model was used by Seyf et al. [81] to simulate the heat transport of NEPCM slurry in a micro-tube heat sink. They presumptively used a lumped mass phase change model for NPs, and they found that the observed particle mass fraction, inflow Reynolds number, and stable temperature in heat sink all improved. In a small channel heat sink with a fixed area, Ho et al.'s [82] investigation of transfer of heat of NEPCM flow revealed a 70% larger in heat transfer and a 45% improvement in performance.

Additionally, discovered the nanoparticles are interesting at low Reynolds numbers because liquid moves slowly along channel. In fact, the sufficient time for transfer of heat, interactions over liquid to nanoparticles, and latent heat absorption, when the flow slows through the channel. The divergence angle of 1.38° was taken into consideration by Ho et al. [83] when they NEPCM-water dilutions in a divergent mini-channel heat sink. The test setup and NEPCM suspension loop [83] are shown in Fig. 13, and the increase in the Nusselt number is indicated in Fig. 14.

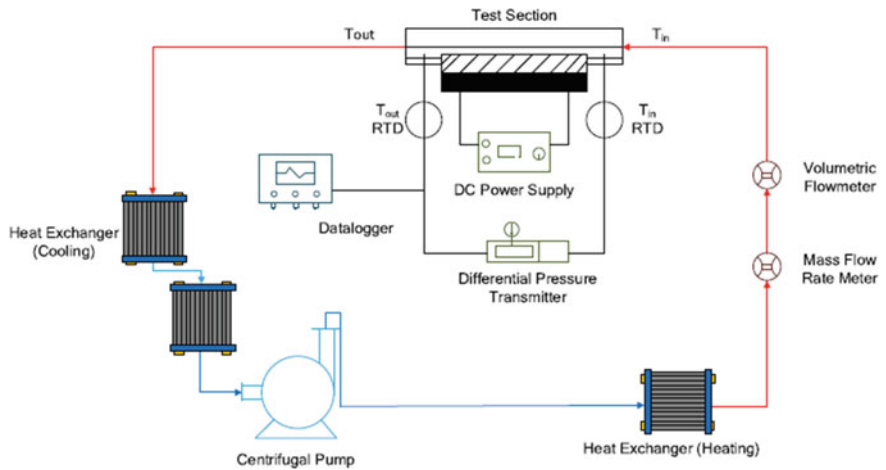


Fig. 13 NEPCM flow suspension loop [83] (Reused with permission from Elsevier, under license number 5577720713192)

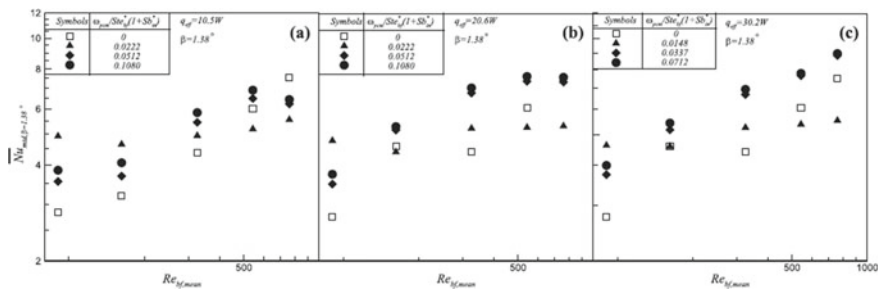


Fig. 14 The Re versus Nusselt number at various power: **a** 10.5 W, **b** 20.6 W, and **c** 30.2 W [83] (Reused with permission from Elsevier, under license number 5577720713192)

7 Concluding Remarks and Future Directions

NEPCMs, also known as nanoparticle-enhanced phase change materials, have shown to have a great deal of potential in a range of applications. This is primarily due to the fact that their thermal properties are far better than those of traditional phase change materials (PCMs). Studies like the ones we've just discussed show there are many different ways to synthesize NEPCMs. These methods can be used to produce a homogenous dispersion of nanoparticles in the base PCM. They include one-step and two-step processes, as well as various sonication methodologies and treatment durations. In the research we just discussed, these tactics were put into practice.

Finally, nanoparticle-enhanced phase change materials, or NEPCMs, have been shown to have considerable potential in a range of applications. This is primarily due to the fact that their thermal properties are greatly enhanced when compared

to those of conventional phase change materials (PCMs). Studies like the ones we just discussed show the wide range of techniques that can be utilized to synthesize NEPCMs. One or more of these can be utilized to create a homogenous dispersion of nanoparticles in the base PCM, along with one- and two-step processes, different sonication techniques, and treatment times.

In the research we just discussed, these tactics were put into practice. Despite the advancements made in NEPCM synthesis, there are still a lot of challenges to be resolved. For instance, particle aggregation could lead to thermal properties that are less than optimal and lower the effectiveness of NEPCMs. More research is needed to address this issue and improve the stability of nanoparticle dispersions in the PCM base.

8 Possible Future Paths for Study in NEPCM Include the Following

1. Exploring new nanoparticles and combinations of nanoparticles as a means of further improving the thermal properties of NEPCMs, this could lead to a larger variety of applications in a number of different industries.
2. An investigation into the NEPCMs' long-term stability is being carried out in order to guarantee their longevity and efficiency throughout time. To accomplish this goal, research into the impact of temperature cycling and aging on the performance of NEPCMs might be necessary.
3. Creating innovative synthesis processes that are both more effective and more efficient, thereby mitigating the limitations of existing methods such as particle agglomeration and making it possible to produce on a larger scale at a cheaper cost.
4. Aiming for the ideal equilibrium between thermal performance and material stability requires that the concentration of nanoparticles and surfactants in NEPCMs be fine-tuned to their optimum levels.
5. Evaluating the environmental impact of NEPCMs, which includes doing a life cycle analysis and determining whether or not these materials can be recycled, is necessary in order to assure the materials' continued viability and reduce any adverse effects on the surrounding environment.
6. The development of NEPCMs has the potential to revolutionize the domains of thermal management and energy storage if these problems are addressed and these future research objectives are pursued. This would result in solutions that are both more efficient and more environmentally friendly for a variety of different industries.

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Chapter 4

Influence of Nanoparticles on Thermophysical Properties of PCMs



Arun Kumar Tiwari, Amit Kumar, and Zafar Said

1 Introduction

Modern day's researches on energy consumption and management have the ultimate aim of sustainable development of society. As the energy generation from non-renewable energy sources (fossil fuels) are putting an adverse effect on the environment [1, 2]. Thus, the researchers are trying to develop cost-effective and high-performance methods of energy generation from renewable energy sources like solar energy demonstrate great potential to generate energy for sustainable future, however, the performance is greatly influenced by their intermittent behavior. Nowadays, thermal energy storage (TES) systems have become an integral part of solar thermal energy generation to eliminate its intermittent behavior. The TES materials have the ability to store surplus energy either as sensible, latent, or chemical energy [3, 4]. This chapter discusses latent heat storage.

Phase change materials (PCM) are employed for storing heat energy in the form of latent heat. What makes these materials distinct is their capacity of storing and

A. K. Tiwari (✉) · A. Kumar

Mechanical Engineering Department, Institute of Engineering and Technology, Dr. A.P.J. Abdul Kalam Technical University, Lucknow 226021, Uttar Pradesh, India
e-mail: aruntiwari@ietlucknow.ac.in

A. Kumar

e-mail: ami36322@gmail.com

Z. Said

Department of Sustainable Renewable Energy Engineering, University of Sharjah, Sharjah, United Arab Emirates

Department of Industrial and Mechanical Engineering, Lebanese American University (LAU), Byblos, Lebanon

Z. Said

e-mail: zsaid@sharjah.ac.ae

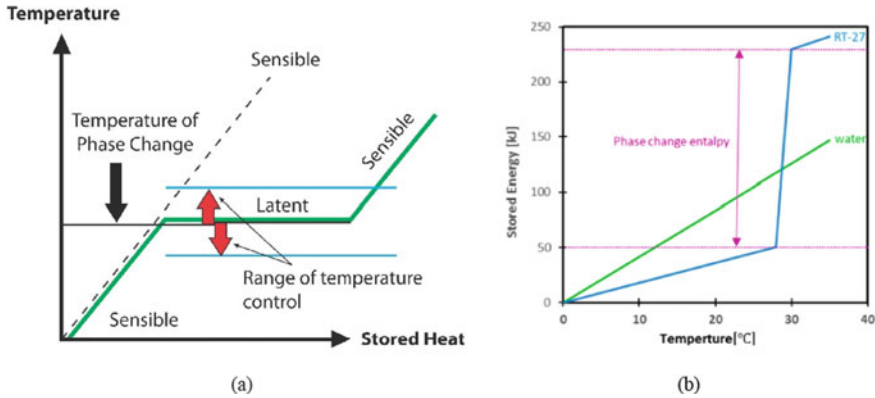


Fig. 1 **a** Process of energy storage, **b** energy storage capability of water and PCM [8]. Copyright Elsevier {Lic # 5510280905238}

releasing large quantities of thermal energy while maintaining a constant temperature, with minimal variation during their phase transition. The PCMs absorb heat energy in solid phase, store it in liquid phase and release it further by transforming its phase from liquid to solid [5–7]. Further, Fig. 1a shows the process of TES. The heat-storing capacity of PCMs is greatly influenced with their thermophysical properties especially thermal conductivity. The valuable feature of PCMs is their large capacity for storing energy. Figure 1b shows the great energy storage capability of PCM. It has been observed that the amount of energy stored in the PCM increases significantly (as indicated by the blue line) during a phase change compared to when the PCM undergoes only sensible heat transfer (as indicated by the purple line). The latent heat energy can be defined using Eq. (1).

$$Q_l = m \times h_{fg} \quad (1)$$

Herein, Q_l denotes latent heat, m denotes mass and h_{fg} denotes enthalpy during phase change. PCMs can undergo three types of phase changes: solid–liquid, liquid–gas, and solid–solid. Among these, based on their composition, solid–liquid PCM can be further categorized into three types: inorganic, organic, and eutectic (Fig. 2). Organic PCMs are rich hydrocarbons and derived from oils having the chemical formula $C_{2n}H_{2n+2}$, where $n \leq 5$ (at 25 °C) are gas, those with $5 < n < 15$ are liquid and the rest are solid. Non-organic PCMs have chemical formula $CH_3(CH_2)_{2n}COOH$ [9].

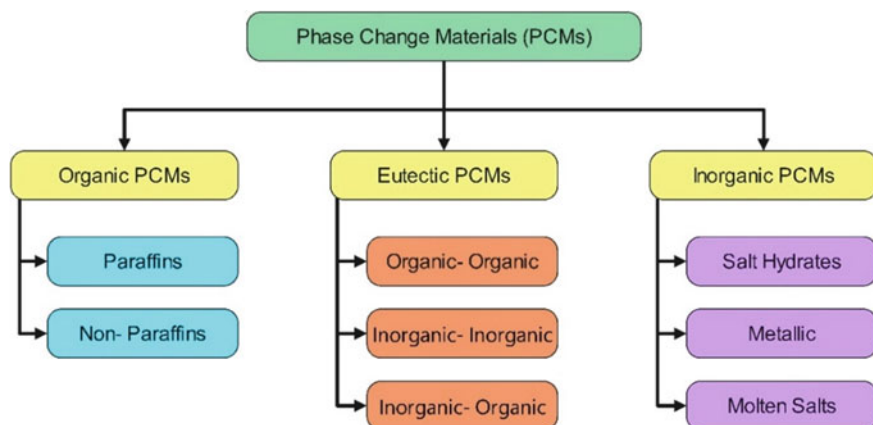


Fig. 2 Classification of PCMs [10]. Copyright Elsevier {Lic # 5510290133613}

2 Influence of Nanoparticles on Thermophysical Properties of PCMs

The majority of PCMs have an unacceptably high energy density and poor thermal conductivity. To mitigate the shortcoming of poor thermal conductivity of PCMs to be used in thermal energy storage applications, methods for improving heat transfer will be explored. To enhance thermal performance, one suitable method is to incorporate nanoparticles into the base PCM [11]. Thus, nano-enhanced PCM (Ne-PCMs) is the advanced class of PCM, which are a mixture of nanoparticles and PCMs. The nanoparticle like Al_2O_3 , CuO , MWCNT, TiO_2 , SnO_2 , SiO_2 , etc., are loaded in PCM to enhance their thermophysical and heat transport properties like latent heat capacity, thermal conductivity, and phase change temperature [12].

2.1 Melting Point

The melting point of a PCM is a crucial property in determining the temperature range within which the PCM can efficiently store and release thermal energy. In general, a higher melting point corresponds to a higher temperature range for thermal energy storage, but also to a higher operating temperature for the system [13]. The nanoparticles suspension into PCMs can affect the melting point of the PCM in various ways, depending on the nanoparticle's types and concentration and the composition of the PCM [14, 15]. For example, the addition of nanoparticles such as Al_2O_3 , SiO_2 , and TiO_2 to paraffin wax can lower the melting point of the wax by a few degrees Celsius, due to the reduction of the intermolecular forces between the wax molecules. As a result, an increase in the melting point of a PCM can expand its temperature range for

storing thermal energy, making it more versatile for use in applications that require lower operating temperatures [16].

Conversely, incorporating nanoparticles such as graphene nanoplatelets, CuO, and ZnO into the PCM can elevate its melting point. This is attributed to the ability of nanoparticles to establish a network structure within the PCM, which enhances the intermolecular forces between the PCM molecules, resulting in an elevated melting point [17]. Incorporating nanoparticles into PCMs can bring about various advantages besides elevating their melting point, including enhancing their thermal stability, TES density, and mechanical properties. Nevertheless, the nanoparticles influence on melting point of PCMs majorly depends on the type and concentration of nanoparticles, the PCM's composition, and the specific Ne-PCM application [18].

In their study, Ibrahim et al. [19] use two models to examine nanoparticle's influence on solid-liquid phase change as well as heat transfer. An analysis of melting in 1-D through conduction and in 2-D through free convection with varying boundary conditions was carried out, utilizing copper nanoparticles in a water-based fluid. The study compares the results with analytical solutions and investigates the effects of nanoparticles on various aspects of the melting phenomena. Zhang et al. [20] examined the melting performance augmentation of PCM for TES systems by combining a new fin structure and Al_2O_3 nanoparticles. The study validates a mathematical model for triple-tube heat exchanger to evaluate melting phenomena with experimental data, hence to analyze the impact of various fin arrangements and nanoparticle loading. The results proposed the use of novel fins by reducing the melting time up to 80.65%, with a further 18.8% reduction while adding nanoparticles. The study concluded that integrating fins and nanoparticles is an effective approach for the augmentation of melting process of PCMs for TES systems. In a study performed by Ghalambaz et al. [21], using the finite element technique, they examined the melting process of Ne-PCMs in a square cavity and obtained an improved melting process. Specifically, the study found that the melting process was accelerated when the increase in thermal conductivity exceeded the increase in dynamic viscosity. Furthermore, the research showed that hybrid nanoparticles consisting of Mg-MgO had the most effective melting performance compared to other types of nanoparticles. Kumar et al. [22] inspect the thermal characteristics of SiO_2 -loaded paraffin wax. The SiO_2 nanoparticles loading into paraffin wax (PW) results in a reduction in melting point of Ne-PCM at mass percentages of 0.5, 1.0, and 2.0%. The melting points of the samples were found to be 63.10 °C, 62.72 °C, and 62.08 °C, respectively for SiO_2 based Ne-PCM compared to 63.74 °C for pure paraffin PCM. The impact of Al_2O_3 , MgO, and SiO_2 nanoparticle doping on the thermal properties of PCM-based LHTES systems was investigated by Singh et al. [23]. The findings suggest a significant surge in the charging efficiency of Al_2O_3 , MgO, and SiO_2 Ne-PCMs, with rates increasing by 33.8%, 33.8%, and 41%, respectively. Moreover, the discharging rate witnessed an upsurge of 19.6%, 25%, and 30% for Al_2O_3 , MgO, and SiO_2 Ne-PCMs, respectively. Notably, SiO_2 -based Ne-PCMs with a volume concentration of 0.3% showed the most optimal results. SiO_2 -based Ne-PCMs samples displayed exceptional thermal response in comparison to the other Ne-PCM samples, rendering them ideal for deployment in commercial applications.

2.2 Thermal Conductivity

Thermal conductivity is an important desirable property for PCMs, which should have a higher value for the efficient working of PCM [24]. Unfortunately, most of PCMs possess lower thermal conductivity value (lower than 0.3 W/m-K). The augmentation in thermal conductivity is essential for improved charging and discharging rate to reduce the length of delayed solidification [25]. Thus, the incorporation of higher thermal conductivity particles (like nanoparticles) into the PCMs can lead to improve PCM's thermal conductivity. Also, distinct factors like nanoparticles concentrations, shape and size of nanoparticles, surfactant, etc. may affect Ne-PCM's thermal conductivity [26]. Li et al. [27] synthesized MWCNT nanoparticle-based paraffin Ne-PCMs and obtained a 65% augmentation in thermal conductivity. Fan et al. [28] synthesized CuO/cyclohexane Ne-PCM with varying mass concentration and examine their thermal conductivity. The researchers noted a clear and direct correlation between thermal conductivity and temperature in the solid phase. However, the thermal conductivity displayed an inverse relationship with temperature in liquid phase (Fig. 3).

Sharma et al. [29] investigated the phase change characteristics of acid/TiO₂ Ne-PCMs at varying nanoparticles loading. The augmentation in thermal conductivity was proportional to wt% (i.e., 46.6% and 80% for 3 and 5 wt% respectively) of nanoparticles along a non-linear incremental curve. Bayat et al. evaluate the performance of finned heat sink using Paraffin wax/CuO and Al₂O₃ Ne-PCM. The result demonstrates the substantial augmentation in thermal conductivity of Ne-PCM at elevated temperature and varying nanoparticles loading (as shown in Fig. 4).

There is no assurance that loading of highly thermally conductive nanoparticles to PCM would result in a greater thermal conductivity compared to the loading of less thermally conductive nanoparticles [31]. It's important to also take into account factors like the homogeneous distribution of particles in PCM. Increased Van der

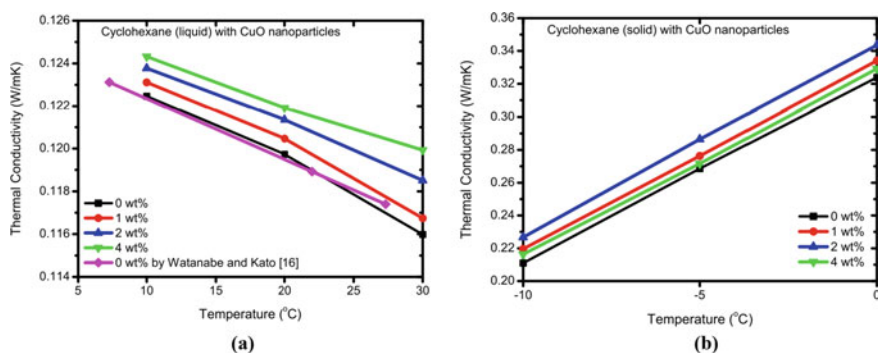


Fig. 3 Thermal conductivity of CuO/cyclohexane Ne-PCM **a** liquid phase, **b** solid phase [28]. Copyright Elsevier {Lic # 5510650453215}

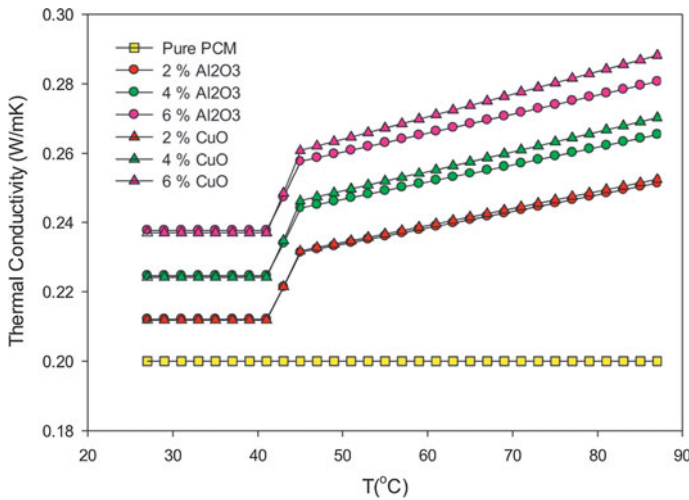
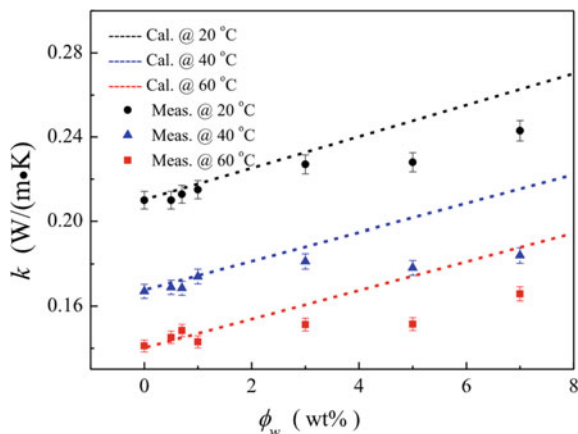


Fig. 4 Thermal conductivity variation with temperature at different nanoparticles concentration [30]. Copyright Elsevier {Lic # 5510290512720}

Waal forces between nanoparticles are thought to be the cause of particle agglomeration [32]. The nanoparticles are drawn to each other by this force and adhere to one another. In addition to mechanical techniques, such as the sonication process, the augmentation of particle dispersion in PCM can be accomplished through particle surface modification and the addition of surfactants, which have been found to be effective methods.

Sami et al. [31] analyzed the thermal characteristics of paraffin/TiO₂ Ne-PCM. A surfactant, sodium stearoyl lactylate (SSL) is added to prevent nano-particle agglomerations. The characterization results of Ne-PCM demonstrated a 35.25 and 24.46% increment in thermal conductivity at 3 wt% and 30 °C with and without using surfactant. Hashempour et al. [33] prepared Ne-PCMs by dispersing carbon nanotubes (SWCNT, MWCNT and modified MWCNT) nanoparticle into the Butyl stearate PCM at 1, 2, 3, 4, 5 wt% and obtained the best thermal characteristics for modified MWCNT. Wang et al. [34] inspected thermal conductivity of TiO₂/Paraffin wax Ne-PCM. The TiO₂ nanoparticles loading increased the thermal conductivity of the composite. However, there were some exceptional cases where this was not observed (as shown in Fig. 5). Specifically, at 60 °C with 1.0 wt% loading and at 40 °C with 0.7 and 5.0 wt% loading, the thermal conductivity is not enhanced. According to the authors, the reason for this could be the agglomeration of particles in the liquid phase, which consumes the free particles that would have otherwise boosted thermal conductivity in composite. The composite's microstructure confirms that, as the particles in the 1.0 wt% TiO₂/Paraffin wax composite begin to agglomerate in the liquid state and provide lower thermal conductivity of composite in the liquid phase.

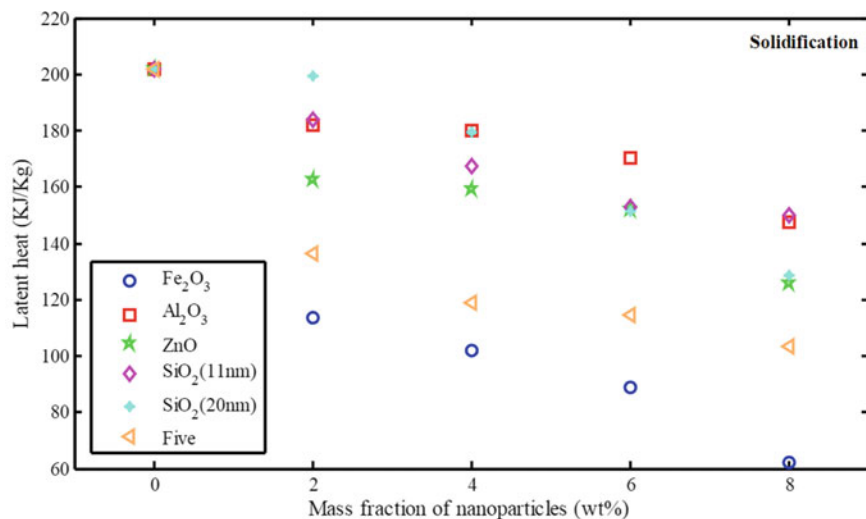
Fig. 5 Thermal conductivity variation of TiO₂/paraffin wax with nanoparticles concentration [34].
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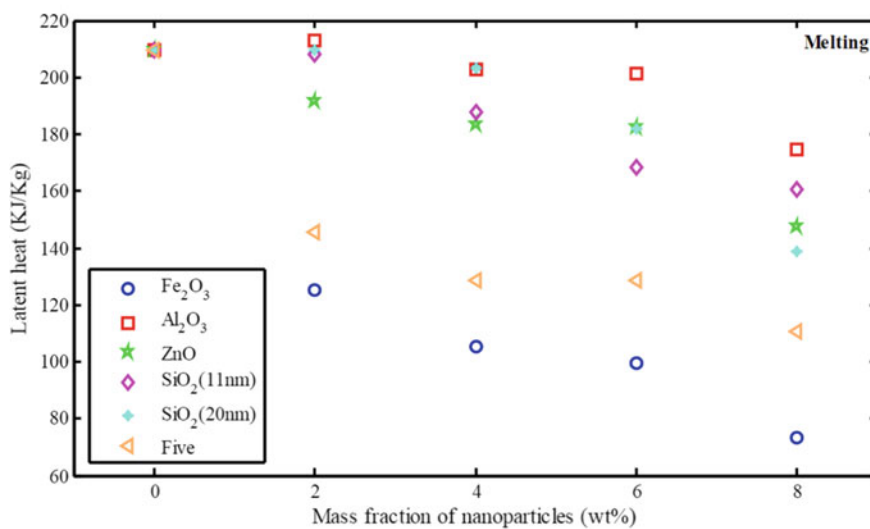
2.3 Latent Heat Capacity

The latent heat capacity of a PCM is the measure of the quantity of thermal energy necessary during phase transformation at a constant temperature [35]. It is an important property that determines the thermal energy stored or released during a phase transition. This property makes PCMs suitable for distinct applications, including thermal energy storage, temperature regulation, as well as heat conduction [36]. The nanoparticles loading enhances the latent heat storage capacity of PCMs by promoting solidification and melting through increased surface area-to-volume ratio, thereby acting as nucleation sites. This lead to augmentation in thermal conductivity as well as energy storage and transfer efficiency [37]. Ne-PCMs have potential applications in several areas, including solar energy storage, building insulation, and electronic device thermal management, to improve energy consumption and system efficiency [38]. Colla et al. [39] inspected the feasibility of enhancing thermal characteristics Ne-PCMs loaded with Al₂O₃ as well as Carbon Black (CB) nanoparticles. The investigation showed that introducing Al₂O₃ to RT20 paraffin wax resulted in a considerable rise in latent heat (+10.8%). In contrast, CB nanoparticles loading led to a minor enhancement (+3.4%) in the case of RT20. Babapoor et al. [40] conducted a comparative investigation to analyzed thermophysical characteristics of various Ne-PCMs. Based on their analysis, they conclude that nanoparticles loading into the PCMs leads to reduction in latent heat capacity. Figure 6 shows that the latent heat of Ne-PCMs during melting shows a non-linear decrease with increasing mass percentage of nanoparticles. This trend is commonly observed, with the most significant drop of 65.04% occurring in sample 2.d, possibly due to the strong magnetic properties of Fe₂O₃ nanoparticles.

The nanoparticles loading to the PCM can increase the amount of heat gained or lost during phase change process. However, it is important to note that loading the PCM with a high concentration of nanoparticles can actually have a negative impact on the latent heat. Therefore, it is crucial to find an optimal balance between the



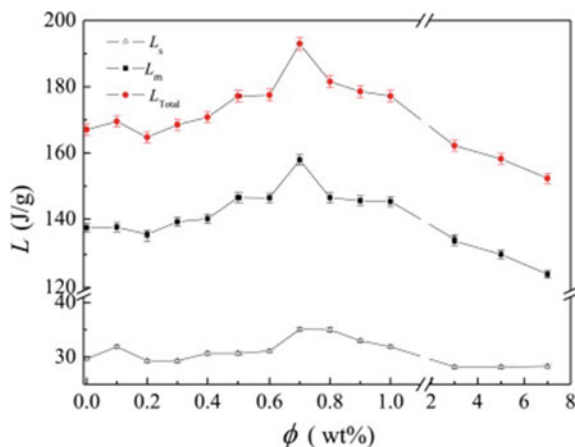
(a)



(b)

Fig. 6 **a** The latent heat comparison of NEPCMs during solidification process **b** the latent heat comparison of NEPCMs during melting process [40]. Copyright Elsevier {Lic # 5510291147380}

Fig. 7 Variation in latent heat capacity of TiO₂/paraffin wax with volume concentration [34].
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amount of PCM and nanoparticles to ensure maximum enhancement of the latent heat [26]. Wang et al. [34] explored the impact of TiO₂ nanoparticles loading into a paraffin wax matrix for possible improvement of thermal properties of the resulting composite material. The results indicated that the composite's phase-transition temperature and latent heat storage capacity were dependent on concentration of nanoparticles. The optimal loading level for achieving maximum latent heat capacity was identified as approximately 0.7 wt% (as shown in Fig. 7), while loading levels above 2 wt% lead to a reduction in latent heat capacity. In their study, Shaikh et al. [41] investigate the impact of carbon nanoparticles on the latent heat of fusion of a PCM. The findings indicated that SCNTs and carbon nanofibers loading into the wax resulted in an increase in its latent heat of fusion. The composite with a 1% loading of SWCNT exhibited the highest improvement of approximately 13%. The experimental results were consistent with Lennard–Jones potential model. It was concluded by the study that intermolecular attraction in the wax/SWCNT composite was facilitated by the greater molecular density and larger surface area of SWCNT.

2.4 Phase Change Temperature

Phase change temperature of PCMs is the temperature at which the material changes phase. The phase change temperature of Ne-PCMs can be affected by several factors, like the size and shape of the nanoparticles, their chemical composition, and the presence of impurities. Generally, decreasing the particle size of the PCM can lower its phase change temperature, as smaller particles have a larger surface area to volume ratio and thus experience more surface energy effects.

In their review study, Yang et al. [17] summarized effect of nanoparticles loading in PCM by reviewing previous important studies and draw conclusions (as shown in Fig. 8). The nanoparticles loading into PCM generally decreases their phase change

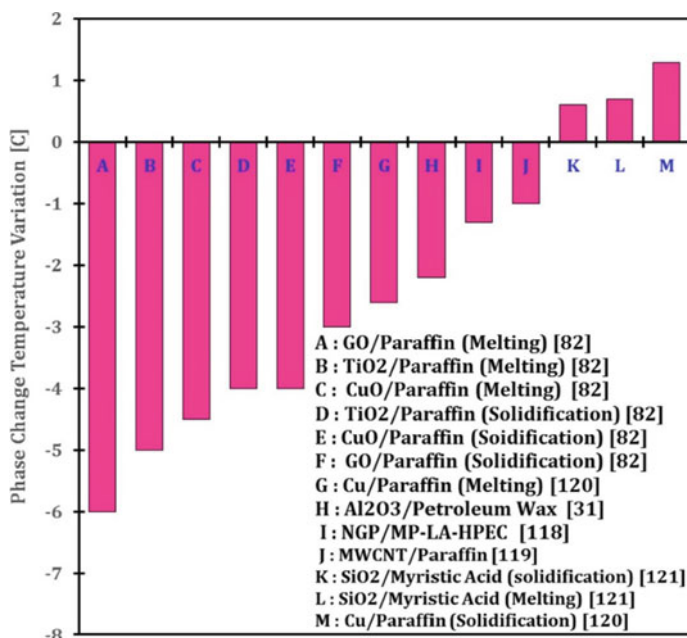


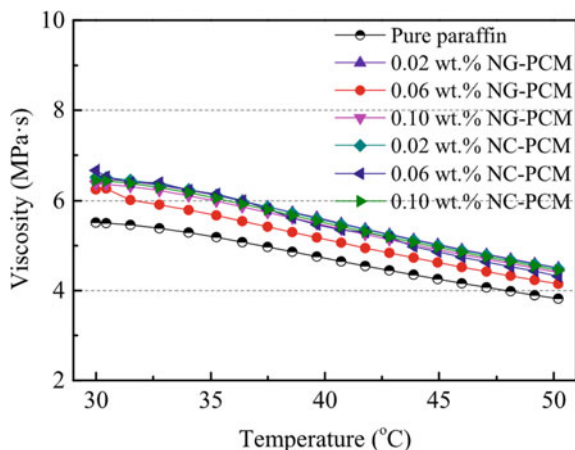
Fig. 8 The effect of inserting nanoparticles on the phase change temperature (the number in square bracket represents the references cited in review study Yang et al. [17]). Copyright Elsevier {Lic # 5510291381361}

temperature. In their study, Wang et al. [42] examined the influence of MWCNT nanoparticles loading to PCM on its thermophysical properties. It was identified that augmentation in mass fraction of MWCNTs in the PW/MWNT composites leads to a reduction in phase change temperature. Additionally, composite's melting temperature containing 0.2, 0.5, 1.0, and 2.0 wt% of MWCNTs were lower than that of pure PW by 0.04, 0.35, 0.57, and 1.06 K, respectively. Lin [43] reported similar findings where the melting and solidification temperature of PW were measured to be 60.42 °C and 55.23 °C, respectively. Upon adding Cu nanoparticles, the melting temperature decreased, resulting in faster melting times. Specifically, the melting temperatures of Nano Cu-PCM at 0.5 wt%, 1 wt%, 1.5 wt% and 2 wt% were measured to be 59.57 °C, 58.97 °C, 58.15 °C, and 57.81 °C, respectively. While the solidification temperature was increased by 5.22 °C, 3.95 °C, 1.60 °C, 1.80 °C and 1.32 °C respectively.

2.5 Viscosity

Viscosity of fluids measures the flow resistance in fluids. In the context of Ne-PCMs, viscosity is an essential parameter in determining their thermal properties and energy storage capabilities. The viscosity of Ne-PCMs predominantly depends

Fig. 9 Influence of temperature and nanoparticle's wt% on viscosity of PCMs [44].
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upon particle size, shape, surface chemistry, and temperature. Studies showed an increment in viscosity while loading smaller nanoparticles. This is because the particles become more tightly packed, leading to greater inter-particle interactions and higher resistance to flow [44]. As the temperature increases, the viscosity decreased (as shown in Fig. 9). This can be attributed to augmentation in kinetic energy and reduction in attractive binding energy. It is worth noting that the viscosity of Ne-PCMs was higher compared to pure paraffin. The higher viscosity in Ne-PCMs could suppress natural convection within the liquid during melting, which could offset the benefits of increased thermal conductivity. To overcome the high viscosity of Ne-PCMs, researchers have developed various techniques such as encapsulation, functionalization, and blending with other materials [45].

Bahiraee et al. [46] determined the viscosity of paraffin wax-based nanocomposite containing carbon-based nanoparticles, including CNF, GNP, and graphite nano-powder, with a melting temperature of 60 °C. The results demonstrated that the rise in nanoparticle concentration led to a corresponding increase in viscosity, in agreement with anticipated outcomes. However, at elevated temperature (i.e., 60–90 °C), there was a slight decrease in viscosity due to the higher kinetic energy of the particles. Chen et al. [47] examined how the addition of SDBS dispersant affects the viscosity of a 30% PCM slurry containing 0.1% TiO₂ at different temperatures. The results indicated that the dispersant mass fraction had a notable impact on the suspension's viscosity, initially decreasing before increasing as the SDBS mass fraction increased. The maximum viscosities were observed at 0.3 wt% of SDBS. However, the suspension's viscosity increased with temperature at a constant wt% of SDBS. The lowest viscosity was achieved at 0.1% SDBS mass fraction, which was 13.4% lower than that without a dispersant. Based on these results, the study recommended 0.1% SDBS as the optimal choice for PCM considering stability, thermal performance, and viscosity.

Chereches et al. [49] investigated the viscosity and isobaric heat capacity of PEG 400 based Ne-PCM with ZnO nanoparticles. They found a 5.78% increment in

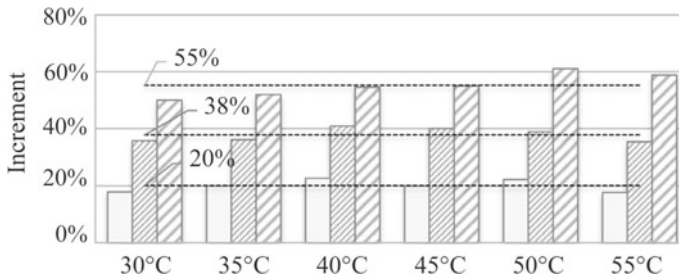


Fig. 10 Percentage increment CuO based Ne-PCMs at 2.5% w/v, 5% w/v, and 10% w/v, respectively at different temperature [48]. Copyright Elsevier {Lic # 5510300277522}

viscosity at 2.5 wt% of ZnO. Águila et al. [48] conducted an experimental study on Ne-PCMs consisting of Octadecane as a base fluid and CuO nanoparticles (Fig. 10). The data shows that the increase in viscosity is nearly constant at 2.5 and 5% concentrations across the temperature range. However, at a 10% concentration, the increase in viscosity varies with temperature, with a higher increase at higher temperatures. On average, the increase in viscosity for concentrations of 2.5% w/v, 5% w/v, and 10% w/v are 20%, 38%, and 55%, respectively. Motahar et al. [50] examined the use of mesoporous silica (MPSiO₂) nanoparticles as a thermal storage composite material. Stable composites containing 1, 3, and 5% MPSiO₂ nanoparticles were created. Results showed that the addition of MPSiO₂ nanoparticles increased thermal conductivity up to 6% at high temperatures, but the increase was non-monotonic in the solid phase with 60% augmentation viscosity in the liquid PCM for 5% MPSiO₂ at 35 °C. Kumaresan et al. [51] examine the effect of CNT nanoparticles dispersion on PCMs and concluded the increment in dynamic viscosity with increased nanoparticles concentrations (as shown in Fig. 11).

2.6 Density

The density of NEPCMs varies with the material composition, but it generally tends to be higher than traditional PCMs due to the presence of nanoparticles [52]. Their high density, combined with their enhanced thermal conductivity, makes them particularly well-suited for use in applications where space is limited and efficient TES is required [53, 54]. After analyzing the thermal characteristics of paraffin-based PCM, Warzoha et al. [55] added graphene, MWCNT, and TiO₂ nanoparticles and concluded that incorporating 20 vol% of graphene nanoparticles to paraffin resulted in a notable increase in PCM density. This increase in density caused a negligible reduction in the paraffin volume per unit, while simultaneously augmenting the absolute phase change enthalpy. It is anticipated that the paraffin-graphene nanocomposite PCM will have the ability to store roughly 10% additional thermal energy during solidification compared to the pure paraffin PCM. Conversely, other types of nanocomposite PCMs

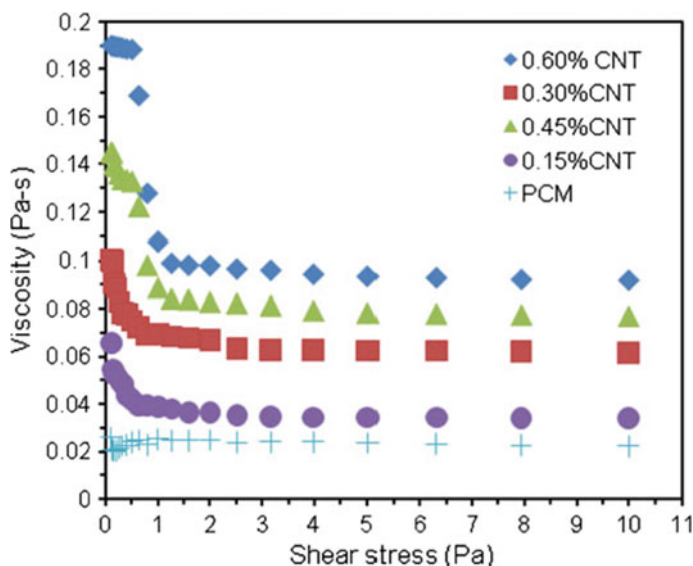


Fig. 11 Effect of CNT nanoparticles on viscosity of PCMs [51]. Copyright Elsevier {Lic # 5510300494359}

are likely to experience a reduction of roughly 17–20% in the amount of thermal energy that can be stored during solidification. In their experimental study, Saeed et al. [56] investigated that incorporating n-GPs (graphene nano-platelets) into PCM leads to an increase in density. The addition of 10% n-GPs resulted in a 13.31% increase in the density of both the melted and solid-state PCM. This increase in density is advantageous as it enables a higher amount of energy to be stored per unit volume. Additionally, the form-stable PCMs with incorporated n-GPs showed a reduced volume expansion during phase change compared to their pure or form-stable counterparts.

2.7 Thermal Diffusivity

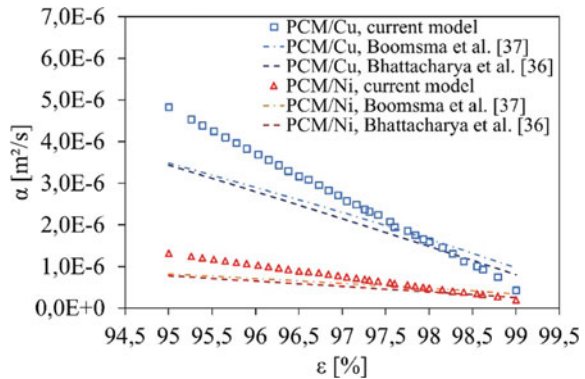
Thermal diffusivity plays a crucial role in characterizing heat conduction rate through a material. It is the ratio of thermal conductivity to specific and density of material. In the case of PCM, thermal diffusivity is particularly significant as it governs heat transfer rate during phase transformation. By nanoparticles loading to PCMs, thermal diffusivity can be augmented by promoting better interfacial contact between the nanoparticles and the PCM. Nanoparticles function as thermal bridges, which facilitate the heat transfer between PCM and surrounding [57, 58].

The concentration and type of nanoparticles can significantly affect the thermal diffusivity of the Ne-PCMs. However, the concentration of nanoparticles must be

carefully controlled to avoid agglomeration, which can decrease the thermal diffusivity. Another factor that affects the thermal diffusivity of Ne-PCMs is nanoparticle's shape and size. Studies have shown that smaller nanoparticles with higher surface area to volume ratio not only improve the heat transfer but also augment the thermal diffusivity. Moreover, the shape of the nanoparticles can also affect the thermal diffusivity, with elongated particles having higher thermal conductivity along their axis.

Sabrina et al. [59] analyzed the thermal diffusivity of copper and nickel-based PCM composite (as shown in Fig. 12). Figure 12 indicate that when the porosity of a composite material decreases, its thermal diffusivity increase. This is due to an increase in the porosity, which decrease the volumetric capacity and effective thermal conductivity of composite. When porosity is reduced, the voids within structure decrease, and density of the metal increases, which results in larger specific surface. As a result, low-porosity materials are better suited for the diffusion and absorption of heat throughout the sample. It is worth noting that the thermal diffusivity of the PCM/Cu composite varies 3.4 times more, than those of the PCM/Ni composite, as the thermal conductivity of copper is higher than that of nickel. García-Vidal et al. [60] evaluated the thermal diffusivity of an acrylic resin containing graphene nanoplatelets (GNPs) at concentrations ranging from 0.02 to 0.12 wt% through the thermal wave resonant cavity (TWRC) technique. The concentration-dependent behavior of thermal diffusivity is demonstrated, indicating a linear increase as the concentration of GNPs in the resin composite increases. This implies that the thermal diffusivity of the composite is enhanced with higher concentrations of GNPs, eventually reaching an optimal enrichment level.

Fig. 12 Variation in thermal diffusivity for PCM/Cu and PCM/Ni composite [59]



2.8 *Effect of Thermal Cycle*

Current studies on Ne-PCM are focused on examining how their performance is affected by repeated temperature changes, with the goal of identifying their potential use in storing thermal energy. The effectiveness of these materials is dependent on their ability to withstand cyclic heating and cooling while maintaining their thermal stability and durability. Studies have indicated that thermal cycling results a decrease in the thermal properties of Ne-PCMs, including melting and solidification enthalpy, thermal conductivity, and diffusivity. This decline is linked to the formation of cracks, voids, and agglomeration of nanoparticles during the heating and cooling cycles, resulting in reduced surface area and active nucleation sites [61]. To counteract the negative effects of thermal cycling, various strategies have been proposed. These include the use of stabilizing agents, such as surfactants or polymers, to prevent agglomeration. The incorporation of thermally conductive additives, like carbon nanotubes or graphene, is also suggested to maintain or increase the thermal conductivity of Ne-PCMs during thermal cycling [17].

Xu et al. [62] analyzed the durability of the PCM samples to withstand repeated temperature changes using a programmable chamber. The chamber was programmed to alternate temperature and humidity, with temperature fluctuations between 10 and 40 °C within an hour. The thermal cycling process involved heating the samples from 10 to 40 °C in 20 min, followed by holding at 40 °C for 10 min then reduce to 40 °C in 20 min, and at last hold at 10 °C for 10 min. Similarly, Suresh et al. [63] carried out a thermal cycling test on the PCM by repeatedly heating and cooling it using a thermal cycling device at a rate of 10 °C per minute. The test started at 30 °C, and the temperature was raised to 210 °C, where it remained for 5–10 min before being cooled back down to 30 °C at the same cooling rate. The researchers performed several tests, such as DSC, TGA, and FTIR analyses, on the PCM samples before and after subjecting them to 100 thermal cycles to evaluate their thermal and chemical stability.

3 Conclusion

The investigation of nanoparticle influence on the thermophysical properties of PCMs has garnered significant attention in recent, due to their potential applications in diverse areas, such as energy storage, thermal management, and building materials. The nanoparticles loading into PCMs showed a substantial improvement in their thermophysical properties, leading to improved energy storage and release capabilities. The high volume to surface area of the nanoparticles facilitates interfacial heat transfer between PCM and surrounding environment, resulting in increased thermal conductivity and diffusivity. Furthermore, the existence of nanoparticles in PCMs can alter their crystallization behavior and nucleation sites, resulting in changes in phase change and enthalpy. However, the effectiveness of nanoparticles in enhancing

the thermophysical properties is determined by factors such as their type, concentration, and size, as well as their dispersion and interaction with the PCM. Therefore, more research is needed to optimize the nanoparticle-PCM composites for specific applications and to investigate their long-term stability and durability. In summary, the study of nanoparticle-PCM composites has opened up new opportunities for the development of advanced materials with enhanced thermophysical properties for various energy-intensive applications.

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Chapter 5

Nanostructure-based Colloidal Suspension for Thermal Enhancement for NEPCM



Suman S. Kahandal, Sandeep K. Jare, Yelim Kwon,
M. H. Ansari Abdul Wadood, Balasaheb P. Pagar, Anuradha B. Bhalerao,
Ji Man Kim, and Ravindra N. Bulakhe

1 Introduction

Due to industrialization, environmental pollution, and high cost of fossil fuels, renewable energy sources have drawn significant attention in recent years. There is an immediate demand to identify alternative energy sources to nonrenewable sources [1–3]. Energy source sustainability is a major issue for all scientists, engineers, and researchers. In recent year's diverse renewable energy sources, i.e., sun-powered energies, wind attracted attention, but maximizing the use of present energy sources

S. S. Kahandal · M. H. Ansari Abdul Wadood · A. B. Bhalerao
Department of Applied Science & Maths, K. K. Wagh Institute of Engineering Education and Research, Nashik, Maharashtra 422003, India
e-mail: ahansari@kkwagh.edu.in

A. B. Bhalerao
e-mail: acpawar@kkwagh.edu.in

S. S. Kahandal · B. P. Pagar
Department of Chemistry, K. T. H. M. College, Nashik, Maharashtra 422002, India

S. K. Jare
Department of Electronic Science, New Arts, Commerce & Science College,
Ahmednagar 414502, India

Y. Kwon · J. M. Kim · R. N. Bulakhe (✉)
Department of Chemistry, Sungkyunkwan University, Suwon 16419, Republic of Korea
e-mail: bulakhe@skku.edu

Y. Kwon
e-mail: dpfla0213@naver.com

J. M. Kim
e-mail: jimankim@skku.edu

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is equally important. Due to its limitless, unlimited supply and eco-friendly nature, solar energy has drawn significant attention and is emerging as an ideal energy source. Climate change and the operation of solar heating devices are major obstacles to obtaining solar energy. Storage and optimization of current energy sources is an important concern with the scarcity of current energy sources. Numerous strategies exist to store renewable energy, including thermal energy storage (TES), flywheels, batteries, compressed air, and pumped hydroelectricity. Thermal energy storage systems are an efficient method of storing energy. These are divided into three categories: thermochemical storage, latent heat storage, and sensible heat storage [4–6]. TES is the storing of thermal energy for future use. The phase change material (PCM) has been discovered to be an excellent candidate for thermal energy storage in a variety of applications. Sensible heat storage, according to reports, has a lower thermal energy storage density than latent heat storage [7, 8]. PCMs are classified into three categories based on their physical states: solid-solid, liquid-gas, and solid-liquid. During the phase transition process, PCMs absorb and release considerable energy in solid-liquid states. Organic PCMs, inorganic PCMs, and eutectic PCMs are the three types of solid-liquid. PCMs have greater heat storage capacity than conventional heat storage. During the phase transition process, PCMs leakage can be avoided by the encapsulation process.

Macro, micro, and Nano scale encapsulation are used for better thermal efficiency. The thermal stability of macroscale and microscale is less compared to nanoscale PCMs. Because of the reduction in the size of Nano-enhanced P.C.M.s (NEPCMs) enables better thermal transport. It is reported that PCMs have a low thermal conductivity, but they can be improved by adding nanostructures like nanoparticles, nanotubes, and nanofibres, etc., in PCM material. Due to the reduction in viscosity and easy fluid-flowing properties, better efficiency is obtained for colloidal suspensions of NEPCMs [8–10]. Colloidal suspension is shaped by blending immaculate PCMs and nanostructure fabric like nanoparticles, nanofibres, or nanotubes. Most of the PCMs development is based on colloidal suspension due to its high TES, high Thermal Conductivity, and free fluid flow characteristics. This chapter provides a broad view of various types of NEPCMs, their thermophysical properties, and the different uses of NEPCMs are discussed.

2 Nano Enhanced Phase Change Material (NEPCMs)

PCMs capture and release heat energy as they go through phase changes. This energy, known as latent heat, can be absorbed, stored, and released in substantial quantities by PCMs as the material changes temperature. When PCMs are coupled with nanostructured materials, their heat conductivity improves.

2.1 *An Ideal N.E.P.C.M.*

Following are the characteristics of ideal NEPCMs.

- (a) **High thermal conductivity**—transference of heat is a property of all materials. Any PCM material with high conductivity indicates that heat is released or stored within a short period of time. For effective thermal energy storage, a fast heat transfer rate is essential.
- (b) **Suitable phase change temperature**—As the phase change temperature should be aligned with the operating temperature, the temperature at which heat can be absorbed or released is critical. Temperature ranges have been found for paraffin wax-based phase change materials (PCMs) [11].
- (c) **Higher latent heat**—Latent heat is the energy that a substance assimilates or releases when it undergoes a phase change in its physical state without changing its temperature. More amount of latent heat is present in an ideal NEPCMs material [12].
- (d) **Small volume change**—It is always desirable to a very small amount of volume change during the phase transition process to reduce complexity in PCMs material [13].
- (e) **Low super cooling temperature**—In any material with increased thermal conductivity, better heat transfer takes place. For a good heat transfer, a low super cooling temperature is needed. At higher super cooling temperatures, the PCM will not solidify [13].
- (f) **Low cost**—To reduce the total cost of processing, selected PCMs should be low cost.
- (g) **Safe**—Selected PCM should be safe to use and possess no harmful, flammable, or corrosive qualities.
- (h) **High stability**—There should not be any change occurring in PCM material during its heating and cooling process. It must possess chemical stability [14].
- (i) **High thermal diffusivity**—The ideal PCM should transfer heat rapidly.

2.2 *Thermo-Physical Properties of Nano-Enhanced PCM*

The different thermophysical properties of NEPCMs materials, such as thermal conductivity, latent heat capacity, super cooling, density, and viscosity, are given here.

2.2.1 Thermal Conductivity

Till today, different forms of nanomaterial were synthesized, like nanoparticles, nanofibers, nanorods, nanosheets, nanotubes, etc. Because of high surface-to-volume ratio of nanomaterials, it shows unique magnetic, electrical, and optical properties

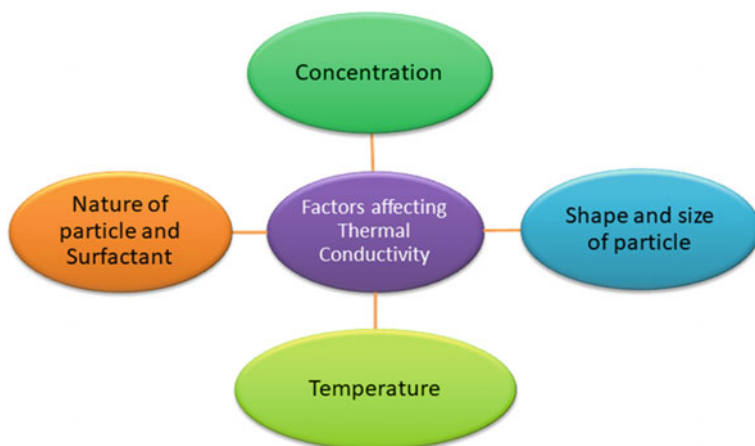


Fig. 1 Factors affecting thermal conductivity

compared to bulk materials [15]. The thermal conductivity of PCM materials is very low, which can be improved by mixing PCM with nanomaterials to create NEPCM [16].

Thermal conductivity of NEPCMs is depicted in Fig. 1 and described as follows:

- (a) **Concentration:** A sufficient amount of nanoparticles is required to generate a good thermally conductive network and good heat transfer in PCM materials.
- (b) **Surfactant:** To improve particle suspension in PCM, the addition of surfactant is essential. Surfactants change the surface properties of the nanoparticles [17]. However, excessive surfactant use reduces thermal conductivity while raising thermal resistance.
- (c) **Temperature:** Conflicting results were obtained about the effect of temperature on thermal conductivity. This suggests that the conductivity depends on the PCM material type rather than temperature [18].
- (d) **Type of particle:** Liquid NEPCMs have poorer thermal conductivity than their solid counterparts.
- (e) **Shape of particle:** Nanoparticles can be found in sphere, cube, and rod shapes. Of the three shapes, the cubic shape has the largest surface area. In any case, the process of producing cubic nanoparticles is expensive and laborious [18, 19].

2.2.2 Latent Heat Stability

Latent heat and sensible heat are two types of heat that are generated during the cooling or heating process. The former heat causes no temperature change during the heating/cooling process, whereas the latter exhibits temperature changes during the heat transfer process. There are two types of latent heat: fusion latent heat and vaporization latent heat. The latent heat of fusion is concerned with the transition from

solid to liquid states or vice versa, whereas the latent heat of vaporization is concerned with the transfer from liquid to gas states or vice versa. The latent heat of fusion is taken into account since nano-enhanced phase change materials (NEPCMs) are used in both solid and liquid states. NEPCMs have a significant amount of latent heat resistance. The overall latent heat can be raised by altering the interaction between the PCM and nanomaterials; however, excessive expansion of nanoparticles within the PCM may lower the latent heat [20].

2.2.3 Super Cooling

Super cooling is the process in which material cools below the freezing point without solidification or crystallization. It is also known as undercooling. In this process, material temperature decreases below the freezing point without solidification. It is an important parameter for the cooling process [21], and if the super cooling effect is high, it causes difficulty in releasing the stored heat.

2.2.4 Density

With an increase in the concentration of nanoparticles density of NEPCMs also increases. When Low volume PCM is used, then high-density PCM is mostly preferred [22].

2.2.5 Viscosity

The resistance of a liquid to changing shape or developing regions adjacent to each other (flow restriction) is called viscosity. Expansion of nanoparticles makes liquid flow more difficult. Thus, the enlargement of nanoparticles within PCM increases viscosity [23].

2.3 Preparation Methods for NEPCM

To obtain homogenous dispersion of PCM and nanomaterials, proper mixing and stabilization process are used during the synthesis of NEPCMs rather than mixing nanoparticles directly into the base PCM. Methods such as One-step and two-step are used for the preparation of NEPCMs. The primary nanomaterial is ready and then sprinkled onto the base PCM material in a two-step strategy. At the same time, the one-step strategy involves the generation and continuous scattering of nanomaterials within the base PCM. The two-stage strategy is less expensive than the one-stage one and is now widely used for constructing large-scale NEPCMs [24–26].

2.3.1 One-Step Method

A one-step strategy involves creating nanomaterials and their permanent scattering within the base PCM. This strategy does not require the nanomaterials to be dried, mixed or stored in his PCM, resulting in lower particle agglomeration [27]. The one-step method is useful only for small scale due to its high cost. NEPCMs of different concentrations of Al_2O_3 , TiO_2 , SiO_2 and ZnO were mixed with paraffin wax and the mixture was mixed by magnetic stirring method to induce homogeneous accumulation [28]. Using microwave and sonication methods, synthesized NEPCMs of $\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ and urea mixture were added to petroleum wax, and required NEPCM were prepared [29].

2.3.2 Two-Step Method

In a two-step process, dry powder nanomaterials are first fabricated using various mechanical and chemical methods such as sol-gel strategy, ball milling, and chemical reduction. At this point, this powder was mixed with PCM using various methods, such as magnetic stirring and homogeneous ultrasonic bath mixing. A two-step strategy is used for the industrial production of NEPCMs materials. Aggregation issues within the two-step strategy can be minimized by including various surfactants that make a difference in lowering the surface tension between the liquid and nanomaterials and stabilize the assembly. PCM nanocomposites were assembled by mixing capric and palmitic acids into graphite nanosheets through a sonication strategy [30]. Paraffin expanded perlite with graphene Nano platelets composite formed in acetone by ultrasonic probe sonicator method [31]. A two-step strategy to place NEPCMs of TiO_2 , CuO , and ZnO with lauric acid and stearic acid by sonication strategy was performed [32]. Made from palmitic acid and multi-walled carbon nanotubes, NEPCM is shaped to enhance its thermal properties. Carbon nanotubes were mixed with potassium hydroxide, and the resulting mixture was ball milled. Then the mixture was diluted with water and proceeded for the drying process. The composite was prepared by carbon nanotube with palmitic acid by sonication method [33].

2.4 Applications of N.E.P.C.M.

The application part of NECPMs focused on two areas:

(1) Thermal Management

Numerical and exploratory studies on novel applications of NEPCM in buildings are conducted to find the balance between thermal subsidence and energy use. NEPCM has been found to save 22% of the energy used in heating and cooling

processes while capturing and reducing CO₂ levels. It also helps to monitor the thermal condition of the photovoltaic system [34–37].

(2) Thermal Storage

Thermal industrial systems can be entirely revolutionized by instantaneous, free, clean thermal energy captured and stored by NEPCM and released on demand through phase transitions. This energy will also benefit the environment and provide high-quality energy, especially the use of solar energy storage, which can produce outstanding results when paired with NEPCMs [38, 39]. Thermal energy storage includes applications such as photovoltaic walls, solar control panels, solar cookers, solar-based dryers, and solar-powered air heaters.

3 Classification of Nanostructure Based Enhanced PCM

In heat exchange devices, the use of PCM increases the huge TES capacity over a wide temperature range. However, the low thermal conductivity of PCM limits its application in such devices, as it requires both high capacity and high heat removal rate. According to the Gibbs hypothesis, increasing temperature causes misalignment of atoms in the lattice structure. This is due to the low thermal conductivity of PCM. If the PCM contains nanostructured materials with good thermal conductivity, this will reduce the void and nucleus misalignment, ultimately increasing the heat storage capacity and heat release rate. This area focuses on improving thermal conductivity with most types of nanostructures (nanoparticles, nanotubes, and nanofibers) based on colloidal suspensions [40].

Figure 2 depicts the various forms of nanostructure-based enhanced PCMs like nanoparticles, nanowires, and nanotubes.

3.1 Nanoparticle-Based Colloidal Suspensions

The introduction of nanoparticles in PCM directly corresponds to an increase in thermal conductivity by reducing the voids in the crystal structure. Further, nanoparticle-based colloidal suspensions, prepared by combining molten PCMs and nanoparticles, show liquid-like properties. Colloidal suspensions based on nanoparticles have been considered for their high thermal conductivity, heat retention, and heat release rate. Therefore, current research on TES scaffolds focuses on preparing PCM emulsions by finding suitable processing conditions [41].

These PCM emulsions are liquid–liquid mixtures of colloidal suspensions and nanoparticles, such as KNO₃ liquid salt containing nanometer-sized oxide nanoparticles of Al₂O₃ and SiO₂. In colloidal suspension-based PCMs, latent heat changes remarkably, while the melting point remains unchanged after the accumulation of nanoparticles. Latent heat change of PCMs shows an increasing trend due to single species of nanoparticles while decreasing trend is observed due to hydrophilic fumed

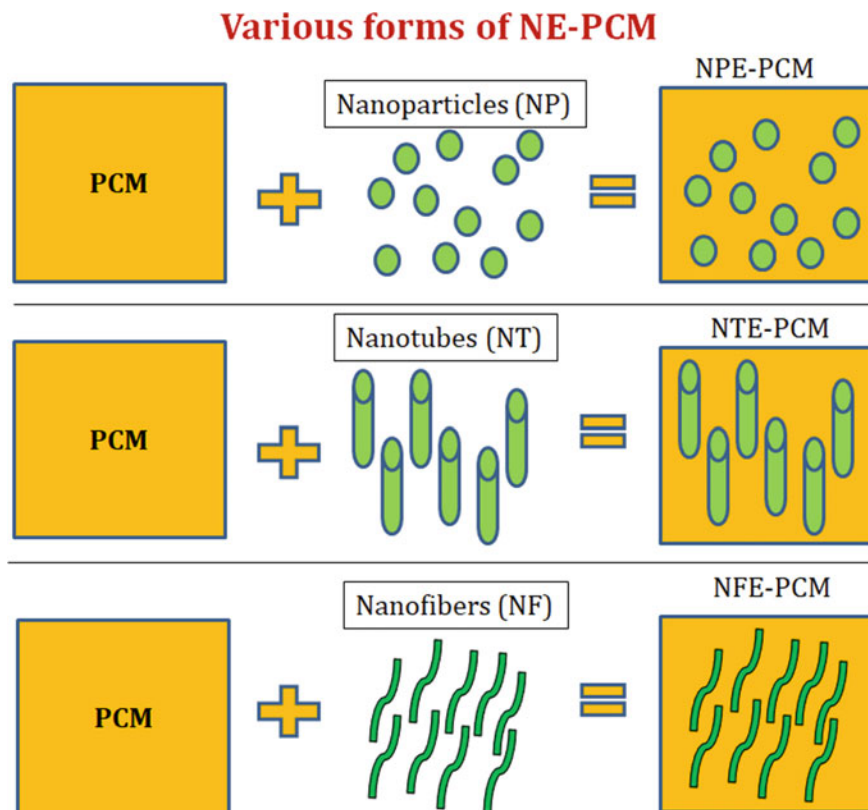


Fig. 2 Various forms of nanoenhanced PCMs

mixing of nanoparticles. TES capacity of PCMs increases by 16% after the addition of nanoparticles. Further, surfactant addition reduces super cooling effect in PCMs and enhances thermal conductivity to solve two major issues with colloidal-based PCMs [41].

3.1.1 Various Methods of Preparation of a Colloidal-Based Suspension of Nanoparticles

NEPCMs are stable and long-lasting suspensions with minor particle agglomeration in the solid–liquid mixture and no chemical change. The one-step technique and the two-step strategy are the two basic ways of synthesizing NEPCM. The one-step procedure involves nanoparticle assembly and simultaneous scattering in PCM. While in the two-step technique, pre-synthesized nanoparticles are dispersed in PCM base using various methods like mixing, ultra-sonication, autoclave, absorption, vacuum impregnation, etc. In addition to the methods described above, mixing

encapsulated PCM and nanoparticles into a liquid is a potential way to create nanoparticle-based colloidal suspensions [42].

3.1.2 Properties of Colloidal Suspension of Nanoparticles

Based on the synthesis steps and methods, NEPCMs-based colloidal suspensions' properties show variation. However, some of the general properties, such as thermal conductivity, latent heat capacity and supercooling effect are further discussed. The effect of the expansion of colloidal suspensions of nanoparticles in PCM on thermophysical properties is also addressed.

- (1) **Thermal Conductivity:** As discussed earlier and as depicted in Fig. 1, Various components such as particle agglomeration, particle size, shape, surfactant, and temperature play important roles in influencing the thermal conductivity of nanoparticle-reinforced PCMs. The thermal conductivity of PCMs depends more on the uniform distribution of the particles than on the nanomaterials involved. Particle dispersion may be a function of van der Waals forces between nanoparticles. These forces attract and stick nanoparticles together, causing particle agglomeration. Enlarging the surfactant, which may be accomplished by adding hydrophilic and lipophilic groups to long organic particles, prevents the formation of clusters and makes a substantial contribution to the uniform distribution of nanoparticles in PCM. A large surface area to volume ratio is another factor that contributes to high heat conductivity. When the nanoparticles' size is reduced, the rate at which their thermal conductivity is increased is proportionally increased. Having said that, it is also dependent on the temperature. It has been discovered that the thermal conductivity of paraffin wax in solid form increases with rising temperature within temperatures that are between 25 and 50 degrees Celsius lower than its melting point. In contrast, an increase in temperature results in a decrease in the thermal conductivity of the paraffin wax that is contained in the TiO_2 nanoparticles [5, 6].
- (2) **Latent Heat Capacity:** High latent heat capacity is PCMs' key property, while low thermal conductivity is their major disadvantage. Foreign substances like thermally conductive nanoparticles are embedded in PCMs to overcome this lacuna to form NEPCMs. This process adversely affects the latent heat capacity of NEPCMs. Hence, more research is focused on this direction to retain latent heat along with raise in the thermal conductivity of NEPCMs [5, 6].
- (3) **Super cooling:** Latent heat dissipation in PCMs starts at a temperature below solidifying temperature. As discussed earlier, the high super cooling effect causes difficulties in releasing stored heat. The process of formation of NEPCMs involves including external substances like nanoparticles in PCMs. This triggers a crystallization process known as hetero nucleation that can reduce the powerful effects of supercooling. Thus, nanoparticles, in such cases, function as nucleation agents in the PCM [5, 6].

Thermal conductivity, Latent heat, and super cooling effect are interdependent on each other. When work is carried out to enhance one thermo-physical parameter's performance, another parameter gets affected adversely. To maintain all thermo-physical properties simultaneously, NEPCMs must be utilized more than bare PCMs. The effect of NEPCM can be enhanced by changing the shape of nanoparticles such as nanotubes and nanofibers.

3.2 *Nanotube-Based Colloidal Suspensions*

Graphite and diamond are two common allotropes of carbon discovered before the nineteenth century. In 1985, scientists discovered the third allotrope of carbon containing sixty perfectly arranged carbon atoms, a major breakthrough to carbon nanochemistry. Carbon nanotubes are widely used in various fields such as electronics, aerospace, pharmaceuticals, fuel cells, sensors, and storage devices. They can also be used in bio-medical, industrial, molecular, biological systems. Carbon nanotube is a cylindrical form of graphene with a few nanometers in diameter. Single-walled carbon nanotubes (SWCNT) and multi-walled carbon nanotubes (MWCNT) are both different types of CNT with diameters 1 nm and 100 nm, respectively. By rotating the graphene sheet just 30 degrees, the nanotubes that form it change from armchair to zigzag and vice versa [43, 44].

- (1) **Preparation of SWCNT Dispersions:** 8 mg of carbon material was added to an aqueous phospholipid solution (0.8% w/w). The lipid concentration was maintained above 0.1 wt% of its basic micelle concentration (CMC) value. Ionic quality was maintained at 10 mM using NaCl. Scatterers were sonicated with a Branson-Bad sonicator for 4 h. As a control, SWCNTs were dispersed in an aqueous medium containing 10 mM NaCl and treated as previously described [44]. A comprehensive presentation of the rationale for the production of an aqueous C60 solution was given. Using colloidal surfactants, phospholipids, or polyvinylpyrrolidone (PVP) as solubilizers and/or dispersants that have been generated through chemical modification is one way to produce suspensions. Particle dispersion in water is affected by three different factors: (i) repulsion between particles caused by the zeta potential, (ii) steric hindrance from the adsorption layer, and (iii) a decrease in hydrophobic bonding among particles. Carbon nanotubes (CNTs) that are available for purchase on the market often exhibit a poor rate of dispersion in solutions and do not possess well-defined, chemically flexible groups that are amenable to modification. In agreement with the findings of prior research, surfactants have the ability to modify the interface between the particles and the suspension medium, thereby preventing the particles from aggregating over the long term. In order to gain an understanding of how surfactant molecules contribute to the dispersion of CNTs, 0.02 g of CNTs were encapsulated in 0.1 g dm⁻³ of dodecyl sulfate (SDS) solution and

then sonicated to disperse the CNTs. This was done in order to gain this understanding. With the help of laboratory grade NaOH, the pH was brought up to 9. After that, the suspension was dried for a full day at a temperature of 140 degrees Celsius.

- (2) **Preparation of MWCNT Dispersions:** After adding the required amount of 1-cyclohexyl-2-pyrrolidone (CHP) to water, a mixture of 1-cyclohexyl-2-pyrrolidone (CHP) and water had been produced. Prior to this, the formula for calculating the gravimetric concentration of water in CHP was $X = [\text{water}] / ([\text{C.H.P.}] + [\text{water}])$. CHP and water were combined, and then a predetermined amount of multi-walled carbon nanotubes (MWCNT) were added to the mixture in order to create a suspension consisting of CHP, water, and MWCNT. The suspension had been sonicated using an ultrasonic disperser with a frequency of 44 kHz and a power of 400 W. The suspension had been sonicated in a bath of cold water in order to prevent it from getting too hot and thus ensure that the temperature did not go higher than 313 K. The MWCNTs had been damaged by the sonication process, despite the fact that it had helped to disperse knotted or aggregated MWCNTs. In the experiments, each suspension had been sonicated for ten minutes prior to being used, and the preparation was done right before the experiment. An investigation was conducted on a number of samples, each of which had an MWCNT concentration (C) ranging from 0.0 to 1.0 wt% and a water concentration (X) ranging from 0 to 1[45].
- (3) **Nanotube-Based PCM improves thermal energy storage:** Thermal energy storage, often known as TES, has the potential to become an important point of reuse for several types of renewable energy, including solar energy. PCMs are able to both store and utilize energy thanks to their ability to absorb and then release heat to the surrounding environment as their physical state changes from solid to liquid. To prevent PCM from spilling into the environment during the conversion process, PCM must be mixed. In general, there are three scales of PCM mixing. H. Macroscale (>1 mm), Microscale (~ μm), Nanoscale (<1000 nm). As a result of unsatisfactory thermal stability and fairly low thermal conductivity (TC), the capacity of macroscale PCM TES does not satisfy the requirements of the power industry. In order to circumvent this obstacle, innovative phase change materials (PCMs) with unexpectedly high thermal stability and heat storage/release rates have been created.
- (4) The rationale behind the production of aqueous C60 suspensions has been explained in some detail [46]. Using colloidal surfactants, phospholipids, or polyvinylpyrrolidone (PVP) as solubilizers and/or dispersants is one way to produce suspensions. Other options include polyvinylpyrrolidone (PVP) acquired by the process of chemical alteration [47]. Consistent with previous reports [48], surfactants can alter the interface between particles and suspension media, preventing agglomeration over long periods of time. After adding 0.02 g of carbon nanotubes to an aqueous solution containing 0.1 g of sodium dodecyl sulfate (SDS), the mixture was sonicated to distribute the CNTs. The pH of the solution has already been adjusted to 9 using NaOH of analytical grade.

The suspension was recently dried at a temperature of 140 degrees Celsius for twenty-four hours.

- (5) Platinum Green Chemicals Sdn manufactured petroleum-based multi-wall CNTs and hydro-drilling fluids. Bhd., Malaysia, used as received. Hydrogenated oils contain a mixture of straight and branched chain paraffins with carbon chain lengths from C15 to C18, which are naturally formed as non-polar groups. At $80,000\times$ magnification, it can be seen that the CNT bundles with normal outer spacing of 10–12 nm are trapped by only 10–12 nm. Traps can cause CNTs to accumulate in the nanofluid if they are not consistently dispersed. The multi-walled CNTs consist of a fixed inner width with numerous outer CNT layers with a typical thickness of 4.7 nm. Within the range of 6–7 nm, the internal spacing of multi-walled CNTs had been consistently observed. In order to make mixtures of 1-Cyclohexyl-2-pyrrolidone (CHP) and water, the required amount of CHP was first weighed out and then added to the water. Previously, the formula for calculating the gravimetric concentration of water in C.H.P. was as follows: $X = [\text{water}]/([\text{C.H.P.}] + [\text{water}])$. The CHP and water mixture had the required quantity of MWCNTs added to it so that it could be transformed into a suspension consisting of CHP, water, and MWCNTs. After that, the suspension was sonicated with an ultrasonic disperser at a frequency of 44 kHz and a power of 400 W so that it could be more evenly distributed. The suspension had been sonicated in a bath of cold water to prevent it from becoming overheated and ensure that the temperature did not go over 313 K. The heavily entangled or aggregated MWCNT samples were easier to disperse thanks to sonication, but the MWCNTs themselves were damaged as a result of the process. In the experiments, each suspension had been sonicated for ten minutes prior to being used, and the preparation was done right before the experiment. An investigation was conducted on a number of samples, each of which had an MWCNT concentration (C) ranging from 0.0 to 1.0 wt% and a water concentration (X) ranging from 0 to 1 [45].
- (6) It had been determined that a mixture of double-walled alumogermanate nanotubes, also known as Ge-DWINTs and imogolite-like nanotubes (INTs), should be produced. Ge-DWINT had been obtained through the use of a sol-gel technique, much as Levard et al. had stated. The majority of the synthesis had been carried out in a container made of PTFE by vigorously swirling the mixture while adding $\text{Ge}(\text{OEt})_4$ to an aluminum perchlorate assembly with a ratio of 2 of Al to Ge. A concentration of 0.25 mol L⁻¹ of aluminum had to be incorporated into the material to create a nanotube structure resembling a quasi-double-walled tube. The NaOH solution at a concentration of 0.25 mol L⁻¹ was added in increments up until the $[\text{OH}]/[\text{Al}]$ 2 ratio caused the solution to hydrolyze. At this stage, the mixture had been baked in an oven at a temperature of 95 degrees Celsius for a period of five days. Following the completion of the maturation process, the suspension was dialyzed after being allowed to reach room temperature naturally [49].

3.3 *Nanofiber-Based Colloidal Suspensions*

Carbon nanotubes (CNTs) which Iijima discovered in 1991, have attracted attention due to their excellent electrical, mechanical, and thermal properties. Despite these properties, the limited availability and high cost make it unlikely that CNTs will be widely used shortly. On the other hand, vapor-grown carbon nanofibers (CNFs) with typical spacings of 100–200 nm can be used to fabricate reinforced nanocomposites. Nanofibers and nanotubes have comparable structural and physical properties, so they can exhibit comparable general properties when used in composites. A look at nanofibers can give hints for possible applications. In addition, C.N.F.s are attractive candidates for reinforcement or conductive fillers because they can be manufactured in large quantities at a reasonable cost. The extraordinary physical properties make the application of these nanofibers on an industrial scale increasingly feasible [50]. Numerous research projects have been carried out to develop phase change materials (PCMs) for thermal energy storage and recovery. This is because PCMs have a high energy storage density and only a small temperature difference between the storage state and the recovery stage. Efforts have been made. The following are some of the difficulties associated with using fatty acids and related eutectics as additions in non-energetic phase change materials (NEPCMs), despite its use to improve the properties of these materials: PCM leakage is caused by the material's low heat conductivity as well as its periodic solid-liquid phase shift (SLPC). Particle entrapment with high thermal conductivity and reinforcement in materials with permeable structures such as expanded graphite, perlite, activated attapulgite, carbon nanotubes, and diatomaceous earth are only some of the ways that have been investigated in order to boost thermal conductivity. It's been done. Vermiculite as support material [51]. Non-energetic phase change materials (NEPCMs) have been modified by adding fatty acids and their eutectics to improve their properties. However, it may have some drawbacks. Due to the SLPC, the thermal conductivity and PCM leakage become low. Various methods have been used to improve thermal conductivity, such as including high thermal conductivity particles and incorporating porous structural materials such as expanded graphite, perlite, and carbon nanotubes, diatomaceous earth, vermiculite as supporting components. approaches are considered. Also different types of fibers, such as random and brush types employed to observe effect on thermal conductivities. The findings of the experiments indicate that carbon nanofibers, also known as CNF, can be utilized to increase the effective thermal conductivity of the packed bed [52]. Carbon nanofibers, also known as CNF, are a type of nanofiber that has been utilized to enhance the thermal performance of phase change materials, also known as PCMs. The thermal characteristics of PCM are significantly enhanced with the incorporation of CNF. Increasing the CNF mass fraction during the solidification process of the novel nanocomposites results in faster cooling rates. The rate of heat transmission in the nano-range was shown to rely on the surface area in comparative research because they scatter much better within the matrix, carbon nanofibers (CNF) are a much more viable option than carbon nanotubes (CNT) when it comes to using fillers to improve the thermal

properties of a material [53]. The temperature behavior and thermal conductivity of PCM composites can be improved by using CNF as an addition. This can be done without a reduction in the latent heat storage capacity of the composites [54]. It has been looked into whether or not organic phase change materials (PCMs) can benefit from the incorporation of nanoparticles in order to enhance their thermal properties [55]. Graphite nanofibers with a weight distribution of 10% were found to be capable of reducing discharge time by 61%, according to the findings of Sanushi and colleagues, who embedded three different types of graphite nanofibers in paraffin PCM. This means that if graphite nanofibers are used as an additive in PCM, they can be used for thermal energy exchange applications, etc.. Studies have shown that the heat flux across the nanoparticle interface can be significantly different between the solid and liquid P.C.M. phases, and the contrasting bulk thermophysical properties of HGNF/PCM nanocomposites. increase. It has been shown that nanoparticle dimensionality can affect the heat transport between PCM and its embedded nanoparticles. In addition, we have preliminarily measured the effects of HGNF considerations on the latent heat and melting temperature of the combined mass. Because of this work, our understanding of the tools that can be used to control the flow of heat in PCM nanocomposites has evolved, as has the roadmap for applications in the energy and electronics industries. The purpose of this research was to explore the thermal conductivity, volumetric heat capacity, and thermal conductivity of organic phase-change materials (PCMs) that were reinforced with particular volume fractions of herringbone-patterned graphite nanofibers. According to the findings, the thermal conductivity of HGNF/PCM nanocomposites appears to increase exponentially within the solid phase, but not within the liquid stage until the nanoparticles reach an extremely dense condition. This is because the solid phase contains more nanoparticles. It was found that the volumetric heat capacity was at its highest during the transition from solid to liquid and at its lowest within the liquid phase. On the other hand, the thermal diffusivity in the liquid phase rose with a higher concentration of nanoparticles. This was something that had been identified. Near the melting temperature, the latent heat of fusion was found to be less than one percent of the standard PCM value for each nanocomposite, and it was found that the PCM value was within 90 percent of the standard value. This suggested that the expansion of the nanoparticles did not have any effect on the performance of the PCM in the application [56]. Khodadadi et al. found that nanostructures can improve the thermal conductivity of his PCMs and found that expansion of CNF and CNT into his PCMs resulted in more pronounced thermal conductivity [57]. Furthermore, we found that the degree of strengthening depends on the size, shape, and concentration of the metal and metal oxide nanoparticles. In any case, we observed that the dynamic viscosity decreased with increasing concentration of nanoparticles in PCM. This suggests that certain measures should be taken to predict heat loss during phase change. CNF also affects alignment and concentration. The z-oriented carbon nanofiber (CNF) reinforcements were observed to affect the thermal conductivity of the paraffin wax as a whole, with the z-oriented thermal conductivity being higher than both the control and non-oriented paraffin wax samples. Thermal conductivity increases with increasing CNF concentration. In the future, this demand may provide guidance for creating

tunable heat storage systems that appear to increase thermal conductivity during charge and discharge cycles. Furthermore, the z-alignment process could provide the desired thermal conductivity performance at a lower nanoparticle concentration, allowing more space for the PCM and, thus, more energy storage per unit volume [58].

When two different-length SCF stacks were stretched in an array of erythritol-based PCCs where the erythritol matrix and SCF filler are practically physically combined, a linear drop in enthalpy was observed. The largest temperature change was 3.2 °C. Both thermal conductivity and phase change enthalpy should be considered when selecting phase change composites, as SCF/erythritol PCC demonstrated excellent performance in temperature regulation property tests. To investigate the effect of filler form on thermal conductivity, the thermal resistance and percolation hypotheses were applied. Higher thermal conductivity and longer SCF suggest higher thermal conductivity. Furthermore, a linear decrease in enthalpy was observed when stacking two different length SCFs was extended to an array of erythritol-based His PCCs in which the matrix and SCF filler were simply physically combined [59].

4 Conclusions

This chapter has focused on NEPCMs, preparation methods, nanostructure-based classification and their applications in quite different fields. A conclusion can be drawn from this chapter.

When determining PCM or NEPCM, several factors are taken into account, including phase change temperature, thermal conductivity, latent heat, thermal diffusivity, volume change, supercooling effects, cost, safety, and density boost. PCMs have low thermal conductivity but can be increased by mixing nanostructure materials like nanotubes, nanoparticles, nanofibers, etc. The proper selection of PCMs and nanostructures is critical to the stability of NEPCM. The thermal conductivity of nano-enhanced PCM increases as the concentration of nanomaterials increases. Surfactants are included to stabilize the surface and ensure even spreading. The concentration, kind, and form of the nanomaterials all play a role in determining the thermal conductivity of NEPCM. The PCM density increases with increasing nanoparticle concentration. The swelling of nanoparticles within the liquid PCM disrupts the liquid flow and increases its viscosity. The NEPCM is employed for thermal management as well as thermal energy storage. Especially suitable for photovoltaic energy devices such as photovoltaic walls, photovoltaic stations, photovoltaic stoves, photovoltaic dryers, and solar heaters.

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Chapter 6

Theoretical Analysis and Correlations for Predicting Properties and Evaluation Methods for NePCMs



Mathew George and Reji Kumar Rajamony

1 Introduction

1.1 Why Prediction and Theoretical Models?

The prediction models allow to conduct numerical simulation, with nanoparticle concentrations that would not have been possible experimentally. However, to generate a predictive model it is important to understand the assumptions carried by the model [1, 2].

Theoretical models offer a foundation for understanding the behaviour of nano-enhanced phase change materials (NePCMs) during phase change processes. This understanding may then be used to make predictions. Researchers are able to make predictions and conduct analyses about the thermal properties, heat transport characteristics, and energy storage capacities of NePCMs by doing research on the underlying principles and mechanisms. This information is essential for building systems that make use of NePCMs in a way that is both efficient and dependable [3].

The optimisation and design of NePCM is a very important factor for thermal energy storage applications, this can be predicted by theoretical models. Many of the researchers are able to investigate the compositions, operating conditions of various phase change materials (PCMs) with different nanoparticles are analysed by theoretical model with computational simulations. These simulations enhance the performance of the NePCMs. The simulations techniques are more cost-effective

M. George

Energy Science Department, Atria University, Anandnagar, Bengaluru 560024, India

R. K. Rajamony (✉)

Institute of Sustainable Energy, Universiti Tenaga Nasional (National Energy University), Jalan IKRAM-UNITEN, Kajang, Selangor, Malaysia

e-mail: rejikumar.r2006@gmail.com

and improve the system's performance. In addition, theoretical models analyse the performance of NePCMs in various situations and conditions. The heat transfer rate, melting temperature energy storage and release capacity were analysed by theoretical models easily. This will help to select the appropriate PCM, required melting temperature for various applications and enhance the performance of the system. Also, theoretical models easily predict thermal behaviours like, latent heat, thermal conductivity, specific heat, melting temperature, etc., for various applications [3, 4].

Furthermore, the theoretical model can help to eliminate the need for significant experimental testing and prototyping, results in time and cost savings. In addition, researchers to save time and resources entire the process by reducing the number of system configurations and potential materials [3].

Theoretical models constitute the basis for further research and development of nan-enhanced phase change materials (NePCMs), and they are employed in this capacity. They provide a starting point for the research of fresh ideas, materials, and applications in the world. The application of theoretical analysis is beneficial in defining research paths and knowledge gaps, which fosters innovation and developments in the field of NePCM technology.

Understanding the behaviour of NePCMs, optimising system design, determining performance, selecting materials, and driving more research and development are all vitally significant reasons why theoretical models of NePCMs should be developed. They make it possible to use NePCMs in a way that is both efficient and effective in a range of applications, which ultimately leads to improved energy storage, thermal management, and renewable energy systems. They do this by making it possible to use NePCMs in a way that is both efficient and successful in a variety of applications [5].

1.2 What Effective Medium Theory?

The effective medium theory (EMT) assumes that the composite material can be described as a homogenous medium with effective properties. For the purpose of calculating these qualities, the individual properties of the constituent materials as well as the volume fraction of each material that makes up the composite are used [4, 6].

The EMT can be used to predict a wide range of features for nanocomposite materials. These qualities include thermal, electrical conductivity, different mechanical behaviours, and dielectric constant. The accuracy of the EMT forecasts depends on the assumptions made about the composite material, which in turn depends on how similar the real microstructure of the composite material is to the idealised models used in the EMT calculations [7]. The EMT is a useful tool for designing and figuring out how to make the best use of composite materials that have certain traits that people want. It is applied extensively in a wide variety of domains, including materials science, condensed matter physics, and geophysics, and it has made a substantial contribution to the development of new devices and materials [8].

2 Overview of Nano-enhanced PCMs

Phase change materials (PCMs) are latent heat storage materials, it has the ability to absorb, store and release more amount of heat energy while the phase changes from solid to liquid or liquid to solid [9]. But the main drawback of the PCM is its lower thermal conductivity. Due to its lower thermal conductivity, the heat transfer rate and storage capability is not adequate. Many of the researchers [10–15] recommended that the inclusion of nano-sized particle into the PCM enhances the thermal conductivity as well as increase the storage capability. An addition of nanoparticles into the PCM is known as nano-enhanced phase change materials [16]. They are generally used for various applications like thermal energy storage, heat transfer and temperature regulation applications. In addition, NePCMs have many other benefits and applications like, electronic cooling, textiles, buildings, battery, desalination, photo-voltaic thermal systems, etc. [17–20]. The overview of the key aspects of NePCM is discussed below.

2.1 *Enhanced Thermal Conductivity*

The thermal conductivity of the thermal energy storage material is an important factor in energy storage applications. The thermal conductivity of the PCM can be improved by the addition of highly conductive nanoparticles into the base PCM. Due to nanoparticles' higher conductivity, very small size, and high surface area-to-volume ratio the thermal performance of the NePCM are excellent. This indicates that heat may be transmitted more efficiently within the material, which leads to faster charging and discharging rates as well as better overall thermal performance [21].

2.2 *Improved Stability*

PCMs frequently struggle with problems such as supercooling, which is when they continue to exist in a liquid form below their melting point, and subcooling, which is when they continue to exist in a solid state above their solidification point. Nanoparticles can be of assistance in resolving these problems because of their ability to function as nucleation sites, which speeds up the phase change process and promotes transitions between the solid and liquid states that are more stable [13].

2.3 Enhanced Energy Storage

It is possible for nanoparticles to be included in PCMs in order to enhance their capacity for energy storage. Because the nanoparticles offer additional sites for energy storage, a greater quantity of energy can be taken in or given off during phase change cycles. This is made possible by the increased capacity of the nanoparticles. This improved capacity for storing energy is especially useful in situations that call for compact designs and high energy densities [22].

2.4 Tailored Melting/Freezing Temperature

It is possible to modify the temperature at which the NePCMs melt or freeze to conform to a variety of criteria by making the right nanoparticle selection. Because of this versatility, it is possible to customise the solution depending on the application requirements, which enables efficient temperature regulation across a variety of thermal management systems [23].

2.5 Compatibility with Different Type of PCMs

It is possible to create nano-enhanced PCMs by using a wide range of different types of PCMs, such as organic, inorganic, and eutectic materials. Because of this adaptability, it is possible to include nanoparticles in a wide variety of PCM systems, which broadens the scope of possible applications for nano-enhanced PCMs [24].

Applications of nano-enhanced PCMs span across different industries, including building and construction, electronics cooling, solar energy storage, automobile thermal management, and more. They offer improved energy efficiency, enhanced thermal performance, and better temperature control compared to traditional PCMs. It is worth noting that while nano-enhanced PCMs exhibit many advantages, there are also challenges associated with their production, cost, and potential environmental impact [25]. The manufacturing processes and nanoparticle dispersion within the PCM matrix need careful consideration to ensure consistent performance and stability. Additionally, the cost of producing nano-enhanced PCMs can be higher compared to traditional PCMs. Researchers are actively exploring these challenges and working towards optimizing the synthesis techniques and addressing any associated concerns.

3 Ideal Characteristics of Nano-enhanced PCM

NePCM possess several ideal characteristics that make them highly attractive for various thermal management applications. Here are some key characteristics of NePCMs (Fig. 1).

3.1 Enhanced Thermal Conductivity

The thermal conductivity of PCMs is greatly improved by the incorporation of nanoparticles. Nanoparticles, because of their small size and high surface area, allow



Fig. 1 Ideal characteristics of NePCMs

for rapid and effective heat conduction. Because of this quality, rapid charging and discharging rates are possible, which improves thermal performance of NePCMs [12].

3.2 Enhanced Energy Storage Capacity

When compared to conventional PCMs, nano-enhanced PCMs can store significantly more energy. During the phase transition process, a greater amount of thermal energy can be absorbed or released due to the integration of nanoparticles, which provide extra energy storage sites. This quality allows for the storage of more heat in a given volume of material [26].

3.3 Customizable Melting/Freezing Temperature

The use of nanoparticles enables the nano-enhanced PCMs to have a melting or freezing temperature that is tailored to the individual's preferences. The phase change temperature of the PCM can be adjusted to match the needs of a given application if the appropriate nanoparticles are chosen that have a certain set of qualities. This property allows for greater design flexibility in thermal management systems that provide precise temperature control [27].

3.4 Improved Thermal Stability

When compared to normal PCMs, nano-enhanced PCMs have been shown to have improved thermal stability. The presence of nanoparticles in a material enables them to function as nucleation sites, which in turn encourages the material to undergo a regulated phase shift in a uniform manner. Because of this property, problems like as supercooling and subcooling can be avoided, resulting in thermal performance that is predictable and consistent [10].

3.5 Compatibility with Various PCM Types

It is possible to create nano-enhanced PCMs utilising a wide variety of PCMs, including organic, inorganic, and eutectic materials. Due to the fact that this property enables the incorporation of nanoparticles into a diverse selection of PCM systems, these materials can be adapted to a wide variety of applications and industries [28].

3.6 Reduced Size and Weight

PCMs that have had nanotechnology applied to them give a high energy density, which makes it possible to store a significant quantity of thermal energy within a relatively small volume. This quality is especially helpful in situations in which the amount of available space and the total weight are at a premium, such as those found in portable electronic devices and aerospace applications [29].

3.7 Environmental Friendliness

To reduce the negative effects on the surrounding ecosystem, it is preferable to make use of ecologically benign nanoparticles and PCM materials. Nano-enhanced PCMs that are sustainable and safe for both human health and the environment can be achieved by selecting components that are non-toxic and favourable to the environment [30].

3.8 Long Cycle Life

Ideal nano-enhanced phase change materials should have a long cycle life, which indicates that they can go through multiple phase change cycles without suffering a major loss in performance. This quality assures that the material will last for a long time and be resistant to wear and tear in its various applications [31].

3.9 Cost-Effectiveness

When taking into account the price of the nanoparticles as well as the price of the manufacturing process, the production of nano-enhanced PCMs ought to be economical. The cost-effective Nano-enhanced PCMs are made more accessible for widespread usage across a variety of industries [32].

Nano-enhanced PCMs offer improved thermal conductivity, enhanced energy storage, customizable temperature control, stability, compatibility, scalability, environmental friendliness, long cycle life, and cost-effectiveness. These ideal characteristics make nano-enhanced PCMs highly attractive for applications related to thermal management. In order to make even more headway in the field of NePCMs, researchers are constantly investigating and attempting to improve upon these properties.

4 Thermo-physical Properties of Nano-enhanced PCM

4.1 Dynamic Viscosity

NePCMs are composite materials that combine the heat storage capabilities of PCMs with the heat conductivity-enhancing properties of nanoparticles. The viscosity behaviour of NePCMs is a critical factor to consider when designing efficient heat transfer systems [3].

There are several prediction models available to predict the viscosity of the NePCMs. Generally, Brinkman model is used to predict the viscosity of nano PCM and nanofluids in porous media. The Krieger Dougherty model also known as non-Newtonian model used to predict the viscosity of emulsions, polymer solutions and suspensions used for the prediction of the viscosity of fluids in porous media [33]. Further, Vajjha model predicts the viscosity of nanofluid and the Corcione model analyses the viscosity of nanoparticles also, evaluates how nanoparticles and phase transition affect NePCM viscosity [34]. Each model has their own advantage and disadvantage, and they are suited to distinct categories of NePCMs as well as distinct sets of operational parameters. So, it is very important to select a suitable model to predict the viscosity of the NePCMs as well as the work that will be done with the material [35, 36]. The various models and their behaviour were discussed below.

4.1.1 Brinkman Model

The dynamic viscosity of the NePCM can be calculated by Brinkman model as described in Eq. (1).

$$\mu_{np} = \frac{\mu_p}{(1 - \phi)^{2.5}} \quad [37] \quad (1)$$

where, μ_{np} = effective viscosity of NePCM, μ_p = viscosity of PCM and ϕ = nanoparticle volume fraction.

The Brinkman model works well in places where there are less than 3% nanoparticles. The model is based on the idea that nanoparticles are spread out in a material that is continuous. The viscosity model can be used to study PCMs that are made up of nanoparticles [38, 39]. Nanoparticles are added to a PCM in these materials to improve its thermal qualities, such as its latent heat capacity and heat conductivity. But adding nanoparticles to the PCM can also change how thick it is. The model can be used to keep the change in viscosity as small as possible while trying to get the most out of other tasks. The model can also be used to study how the flow variables, like speed and pressure, affect the viscosity of the nanoparticle-dispersed PCM [35].

4.1.2 Kreiger-Dougherty (K-D) Model

$$\mu_{np} = \mu_p \left(1 - \frac{\phi}{\phi_{\max}} \right)^{-A\phi_{\max}} \quad (2)$$

where

$\phi_{\max}$ = maximum packing factor and A = intrinsic viscosity.

Krieger and Dougherty developed this empirical relation based on the EMT. The values of $\phi_{\max}$ and A for particles rods, spheres, cylinders and ellipsoids were found by Holec et al. [40] When estimating the viscosity of non-Newtonian fluids such as polymer solutions, suspensions, and emulsions, the Krieger-Dougherty model is typically utilised since the relationship between shear stress and shear rate in these situations is non-linear. On the other hand, a NePCM, is a kind of heat transfer fluid that transforms its phase while it is being utilised. Because NePCMs typically have a lower viscosity in their liquid form and a greater viscosity in their solid state, their viscosity behaviour is distinct from that of non-Newtonian fluids. This is because NePCMs have a higher viscosity when they are in their solid state. Hence, the Kreier and Dougherty model is useful for modelling the viscosity of no-Newtonian fluids [37]. TiO_2 and Al_2O_3 -based nanofluid thermal properties were analysed and estimated by using Kreiger and Dougherty model [41]. Chen et al. reported that Kreiger and Dougherty model has the best prediction model for analysing the viscosity of the NePCM and nanofluid [42, 43].

4.1.3 Vajjha's Model

$$\mu_{np} = 0.983 e^{(12.959\phi)} \mu_p, 0.01 \leq \phi \leq 0.06, \text{ for } \text{Al}_2\text{O}_3 \text{ nanofluid} \quad (3)$$

$$\mu_{np} = 0.919 e^{(22.853\phi)} \mu_p, 0.01 \leq \phi \leq 0.06 \text{ for } \text{CuO nanofluid} \quad (4)$$

Vajjha model [43] is a mathematical model used to estimate the viscosity of nanofluids and it is developed from Sahoo et al. [44], and Namburu et al. [45]. Brownian motion is the fundamental principle that supports this model. It depicts the irregular movement of particles inside a fluid that is brought on by fluctuations in temperature. This idea served as the foundation for the development of this paradigm. The model works under the assumption that the nanoparticles are evenly dispersed throughout the nanofluid and that the Brownian motion of the nanoparticles is the primary mechanism that contributes to the increase in viscosity. In addition, the model is based on the presumption that the viscosity of the base fluid is the most important component that contributes to the definition of the nanofluid's viscosity. However, it is essential to keep in mind that the model can only be utilised successfully with nanoparticles that are of a size that enables them to be subjected to Brownian motion and with volume fractions of nanoparticles that are less than 5% of the total. This is the only condition under which the model can be utilised successfully. When applied to nanoparticles

with higher volume fractions or those that are larger, it is probable that the model will fail to generate adequate conclusions.

4.1.4 Corcione's Model

$$\mu_{np} = \frac{\mu_p}{1 - 34.87 \left(\frac{d_n}{d_{p,e}} \right)^{-0.3} \phi^{1.03}} \quad (5)$$

Equivalent diameter of the base fluid $d_{p,e} = 0.1 \left(\frac{6M}{N\pi\rho_{p,0}} \right)^{1/3}$.

Where N is the Avogadro number, d_n is nanoparticle diameter, M is the molecular weight of base fluid and $\rho_{p,0}$ density of base fluid at 20 °C.

The Corcione model is a mathematical model that is used to estimate the viscosity of NePCMs. NePCMs are materials that are improved with nanoparticles and go through a phase shift while they are being utilised. The model accounts for the effects of the nanoparticles as well as those of the PCM on the viscosity of the NePCM. The model operates under the presumption that the nanoparticles are evenly dispersed throughout the NePCM and that they contribute to the increase in viscosity as a result of Brownian motion in a manner that is analogous to Vajjha's Model. The model has an extra feature in which it takes into consideration the effects of the phase shift on the viscosity of the NePCM. These effects, which can be significant due to the fact that the viscosity of the solid phase is often significantly higher than that of the liquid phase, are accounted for in the model [46]. The developed model was analysed with a large number of experimental data of nanofluids with deviation of 1.84% including ethylene glycol, water, ethanol, propylene glycol dispersed Cu, Al₂O₃, TiO₂ and SiO₂ nanoparticles. The diameter of the nanoparticles ranges from 25 to 250 nm and the volume concentration ranges from 0.0001 to 0.071% respectively. Also, these experiments were tested with a temperature range of 20–60 °C [38].

First, water, ethanol, polyethylene glycol, and ethylene glycol were used as the base fluids in the models described above. The molecular structures, rheological properties and intermolecular interactions of these base fluids are distinct from those of PCMs, such as eutectic salts and paraffin wax. When attempting to analyse the viscosity of NePCMs using these nanofluid prediction models, there is a possibility of producing uncertainties. Second, surfactants are routinely utilised to increase the nanoparticle's suspension stability. This practise, which was discovered to also raise the nanofluids viscosity, has been widely practised. Nevertheless, none of the aforementioned models took into account this effect [47]. Third, the shape of nano additives has a significant effect on the viscosity; yet, the majority of the models described in the previous paragraphs can only be applied to microspheres or nanospheres. For instance, a recent study found that the viscosity of eutectic PCM increased by 25.0% and 376.9%, respectively, when nano-Al₂O₃ was used in the form of nanorods and nanoparticles [48]. However, multi-walled carbon nanotubes (MWCNT) [49] and graphene [50] reduce the viscosity of nanofluids. This was ascribed to the fact

Table 1 Important prediction models for effective dynamic viscosity

Prediction model	Factors	Morphology	Particle size (nm)	Concentration (Vol %)	Temperature (°C)	References
Corcione's	$\Phi, \mu_p, d_{p,e}, d_n$	Nanoparticles	25–200	0.01–7.1%	20–60	[38]
Vajjha's	Φ, μ_p	Nanoparticle	10–100	1–6% for CuO 1–10% for Al ₂ O ₃	20–90	[43]
K-D	$\Phi, \mu_p, A, \phi_{\max}$	Rod, cylinder, sphere, ellipsoid	>1000	1–2%	20–40	[51]
Brinkman	Φ, μ_p	Microsphere	>1000	1–8%	0–170	[37]

that MWCNT and graphene have a self-lubrication effect on themselves. Consequently, utilising the models described above may result in the production of errors for NePCMs that are mixed with non-spherical nanoparticles (Table 1).

4.2 Effective Thermal Conductivity

The Maxwell model, which is based on the EMT, is referred to as a “static” model since it imagines that there is no slip between the base fluid and the particles. Further extending the Maxwell model [3] to account for non-spherical particles was Hamilton and Crosser's [52] contribution. However, the Hamilton-Crosser model not only failed to account for the influence of nanoparticle size and temperature dependency, but it also underestimated the increase in thermal conductivity that might be achieved by scattering nanosized particles. In contrast, characteristics like thermal dispersion, thermal resistance, size of nanoparticle and Brownian motion are all known to have a major impact. As a consequence of this, a number of expansions were created by incorporating a “dynamic” component into Maxwell model [53]. The following models were used to analyse the effective thermal conductivity of the NePCM and nanofluids.

4.2.1 Thermal Dispersion Model

$$k_{np} = \frac{k_n + 2k_p - 2\phi(k_p - k_n)}{k_n + 2k_p + \phi(k_p - k_n)}k_p + C'(\rho C_p)_{np}|u|\phi d_n \quad (6)$$

where, u = fluid velocity, C' = empirical constant, generally C' values are not obviously stated in any NePCM except the findings [54, 55]. Second portion of the equation stand for the thermal dispersion effect, this was proposed by Xuan and Roetzel [56] and was modelled by Khanafer et al. [57].

4.2.2 Vijjha's Model

$$k_{np} = \frac{k_n + 2k_p - 2\phi(k_p - k_n)}{k_n + 2k_p + \phi(k_p - k_n)}k_p + 5 \times 10^4 \gamma \phi(\rho \mathcal{C}_p)_p \sqrt{\frac{BT}{\rho_n d_n}} f(T, \phi) \quad (7)$$

The second part of the equation represents the enhanced thermal conductivity induced by Brownian motion of nanoparticles. It was reported the applicable range of T and d_n are 25–92 °C and 28–77 nm respectively [58].

$$\gamma = 8.4407(100\phi)^{-1.07304}, 0.01 \leq \phi \leq 0.1 \text{ for Al}_2\text{O}_3 \text{ nanofluid} \quad (8)$$

$$\gamma = 9.881(100\phi)^{-0.9446}, 0.01 \leq \phi \leq 0.06 \text{ for CuO nanofluid} \quad (9)$$

The empirical function $f(T, \phi)$ can be given by:

$$f(T, \phi) = (2.8217 \times 10^{-2}\phi + 3.917 \times 10^{-3}) \frac{T}{T_{ref}} + (-3.0669 \times 10^{-2}\phi - 3.9112 \times 10^{-3}) \quad (10)$$

where B = Boltzmann constant (1.3807×10^{-23} J/K), γ = fraction of liquid volume travelling with nanoparticle [58].

4.2.3 Corcione's Model

Corcione's semi-empirical model was developed by Corcione [38] and is shown in Eq. 11

$$k_{np} = k_p \left[1 + 4.4 Re^{0.4} Pr^{0.66} \left(\frac{T}{T_{fr}} \right)^{10} \left(\frac{k_n}{k_p} \right)^{0.03} \phi^{0.66} \right] \quad (11)$$

$$Re = \frac{2\rho_p BT}{\pi \mu_p^2 d_n} \quad (12)$$

where, Re = Reynolds number of nanofluid, Pr = Prandtl number of base fluid and T_{fr} = Base fluid freezing point.

This model considers the fluid temperature, nanoparticle size, and fluid properties. The empirical equation was developed by the experimental data of ethylene glycol, water, polyethylene glycol with nanoparticles CuO, Cu, Al₂O₃ and TiO₂. The applicable range nanoparticle size, concentration and temperature were 10–150 nm, 0.002–0.09% and 20–50 °C respectively [38].

4.2.4 Nan's Model

$$k_{np} = k_p \frac{3 + \phi[2\beta_{11}(1 - L_{11}) + \beta_{33}(1 - L_{33})]}{3 - \phi(2\beta_{11}L_{11} + \beta_{33}L_{33})} \quad (13)$$

$$\beta_{11} = \frac{k_{11} - k_p}{k_p + L_{11}(k_{11} - k_p)}, \beta_{33} = \frac{k_{33} - k_p}{k_p + L_{33}(k_{33} - k_p)}$$

$$L_{11} = \frac{a^2}{2(a^2 - 1)} + \frac{a}{2(a^2 - 1)^{3/2}} \cosh^{-1} a, \text{ for } a > 1 \text{ and } L_{33} = 1 - 2L_{11}$$

$$L_{11} = \frac{a^2}{2(a^2 - 1)} + \frac{a}{2(1 - a^2)^{3/2}} \cosh^{-1} a, \text{ for } a > 1 \text{ and } L_{33} = 1 - 2L_{11}$$

$$L_{11} = L_{33} = \frac{1}{3}, \text{ for } a = 1$$

where, a = aspect ratio of nanostructure, L_{11} , L_{33} are the geometrical factors of nanostructure and K_{11} , K_{33} are the thermal conductivity at distinct cell directions.

$$k_{11} = \frac{k_n}{1 + \frac{\theta L_{11} k_n}{k_p}}, i = 1, 3$$

where

$$\theta = \begin{cases} (2 + \frac{1}{a}) \frac{Rk_p}{l_p}, & \text{for } a \geq 1 \\ (2 + 2a) \frac{Rk_p}{d_n}, & \text{for } a \leq 1 \end{cases}$$

where R = thermal boundary resistance. The principal function of the EMT-based empirical models is the interfacial thermal resistance, morphology was considered [59]. The Nan's model the nanostructures shapes are laminated flat plates, continuous fibers, spheres and ellipsoidal particles. It was found that the thermal conductivity of graphene nanoplatelets dispersed eicosane at 10 °C displayed the best agreement with experimental results for $R = 9 * 10^{-9}$ m²K/W [60]. Similarly, the graphene nanoplatelets/lauric acid at 20 °C shows good agreement with experimental results for $R = 10^{-8}$ m²K/W, it was done by Harish et al. [61]. Xu and Kleinstreuer reported that the thermal conductivity experimental values are good agreement with model values [62].

4.2.5 Behrens Theoretical Model

$$\frac{k_x}{k_c} = 1 + (p - 1)\phi - (p - 1)^2 \frac{\sigma - \frac{\epsilon^2}{2}}{1 - \epsilon^2} \left[\frac{(1 - \epsilon^2)\phi - \left(\sigma - \frac{\epsilon^2}{2}\right)}{(p + 1)\frac{\epsilon^2}{2} - (p - 1)(\phi - \sigma)} \right] \quad (14)$$

$$\frac{k_y}{k_c} = 1 + \frac{(p-1)\phi\epsilon^2}{(p+1)\frac{\epsilon^2}{2} - (p-1)(\phi - \sigma)} \quad (15)$$

where $p = \frac{k_d}{k_c}$

$$\sigma = \sqrt{\frac{\epsilon^4}{4} + (1 - \epsilon^2)\phi^2} \quad (16)$$

$$\epsilon = \frac{\text{Major axis of ellipsoid}}{\text{Focal distance}}$$

For circular rods this reduces to

$$k_c = k_c \left[\frac{(p+1) + (p-1)\phi}{(p+1) - (p-1)\phi} \right] \quad (17)$$

and for cubic symmetry of spheres

$$k_c = k_c \left[\frac{(p+2) + (p-1)\phi}{(p+2) - (p-1)\phi} \right] \quad (18)$$

which reduces to Maxwell's equation. Behrens' theoretical model for composite thermal conductivity illustrates how a composite's thermal conductivity is connected to its constituent materials' thermal conductivity and their geometrical arrangement. The model assumes a matrix and scattered phase composite. The matrix material is believed to be continuous throughout the composite, while the dispersion phase material is randomly distributed inside the matrix. NePCM has a phase change matrix and nanoparticle dispersion. Heat transmission in the composite is modelled using matrix and scattered phase conduction [63]. The composite's effective thermal conductivity depends on the relative percentage of the two materials and the geometrical arrangement of the dispersion phase material because the model assumes heat travels along the route of least resistance. Behrens' approach employs equations that take into consideration the matrix and dispersion phase materials thermal conductivities, volume fraction, and shape to calculate the composite's effective thermal conductivity [64].

4.2.6 Bruggeman Theoretical Model

$$1 - \phi = \left[\frac{k_d - k_e}{k_d - k_c} \right] \left(\frac{k_c}{k_e} \right)^{1/3} \quad (19)$$

The Bruggeman model is commonly used simple theoretical model for predicting the effective thermal conductivity of nano PCM composites. Bruggeman derived the implicit equation for dilute sphere suspensions in a homogeneous medium

using different permeability and field strength assumptions than Maxwell [65]. Equation (11) shows the Bruggeman model for predicting the effective thermal conductivity.

4.2.7 Budiansky Theoretical Model

$$\sum_{i=1}^n \frac{\phi_i}{\frac{2}{3} + \frac{1}{3} \frac{k_i}{k_e}} = 1 \quad (20)$$

Budiansky's model analyses composite materials' thermal conductivity. The model assumes the composite is formed of homogenous, randomly oriented spherical inclusions (or particles) of one material (like carbon fibres) embedded in a matrix of another material (like PCMs). The effective thermal conductivity of the composite can be calculated by taking into account the thermal resistance of the inclusions and matrix and assuming heat flows from the inclusions, which have a high conductivity, to the matrix, which has a low conductivity. The model assumes heat flows radially from the core of a spherical inclusion into the matrix [64].

4.2.8 Cheng and Vachon Theoretical Model

If $k_c > k_d$

$$\frac{1}{k_e} = \frac{2}{\sqrt{C(k_d - k_c)[k_c + B(k_d - k_c)]}} \tan^{-1} \frac{B}{2} \sqrt{\frac{C(k_d - k_c)}{k_c + B(k_d - k_c)}} + \frac{1 - B}{k_c} \quad (21)$$

$$\begin{aligned} \frac{1}{k_e} &= \frac{1}{\sqrt{C(k_d - k_c)[k_c + B(k_d - k_c)]}} \\ &\ln \frac{\sqrt{(k_c + B(k_d - k_c))} + \frac{B}{2} \sqrt{C(k_c - k_d)}}{\sqrt{(k_c + B(k_d - k_c))} - \frac{B}{2} \sqrt{C(k_c - k_d)}} + \frac{1 - B}{k_c} \end{aligned} \quad (22)$$

$$B = \sqrt{3\phi/2} \quad C = -4\sqrt{2/(3\phi)}$$

The theoretical model developed by Cheng and Vachon takes into account not only the thermal conductivity of the PCM itself but also the thermal conductivity of the PCM in both its solid and liquid phases. The model assumes that the PCM is spherical capsules or shells dispersed in a matrix material and that the matrix material transfers heat between adjacent capsules or shells. The PCM's effective thermal conductivity can be estimated by taking into consideration the thermal resistance of each of its three phases and assuming heat goes from the phase with the highest conductivity to the lowest. The model assumes that the solid phase has better thermal conductivity than the liquid phase and that the PCM volume fraction is modest enough to allow one-dimensional radial heat conduction between capsules or shells. The model also

requires a minimal PCM volume percentage to allow one-dimensional radial heat conduction between capsules or shells. This model can be used in high nanoparticle concentrations [64].

4.2.9 Donea Variational Model

$$k^+ = \phi k^- + (1 - \phi)k_c \quad (23)$$

$$k^- = \frac{\hat{k}k_c}{k_c + (1 - \phi)\hat{k}} \quad (24)$$

Spheres

$$\hat{k} = \frac{k_c[(p + 2) + 2s(p - 1)]}{(p + 1) - (p - 1)s} \quad (25)$$

where, $p = k_d/k_c$, $s = (a/b)^3$, a = radius of inclination, and $k^+ = k^- = \hat{k}$ [64].

Parallel circular fibers

$$k = \frac{k_c[(p + 1) + (p - 1)s]}{(p + 1) - (p - 1)s} \quad (26)$$

where, $p = k_d/k_c$, $s = (a/b)^2$, a = radius of fiber, and b = radius of largest hollow cylinder surrounding the fiber [64].

The Donea variational model is a theoretical model that is based on the concept of energy conservation and the variational approach of calculus of variations. The model makes the assumption that the NePCM is made up of a pure PCM and a dispersion of spherical nanoparticles with the same dimension and volume fraction throughout the entire system. In addition to this, it is expected that the interfacial thermal resistance will predominate in the heat transfer between the PCM and the nanoparticles, and that heat will be conducted from the PCM to the nanoparticles. Estimating the effective thermal conductivity of the NePCM is accomplished by first minimising the energy dissipation functional with respect to the temperature field of the system. The functional for the dissipation of energy takes into account the latent heat of the PCM, the heat transfer between the PCM and the nanoparticles, and the thermal conductivity of the nanoparticles. The model makes the assumption that the thermal conductivity of the nanoparticles is higher than that of the PCM and that the volume fraction of the nanoparticles is small enough so that the heat transfer between particles can be considered as one-dimensional radial heat conduction. Additionally, the model assumes that the nanoparticles have a smaller volume fraction than the PCM.

4.2.10 Fricke Theoretical Model

$$k_e = k_c \left[\frac{1 + \left(F \frac{k_d}{k_c} - 1 \right)}{1 + \phi(F - 1)} \right] \quad (27)$$

where,

$$F = \frac{1}{3} \sum_1^3 \left[1 + \left(\frac{k_d}{k_c} - 1 \right) f_i \right]^{-1} \quad (28)$$

and

$$\sum_{i=1}^3 f_i = 1 \quad (29)$$

The factor F indicated the ratio of the overall temperature gradients in two phases and f_i is semi principal axes of the ellipsoid. For sphere $f_1 = f_2 = f_3$ and equation reduces to Maxwell's equation [64].

The Maxwell-Eucken theory of effective thermal conductivity serves as the fundamental for the Fricke theoretical model. This model also takes into account the thermal characteristics of the PCM and nanoparticles, as well as the distribution of these components within the composite material. According to the assumptions made by the Fricke model, the NePCM is made up of a pure PCM and a dispersion of spherical nanoparticles that are the same dimension and volume fraction throughout. In addition to this, it is presumed that the nanoparticles in the PCM are dispersed in a haphazard manner and that heat is conducted between the nanoparticles and the PCM. It is also assumed that the thermal conductivity of the nanoparticles is higher than that of the PCM, and that the volume fraction of the nanoparticles is small enough so that the heat transfer between particles can be considered as one-dimensional radial heat conduction. This is accomplished by assuming that the nanoparticles have a smaller volume fraction than the PCM does.

4.2.11 Hamilton and Crosser Semi-theoretical Model

$$k_e = \frac{k_c(1 - \phi) \left. \frac{dt}{dx} \right|_1 + k_d \phi \left. \frac{dt}{dx} \right|_2}{(1 - \phi) \left. \frac{dt}{dx} \right|_1 + \phi \left. \frac{dt}{dx} \right|_2} \quad (30)$$

$$\frac{\left. \frac{dt}{dx} \right|_d}{\left. \frac{dt}{dx} \right|_c} = \frac{nk_c}{k_d + (n - 1)k_c}$$

$$k_e = k_c \left[\frac{k_d + (n - 1)k_c - (n - 1)\phi(k_c - k_d)}{k_d + (n - 1)k_c + \phi(k_c - k_d)} \right] \quad (31)$$

where n = empirical constant. For spherical particle $n = 3$, for nm spherical particle ($0.58 < \psi < 1.0$), ψ = sphericity.

$$n = \frac{3}{\psi}$$

Sphericity is the ratio of surface area of sphere, with a volume equal to the particle, to the surface area of the particles.

$$k_e = k_c \frac{\left[1 - \sum_{i=2}^m \frac{\phi_i (n_i - 1)(k_c - k_i)}{k_i + (n_i - 1)k_i} \right]}{\left[1 + \sum_{i=2}^m \frac{\phi_i (k_1 - k_i)}{k_i + (n_i - 1)k_i} \right]} \quad (32)$$

The semi-theoretical model was developed by Hamilton and Crosser postulates that the NePCM consists of a solid phase of nanoparticles and a liquid phase of PCM. Assuming a pure PCM and a distribution of spherical nanoparticles with uniform diameter and volume fraction, the Hamilton and Crosser model describes the NePCM. This model shares several assumptions with the Fricke theoretical model [39, 64].

4.2.12 Maxwell Theoretical Model

$$k_e = k_c \left[\frac{k_d + 2k_c + 2\phi(k_d - k_c)}{k_d + 2k_c - \phi(k_d - k_c)} \right] \quad (33)$$

The theoretical Maxwell model is predicated on the premise that the NePCM acts as a two-phase medium. The model operates on the presumption that the NePCM is made up of a pure PCM and a dispersion of spherical nanoparticles with the same volume fraction and diameter throughout. In addition to this, it is presumed that the nanoparticles in the PCM are dispersed in a haphazard manner and that heat is conducted between the nanoparticles and the PCM. The Maxwell model makes the additional assumption that the thermal conductivity of the nanoparticles is higher than that of the PCM, and that the volume fraction of the nanoparticles is low enough that the heat transfer between particles may be modelled as one-dimensional radial heat conduction. Both of these conditions are necessary for the Maxwell model to be valid. In summary, the Maxwell theoretical model is the confidential model for determining the thermal conductivity of the NePCM [66].

4.2.13 Russel Theoretical Model

$$k_e = k_c \left[\frac{\phi^{2/3} + \frac{k_c}{k_d}(1 - \phi^{2/3})}{\phi^{2/3} - \phi + \frac{k_c}{k_d}(1 + \phi - \phi^{2/3})} \right] \quad (34)$$

Table 2 Important prediction models for effective thermal conductivity

Model name	Factors	Morphology	Temperature (°C)	Particle size (nm)	Concentration (Vol %)	References
Nan's	$k_n, k_p, k_{np}, R, d_n, \phi$	Spheres, fibers, ellipsoidal	20–70	<1000	1–3	[59]
Corcione's	$k_n, k_p, k_{np}, \phi, \rho_p, C_p, \mu_p, d_n, T$	Nanoparticle	20–50	10–150	0.2–0.9	[38]
Vajjha's	$k_n, k_p, k_{np}, \phi, \rho_p, C_p, \rho_n, d_n, T$	Nanoparticle	25–90	29–77	1–10	[58]
Thermal dispersion	$k_n, k_p, k_{np}, u, \phi, \rho_p, C_p, C', d_n, T$	Nanoparticle	0–80	10–100	1–10	[54]
Maxwell	k_e, k_c, k_d, ϕ	Nanoparticle	–	–	–	[66]
Russel	k_e, k_c, k_d, ϕ	Nanoparticle	–	–	–	[64]
Hamilton and Crosser	$k_e, k_c, k_i, \phi, \psi, n_i$	Nanoparticle	–	–	–	[39, 64]

The Russell theoretical model assumes that the NePCM has a solid nanoparticle phase and a liquid PCM phase. The Russell model assumes that the NePCM is composed of a pure PCM and a dispersion of cylindrical nanoparticles with uniform diameter and aspect ratio. It further assumes that the nanoparticles are oriented randomly in the PCM and that heat is transferred between the PCM and nanoparticles through conduction [64]. Table 2 Summarize the important thermal conductivity prediction models.

5 Other Thermophysical Properties

$$\rho_{np} = (1 - \varnothing)\rho_p + \varnothing\rho_n \text{ [67]} \tag{35}$$

$$(\rho C_p)_{np} = (1 - \varnothing)(\rho C_p)_p + \varnothing(\rho C_p)_n \text{ [67]} \tag{36}$$

$$(\rho\beta)_{np} = (1 - \varnothing)(\rho\beta)_p + \varnothing(\rho\beta)_n \text{ [67]} \tag{37}$$

$$(\rho L)_{np} = (1 - \varnothing)(\rho L)_p \text{ [67]} \tag{38}$$

Other thermophysical properties of interest in NePCM are density, specific heat, thermal expansion coefficient, and latent heat of fusion. Most of the properties can be figured out using the above expressions. “Phi” is the mass fraction of the nanoparticle in the composite. To estimate the composite property, the nanoparticle property plays a part in the overall density of the composite [68]. For example, when a PCM is replaced with a nanoparticle, the latent heat should reduce for the same given mass. The reasoning behind this is the inability of the PCM to change phase and contribute to the latent heat. However, practically this is not always the case. There might be an increment in the latent heat with the addition of nanoparticle as weak van der Waal forces may act between the nanoparticle and the PCM. Similar, instance can be found in other thermophysical properties as well [3].

6 Summary

The present chapter focuses on the theoretical analysis and correlations of thermophysical properties of nano-enhanced PCMs. The effect of various correlations and their performance of both the single-phase and the two-phase techniques have been extensively discussed in this chapter. In addition, the homogeneous model and the thermal dispersion model were also examined in depth. In addition, the various thermal conductivity models of nanofluid and NePCMs were discussed; however, the majority of the NePCM experiments are focused on single-phase approaches, with the underlying assumption that the NePCM is a stable and homogenous mixture; as a result, certain physical phenomena were not taken into account in any of the experiments or studies that were reported. Based on the results of the simulation study, there is an immediate requirement to design new analytical models for NePCM. This is due to the fact that the existing prediction models have considerable uncertainties, which can lead to discrepancies between simulation and experiment. Experimentation investigations employing a variety of characterization methods are strongly encouraged for the goal of achieving this aim. Even so, having an awareness of the propagation of nanoparticles as well as the effect of the thermophysical properties of NePCM as solid, mushy and liquid states.

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Chapter 7

Applications of Nano-enhanced PCMs in Solar Energy



Arun Kumar Tiwari, Amit Kumar, and Zafar Said

1 Introduction

Over the past few years, the energy-related research have shifted towards the development of eco-friendly technologies [1]. The world's future energy matrix relies heavily on renewable energy exclusively in solar energy. Solar energy is abundant and freely available almost anywhere on Earth, making it an attractive source of energy in distinct applications [2, 3]. Currently, solar thermal energy is utilized in different areas like electricity generation [4], Solar air collectors (SAH) as dryer [5, 6], solar water heaters [7–9] and solar water desalination systems [10], etc. However, a significant drawback of these systems is their intermittent nature due to the sun's periodic unavailability, such as during cloudy conditions or at night. To confront these drawbacks, the solar energy needs to be stored using different methods for later utilization. In solar photovoltaic, energy is stored in chemical energy in batteries, while in the case of thermal storage, different types of collectors absorb thermal energy from solar irradiation and transfer it to different thermal energy storage (TES) systems

A. K. Tiwari (✉) · A. Kumar

Mechanical Engineering Department, Institute of Engineering and Technology, Dr. A.P.J. Abdul Kalam Technical University, Lucknow, Uttar Pradesh 226021, India
e-mail: aruntiwari@ietlucknow.ac.in

A. Kumar

e-mail: amit36322@gmail.com

Z. Said

Department of Sustainable Renewable Energy Engineering, University of Sharjah, Sharjah, United Arab Emirates

Department of Industrial and Mechanical Engineering, Lebanese American University (LAU), Byblos, Lebanon

Z. Said

e-mail: zsaid@sharjah.ac.ae

like latent, sensible and thermochemical. Nano-enhanced phase change materials (Ne-PCM) are the recent development in this field, where nanomaterials such as carbon nanotubes, graphene and metal oxide nanoparticles are dispersed into PCM for their thermal conductivity augmentation [11–13] and that leads the augmentation in heat transfer performance of solar energy systems [14]. Thus, the present chapter is dedicated to the potential use of Ne-PCM in different solar applications.

2 Application of Nano-enhanced PCMs in Solar Energy

2.1 Solar Water Heater

The huge demand for hot water in a variety of residential and industrial settings, leads to significant energy consumption. In some cases, water heating can account for up to 40% of the total energy requirement of a household. However, adopting energy-efficient solar power technologies have the potential to meet these energy demands especially in colder countries. This would ultimately help to ease the financial burden of rising energy costs for consumers [15]. SWHs have the potential to provide hot water for various household and industrial applications like washing, bathing, cooking and cleaning [16]. Solar water heaters are a popular application of solar energy, where solar irradiances are utilized to heat water. In this system, water is circulated through a collector that absorbs solar irradiance and transfers the heat to the water [17]. Thus, Ne-PCM can be used to store extra heat from the day and release it during night or cloudy periods. The use of Ne-PCM in SWH can increase its thermal efficiency by reducing heat loss and increasing thermal storage capacity [18].

In their study, Manirathnam et al. [19] conducted a comparative study by analysing TES capacity of an evacuated tube SWH by integrating PCM and Ne-PCM (i.e. SiC and CuO-loaded PCM). Ne-PCM incorporation in the evacuated tube augmented the thermal performance of water heating system. The energy efficiencies for without PCM, PCM and Ne-PCM were determined to be 33.8, 38.3 and 41.7%, respectively. While, exergy efficiency was 1.78, 2.18 and 3.23%, respectively. In their study, Alshukri et al. [20] incorporate Ne-PCM (CuO nanoparticles) into the evacuated tube as well as the storage tank of a heat pipe evacuated tube collector solar water heating (SWH) system. The Ne-PCM improved the performance of thermal energy storage system (TESS) and minimized hot water temperature fluctuations and provide hot water continuously even at overcast weather conditions as well as at night. The Ne-PCM integration in SWH system improves the system efficiency ranging from 36.8 to 50%. While, Ne-PCM integration to evacuated tube alone improves the system's efficiency from 33.85 to 45.7%. Additionally, Ne-PCM integration provides enhanced condensation and evaporation coefficient (Fig. 1).

Al-Kayiem et al. [21] integrated TES with flat plate solar collector to evaluate its performance. Three cases were examined, with and without PCM as well as Cu-based

Fig. 1 Experimental setup of evacuated tube solar water heater by Alshukri et al. [20]. Copyright Elsevier {Lic # 5510340802537}



Ne-PCM, at inclination angles of 10° , 20° and 30° . Water heating was used as the system's performance evaluation criteria. The optimum operational condition was found to be at 10° inclination angle and 0.5 kg/min water circulation rate. The results showed that the best performances were achieved with TES using paraffin wax, with efficiencies of 51.1 and 52.0% for the PCM and Cu-PCM nanocomposite, respectively, at 10° inclination angle. Kumar et al. [22] found that Ne-PCM (SiO_2 and CeO_2 nanoparticles in 50:50 ratio) integrated with SWH system could improve the TES of solar-based water heaters. The maximum augmentation in thermal conductivity of 65.56% was attained at 2 wt% of Ne-PCM. Also, a significant improvement in energy and exergy efficiency (i.e. 19.4 and 1.28%, respectively) is obtained at 1 wt% of Ne-PCM. In continuation to the previous study, Kumar et al. [23] examined the enhancement of thermal storage properties of CeO_2 -based Ne-PCM at varying wt%. The Ne-PCM were tested using various analytical techniques, and their performance was evaluated in a SWH. The results demonstrated that CeO_2 nanoparticles loading into paraffin significantly improves its thermal storage properties. Additionally, incorporation of paraffin and Ne-PCMs enhanced the energy as well as exergy efficiency of SWH system. The study also recommends 1 wt% of CeO_2 nanoparticles concentration as the optimal combination of Ne-PCM in the proposed system. The hourly energy and exergy efficiency of SWH system is shown in Fig. 2.

In their experimental study, Mandal et al. [24] explored the effect of varying nanoparticles concentrations of CuO-enhanced PCM in SWH system. The results demonstrated that increment in wt% of Ne-PCM leads to a significant improvement in thermal conductivity, heat flow, as well as thermal efficiency. The highest thermal efficiency was recorded with 1 wt% of CeO_2 -paraffin, which was 79.2%. Graphene/paraffin showed the maximum augmentation in thermal conductivity (i.e. 3.63 times the PCM). Moreover, the study found that Cu nanoparticles loading in

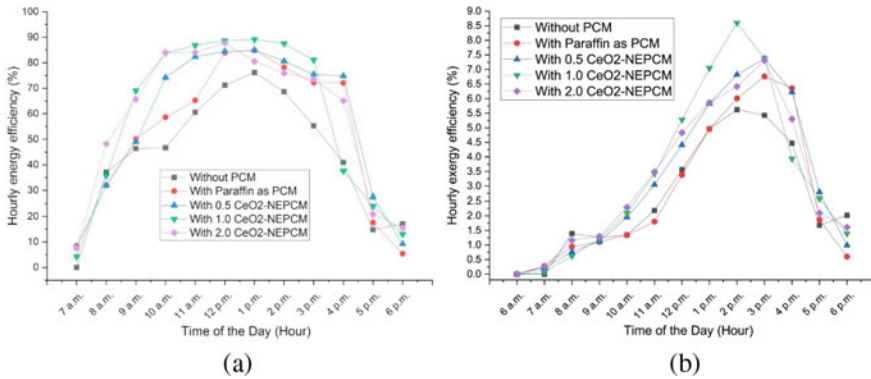


Fig. 2 Hourly energy and exergy efficiency comparison of SWH system by Kumar et al. [23]. Copyright Elsevier {Lic # 5510341033870}

paraffin decreased the melting point by 1.3 °C. In their experimental study on ETSC-based SWH, Chopra et al. [25] investigated that the incorporation of paraffin wax in ETSC system with PCM significantly improves the system's performance. By using PCM in the system, the useful energy output at operating temperatures of 400, 450 and 500 °C was increased by 36.81, 26.97 and 22.72%, respectively, in comparison to reference system without PCM.

2.2 Solar Air Heater

Solar air heaters (SAH) work on a similar principle, where solar irradiance is used to heat air. The air is circulated through a collector that absorbs solar irradiance to heat the air. Ne-PCMs can be used in solar air heaters to store excess heat and release it when needed. The use of Ne-PCMs improves thermal efficiency of SAH by reducing heat loss and increasing thermal storage capacity. Figure 3 shows a schematic representation of SAH.

Jawad et al. [27] designed a SAH specifically for the winter atmosphere of Baghdad, integrated with SiC-based Ne-PCMs along with aluminium chips and obtained an 18.2% augmentation in thermal conductivity, while latent heat capacity is reduced by 4.5%. Moreover, the chips' incorporation in heater boosted its efficiency by expediting the air heating process and decreasing the heating load during morning hours. Despite the limited measurements, the tested SAH achieved high temperatures and continued to function for a minimum of 3 h after sunset, which outperformed a SAH without chip and nano-SiC-paraffin. Elbrashy et al. [28] performed an experimental study on an ETSC-based SAH integrated with Ne-PCM and examined its thermal performance. The experiment evaluated system's performance with and without Ne-PCM across varying flow rates. The experimental outcomes demonstrated a 29.62% augmentation in thermal efficiency along with enhanced heat

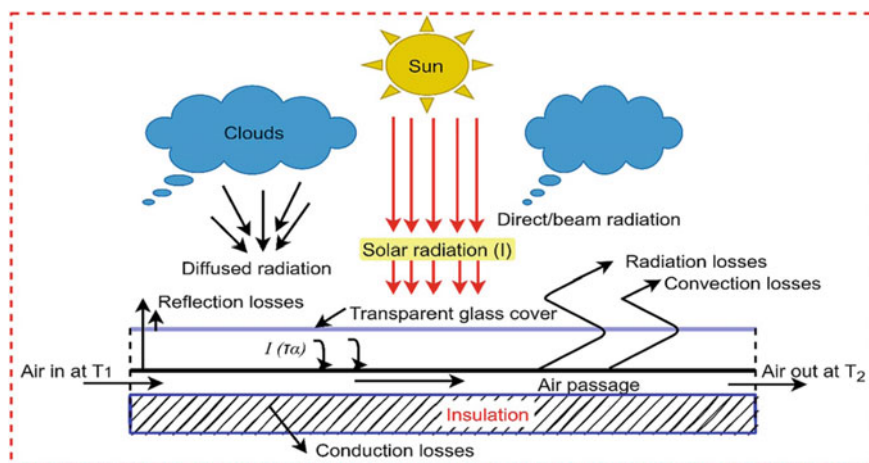


Fig. 3 Schematic representation of solar air heater [26]. Copyright Elsevier {Lic # 5510341216070}

transfer rate with Ne-PCM at 0.05 wt% (as shown in Fig. 4). The study found that the hot air generated by the SAH have different application like in space heating, drying of fruits and vegetables, food processing, dairy and solar cooking.

Habib et al. [29] examined that the use of a nanocomposite material consisting of single-wall carbon nanotubes (SWCNT) and paraffin wax can significantly enhance the thermal storage performance of SAH in Iraq. The SWCNT nanoparticles loading to paraffin wax at 3 wt% enhance its thermal conductivity by 12%, which resulted in a 20.7% increase in stored thermal energy in natural convection compared to pure paraffin wax. The results confirmed the feasibility of using this nanocomposite material in solar air heaters under Iraqi weather conditions. Selimefendgil et al. [30] evaluated the performance of three different types of active greenhouse dryers for preserving agricultural products, including Ne-TES system. The results demonstrated that NE-PCM system significantly reduced drying time by 35–58% and improved exergy efficiency by 36% compared to a conventional dryer. Furthermore, the specific energy consumption values were lowest for the nano-enhanced system, ranging from 1.63 to 1.89 kWh/kg. Sunilraj et al. [31] examined a hybrid solar air heater system for drying capsicum, integrated with Al_2O_3 -based Ne-PCM with a fill ratio of 0.9. The findings from the experiment indicate that moisture removal has significantly improved, and the thermal performance is high. The testing was conducted outdoors on sunny days in Bengaluru, and the air heater with TES system showed a daily variation in thermal efficiency ranging from 12 to 65%. Singh et al. [32] examined the performance of PCM-integrated SAH for different configuration. The experimental findings revealed that the small cylindrical tubes filled with PCM in SAH exhibited a temperature difference from 2 to 9 °C between ambient and exhaust temperature. Overall, the study demonstrates the potential of using SAH

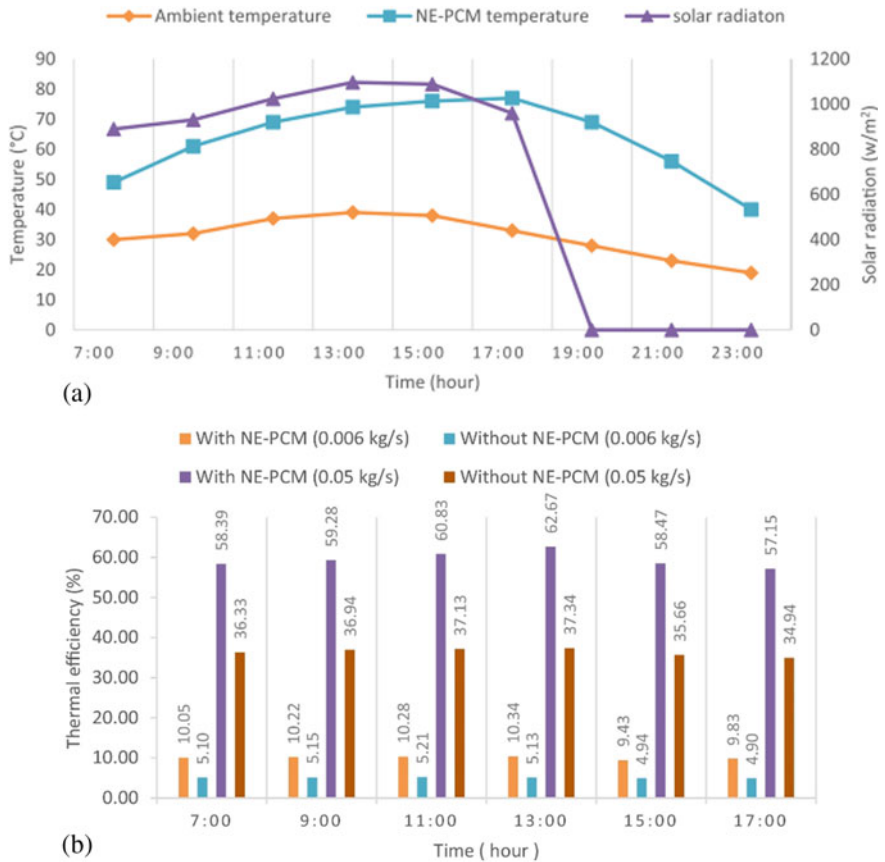


Fig. 4 **a** Peak temperature comparison of PCM and Ne-PCM. **b** Thermal efficiency comparison of SAH PCM and Ne-PCM [28]

with PCM for thermal energy storage and provides insights for further optimization of the system's performance.

2.3 Solar Collector

Solar collectors are utilized to capture solar irradiance and transfer heat to a working fluid for heating or cooling. The Ne-PCM integration in solar collectors increases efficiency by reducing heat loss and increasing thermal storage capacity. Solar collectors (shown in Fig. 5) are mainly classified into concentrating (parabolic trough collector, linear Fresnel collector, dish collector, solar tower, etc.) and non-concentrating collectors (e.g. flat plate collector, evacuated tube collector). There are

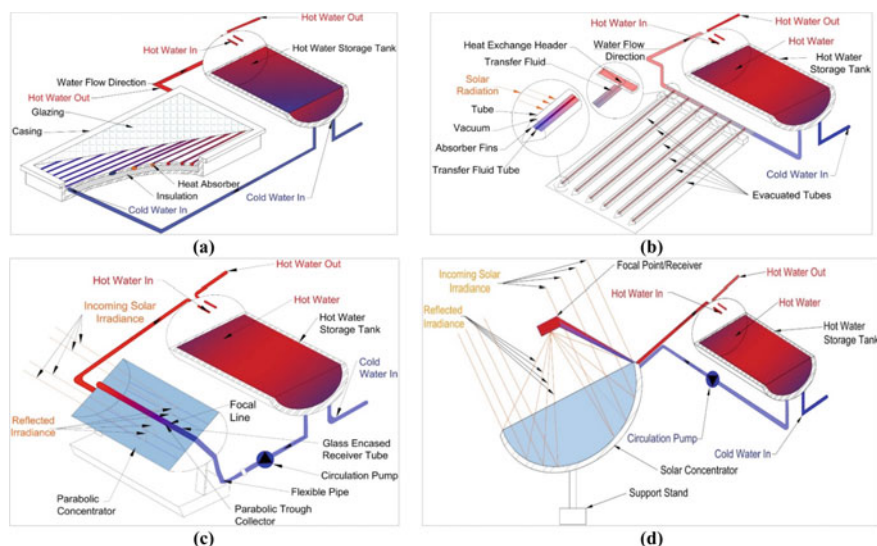


Fig. 5 Schematic representation of **a** Flat plate collector, **b** Evacuated tube collector, **c** Parabolic collector, **d** Dish collector [37]. Copyright Elsevier {Lic # 5510350216976, Lic # 5510350357240}

various review studies [33–36] available summarizing the literature on performance of solar collectors.

Sharma et al. [38] analyse the thermophysical properties of MWCNT-enhanced Amine functionalized paraffin wax PCM attached to a trapezoidal absorber plate of the FPSC in milk pasteurization applications. The experimental results demonstrated that incorporating Ne-PCM at 2.25 lpm flow rate and 0.1 wt% concentration cause a significant reduction in charging ($\downarrow = 21\%$) and discharging time ($\downarrow = 23\%$). Moreover, the system exhibited a 24% improvement in instantaneous charging efficiency and a 28% improvement in instantaneous discharging efficiency. The overall exergy gain for the system with enhanced PCM was 12% compared to the base FPSC. Saw et al. [39] examined the thermal performance of FPSC integrated with Ne-PCM for hot water production. The Cu nanoparticles loading at 1 wt% to the paraffin wax PCM showed promising enhancement in its thermal properties. Three cases were investigated, and it was found that using PCM and Ne-PCM resulted in hot water production at 40.2 and 40.8 °C respectively, compared to hot water produced at 35.2 °C using without PCM. Also, overall system performance is enhanced by 6.9 and 8.4% for PCM and Ne-PCM respectively.

Algarani et al. [40] carried out an experimental study on U-tube ETSC integrated with Ne-PCM. The Ne-PCM as a thermal booster was filled inside the U-tube, which results in 32% increment in thermal efficiency by incorporating 0.33 wt% Ne-PCM. Additionally, it was observed that Ne-PCM/ETSC system provides a continuously hot water supply at 0.08 lpm up to 50 °C for about 2 h longer than the simple ETSC system. Neil and Sobhansarbandi [41] carried out a comparative study of U-tube ETSC with a commercially available heat pipe ETSC through experimental

testing. Results showed that the U-Pipe ETSC provided higher peak temperatures of water, up to a 31 °C, which results in a 13% augmentation in efficiency compared to the HPESTC. Testing with thermal storage media showed that the U-tube ETSC maintained lower peak temperatures compared to the HPETSC. Integration of Ne-PCM with added MWCNT nanoparticles into the U-tube ETSC system resulted in higher peak temperatures of 63.9 °C for the fin tank. Abokersh et al. [42] designed a SWH system that tackles the shortcomings of standard systems, such as space and weight considerations and time difference between energy generation and consumption. This new system integrates a paraffin wax-based phase change material into a U-tube ETSC, eliminating the need for additional components. The system also includes a heat transfer plate (fin) to improve heat transfer and stability. Results show that the new system performs better than typical systems in various scenarios and has higher efficiency. Specifically, the average annual efficiency is 71.8% for the unfinned system, 85.7% for the finned system and 40.5% for the typical system. The daily system efficiency during real water consumption tests is 33% for the unfinned system, 26% for the finned system and 20% for the typical system. Elarem et al. [43] conducted an investigation on the performance of an ETSC system integrated with Ne-PCM and fins. They evaluated the effects of copper nanoparticles loading to paraffin wax on the system's performance and optimized the fin parameters. The results indicated that the use of fins had a significant impact on the phase change heat transfer of the paraffin in the ETSC, and thinner fins resulted in faster PCM melting. Moreover, the addition of 1 wt% of Cu to the PCM was determined to be the optimum mass concentration, leading to a 2 K increase in HTF outlet temperature. Finally, the study revealed that a flow rate of 0.003 kg/s was required to melt the entire mass of the PCM (as shown in Fig. 6).

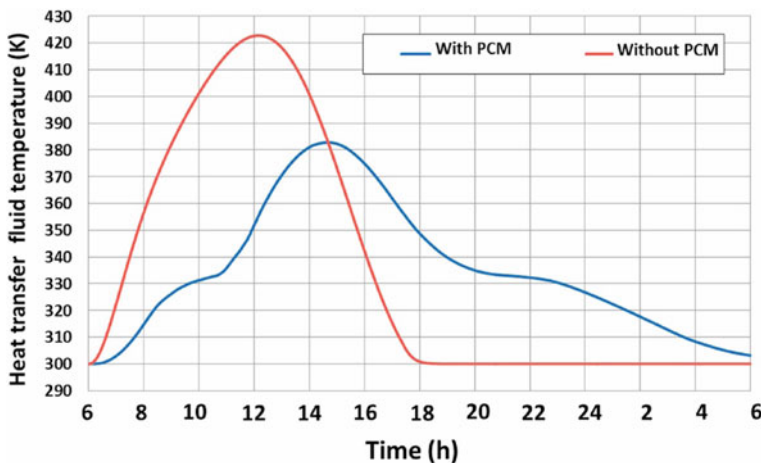


Fig. 6 Effect of PCM on heat transfer fluid temperature [43]. Copyright Elsevier {Lic # 5510350642208}

Kalbande et al. [44] assess the potential of a new hybrid system of Ne-PCM for TES using a parabolic dish solar collector integrated with Ne-PCM. The study compared the heat storage capacity of various Ne-PCM and evaluated a composite of pure paraffin wax with CuO-MWCNT. In accordance with the results, Ne-PCM had a 6.13% greater thermal conductivity and a 66.6% faster transformation from solid to liquid phase than pure paraffin wax. The hybrid system also exhibited a wide useful temperature range from 60 to 180 °C. Chaudhary et al. [45] assessed the impact of Ne-PCM in a PTC through their numerical model. The findings demonstrated that the use of Ne-PCM in the heat exchanger can efficiently exchange significant amounts of heat energy from the system for extended periods. Liu et al. [46] proposed a numerically studied on novel hybrid PV/T collector with microencapsulated phase change slurry. The numerical analysis demonstrated that the utilization of the slurry's latent heat led to a rise in both the thermal and electrical efficiencies. The findings showed a 9.24 and 1.8% augmentation in the thermal and electrical efficiencies, respectively. Afavogh and Zahedi [47] utilized encapsulated Ne-PCM in a hybrid system consisting of geothermal, hydro, biomass, solar and wind power, which also included PTC. Their findings indicated that incorporating encapsulated Ne-PCM caused a significant augmentation in overall efficiency.

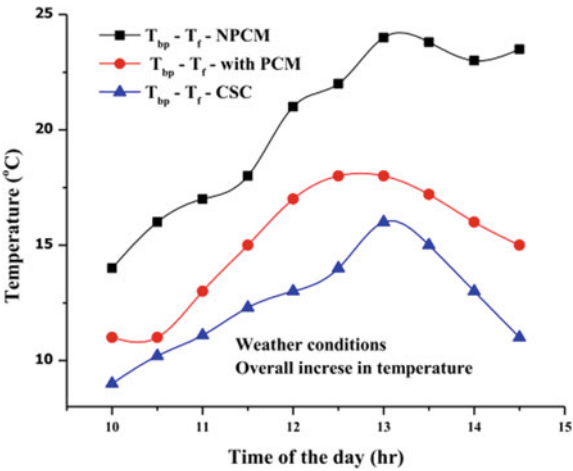
2.4 Solar Cooker

In a solar cooker, the Ne-PCM can be used as TES material that absorbs and stores the heat from the sun during shiny hours and releases it slowly over time to cook food. The nanoparticles loading to PCM increases the available heat transfer area, allowing it to absorb and release heat more quickly and efficiently. The use of Ne-PCMs in solar cookers can also help to mitigate the limitations of traditional PCM-based solar cookers, such as slow heating times and limited heat storage capacity. The thermal conductivity augmentation of Ne-PCMs allows them to absorb more heat in a shorter time duration and release it more quickly, making them ideal for cooking food.

Palanikumar et al. [48] assess the performance of solar box cooker (SBC) both with and without PCM, as well as with the use of Ne-PCM. The proposed SBC integrated with Fe₂O₃-based Ne-PCM exhibited a substantial increase in internal temperature, reaching up to 164.12 °C compared to those with and without PCM. The use of Ne-PCM resulted in an 11% improvement in the thermal performance of SBCs. When subjected to solar radiation of 1,037 W/m², the temperature of absorber plate reached 163.74 °C for SBCs with Ne-PCM, while for SBCs with only PCM and without any PCM, the temperature was 147 and 113.34 °C, respectively (Fig. 7).

In their experimental study, to resolve long cooking times and dependence on solar radiation Papade et al. [49] found that integrating Ne-PCM in parabolic concentrating solar has the ability to enhance energy storage capacity and efficiency of the system. This system provided an excellent cooking alternative and was specifically designed to meet the needs of a small family by allowing for the simultaneous cooking of two dishes while also storing thermal energy for indoor cooking. The results showed

Fig. 7 Comparison of peak temperature for PCM and Ne-PCM [48]. Copyright Elsevier {Lic # 5510351271912}



that rice and dal could be cooked within 17–22 min, both during the day and night, with a temperature decrease ranging from 56 to 70 °C, demonstrating the system’s effectiveness. In another study, Palanikumar et al. [50] improved the performance of SBC (shown in Fig. 8) using fuzzy techniques and thermal image analysis for heat energy utilization under different weather conditions. The efficiency of the cooker was enhanced through the use of PCM loaded with Al_2O_3 nanoparticles. The results showed that the application of fuzzy edge detection and segmentation techniques improved the performance of the cooker, and this technology could be used in various settings such as industrial, hostel, hospital and for families. The cooker’s overall efficiency was determined to be 52.17%, whereas its efficiency when employing PCM and nanoparticles was 75.47%, yielding a 15.41% increase in overall efficiency at some time periods of the day.



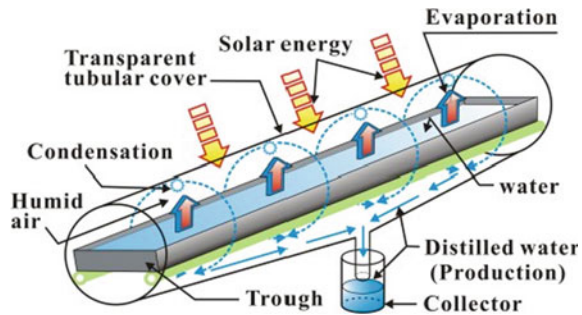
Fig. 8 Schematic diagram of solar box cooker [50]. Copyright Elsevier {Lic # 5510360257627}

Chaudhary et al. [51] examined whether a solar cooker system's efficiency might change if a PCM and parabolic dish collector were combined. The results revealed black-painted solar cooker integrated with PCM stored 26.8% more heat than the PCM in a typical one. Also, the PCM integrated into the solar cooker with the black-painted exterior and glazing stored 32.3% more heat than the PCM in a typical one. Yuksel et al. [52] found that incorporating a PCM into a SBC that featured an inner reflector and was filled with a mixture of metal shavings and PCM. The findings indicated that the solar cooker's thermal performance was optimized at a 30° angle, and the reflector contributed to an 18.35% improvement in thermal efficiency. The PCM was able to attain a maximum temperature ranging between 75.10 and 80.5 °C, which was deemed appropriate for cooking various types of food. Moreover, the reflector was able to increase the PCM temperature by 13.29%, and the cooking time was shortened to approximately 1 h. In their experimental study, Geddam et al. [53] found that adding fins to a solar box type cooker's exterior surface significantly reduces cooking time since it increases the surface area available for heat transfer. Additionally, the incorporation of PCM (paraffin) as a medium in the solar cooker significantly increases its TES capacity, allowing the food to remain hot for up to 3–4 h. Senthil [54] determined that the combination of a solar cooker with internal fins and PCM as well as a parabolic dish collector produced an average energy and exergy efficiency of 22 and 2.6% respectively. The addition of PCM increased the time required to reach 90 °C of water to 120 min, compared to 90 min without PCM. However, the use of PCM significantly improved the solar cooker's off-sunshine hour cooking capability, resulting in a twofold increase in cooking performance.

2.5 Solar Desalination

Ne-PCM has shown great promise in enhancing the performance of solar desalination systems. By improving the thermal conductivity of PCM through the addition of nanoparticles, Ne-PCM can increase the rate of heat transfer, leading to faster water evaporation and higher freshwater yields. This, in turn, can improve the energy efficiency of solar desalination systems, reduce their environmental impact and increase their overall stability and reliability. Ne-PCM can also help to stabilize the temperature of the system, which can prolong its lifespan and reduce the risk of thermal shock. Tubular solar still is primarily used for solar desalination system. As shown in Fig. 9, the tubular solar still consists of a rectangular absorber enclosed by a transparent glass tube. While the cylindrical shape differentiates it from conventional basin solar still, the principle remains the same. The transparent tube cover allows the absorber to receive solar energy, which heats the salty water in the trough. Both the trough and the tubular cover absorb the remaining solar energy. This process causes the water in the trough to evaporate, and the resulting water vapour forms a thin film on the inner surface of the tubular cover. The water vapour then releases its latent heat to condense and flow down due to gravity. The condensed water collects

Fig. 9 Tubular solar still
[55]. Copyright Elsevier
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in the collector situated at the bottom of the trough over the inner surface of the transparent tube cover [55].

Wang et al. [56] added β -AlN nanoparticles with silica gel and polyethene glycol to prepare Ne-PCM material. The nanoparticles loading into PCM materials enhanced its thermal conductivity from 30.22 to 156.6%. In their study, Abdullah et al. [57] determined the performance of trays solar still (TSS) by utilizing finned absorbers covered with jute wick materials and reflecting mirrors on internal sides. Cu nanoparticles-based Ne-PCM were utilized, along with electric heaters and a photovoltaic cell for power. Results exhibited a significant enhancement of 196% in productivity of TSS with electrical heaters and Ne-PCM compared to conventional solar stills. Kandel et al. [58] assessed the efficiency of a modified double slope still (MDSSS) in comparison to the conventional single slope still using various Ne-PCM. Different materials were analysed to determine the optimal ratios, and three cases of MDSSS were examined. The findings revealed that all MDSSS cases exhibited significant enhancements. The productivity, energy and exergy efficiency increased by 113, 112.5 and 190% respectively, and freshwater production costs were reduced by 35.3% in comparison to the CSS. Shoeibi et al. [59] investigated that Ne-PCM with CuO and Al_2O_3 nanoparticles at a concentration of 0.3 wt% improved the productivity of solar stills by 55.8 and 49.5%, respectively. The melting point was reduced by 2.1 and 1.8 °C using CuO and Al_2O_3 nanoparticles at 0.1 wt%, respectively, which increased the water production rate about 5.7%. Safaei et al. [60] dispersed the graphene oxide nanoparticle in paraffin PCM at different wt% (0.2, 0.4, 0.6 wt%) and attained a 25% augmentation in thermal efficiency of the system while using Ne-PCM. They also conclude that the solar still equipped with PCM achieved a daily productivity of 2 kg per 0.4 m². On the other hand, the solar still that used $\Phi = 0.6$ wt% GO/PCM had a higher daily productivity of 2.5 kg per 0.4 m². Abdelaziz et al. [61] evaluate the performance of the TSS system integrated with Ne-PCM, v-corrugated aluminium basin, wick and nanofluid in different combinations. Their experimental investigation led to an increase in energy and exergy efficiency of 82.16 and 221.8%, respectively (Fig. 10).

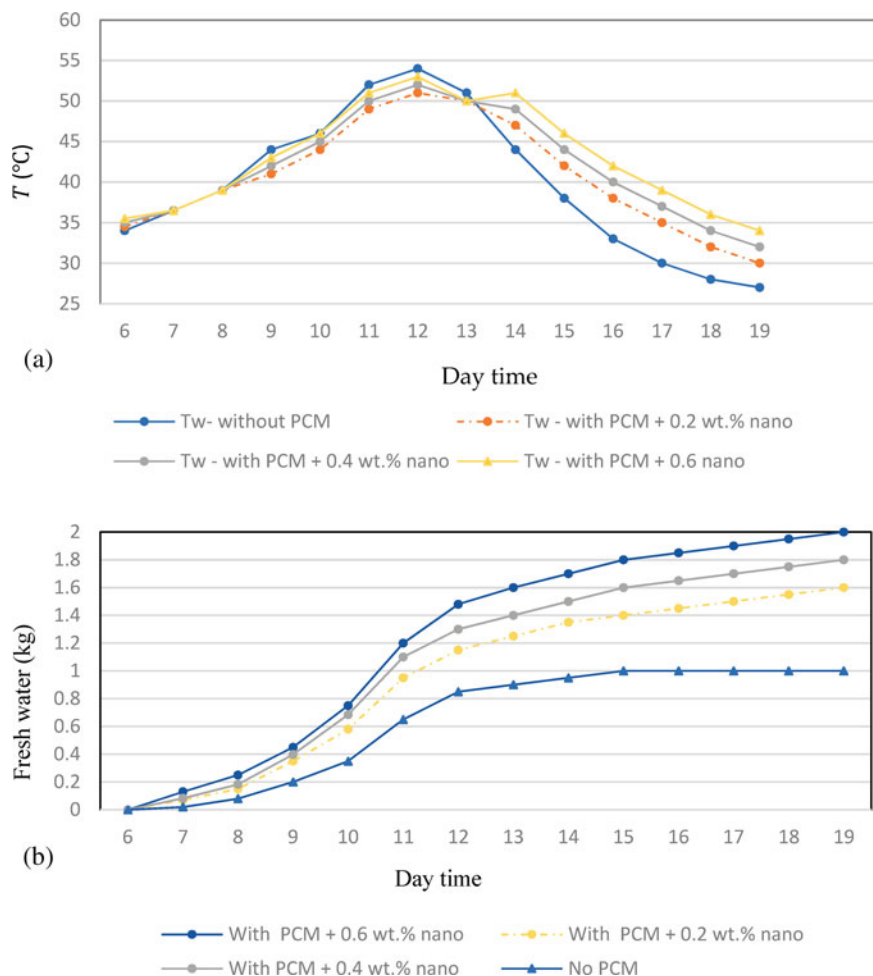


Fig. 10 Comparison of **a** temperature **b** Fresh water production for solar desalination system for Ne-PCM and without PCM [60]

3 Conclusion

In conclusion, Ne-PCM has shown tremendous potential in various solar energy applications. Ne-PCM has been extensively studied in solar cooker applications, and it has been found to enhance the efficiency of solar cookers by reducing cooking time and increasing the heat transfer rate. Moreover, Ne-PCM has been utilized in solar collectors, including solar water heaters, solar air heaters and solar desalination, to improve their thermal performance by increasing their heat storage capacity and reducing heat losses. The Ne-PCMs has been proven to improve their thermal conductivity, thereby increasing their heat transfer rate and enhancing their thermal

stability. Overall, the applications of Ne-PCM in different solar energy systems have demonstrated significant improvements in energy efficiency and storage capacity, which are crucial factors in the transition towards sustainable and renewable energy sources.

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Chapter 8

Application of Nano-enhanced PCMs in Buildings



**Praveen Kumar Tyagi, Rajan Kumar, Zafar Said,
and Pushpendra Kumar Singh Rathore**

Nomenclature

HVAC	Heating, ventilation, and air conditioning
CNF	Carbon nanofiber
TES	Thermal energy storage
MWCNT	Multiwalled carbon nanotubes
CNT	Carbon nanotube
k_T	Thermal conductivity
NEPCM	Nano-enhanced phase change material
Φ_w	Weight fraction of nanomaterial
Φ_v	Volume fraction of nanomaterial
PCM	Phase change material

P. K. Tyagi · R. Kumar (✉)

Department of Mechanical Engineering, Dr B R Ambedkar National Institute of Technology,
Jalandhar, Punjab 144008, India
e-mail: rajank@nitj.ac.in

Z. Said (✉)

Sustainable and Renewable Energy Engineering Department, University of Sharjah, P.O.
Box 27272, Sharjah, United Arab Emirates
e-mail: zsaid@sharjah.ac.ae

Department of Industrial and Mechanical Engineering, Lebanese American University (LAU),
Byblos, Lebanon

U.S.-Pakistan Center for Advanced Studies in Energy (USPCAS-E), National University of
Sciences and Technology (NUST), Islamabad, Pakistan

P. K. S. Rathore

Department of Mechanical Engineering, Amity School of Engineering and Technology, Amity
University, Noida, Uttar Pradesh, India

d_n	Diameter of nanomaterial
T_p	Phase change temperature

1 Introduction

The global highest energy consumer is the construction sector. They are responsible for over one-third of the total energy consumption and associated CO₂ emissions, and it is expected they will rise above 50% by 2050 [1]. The usage of heating and cooling in the building sector is between 60 and 70% [2]. The implementation of effective TES systems provides an opportunity to improve building energy efficiency and thereby reduce commercial and residential energy consumption. Therefore, energy efficiency efforts should focus on both new constructions and retrofitting [3]. In buildings, there are various passive and active TES integration applications. Out of these, passive applications are beneficial for providing comfort in the building by lowering the highest temperature, decreasing electricity requirement, and lowering the cooling and heating load capacity needed to meet peak-load demand. TES reduces the amount of power consumed by equipment while increasing its efficiency by switching system operation to the high-efficiency band in active applications. Furthermore, the TES system facilitates the successful integration of renewable energy by addressing the imbalance between demand and energy availability times [4]. Therefore, TES technologies play a vital role in the development of ultra-low-energy, near-zero-energy, and plus-energy buildings [5]. The latent heat TES materials, i.e., phase change materials (PCMs) are promising in buildings due to their high energy storage capacity, non-toxic nature, and low subcooling. But they have some limitations due to their poor thermal conductivity (k_T). Therefore, Incorporating NEPCM with a building permits a more dynamic usage of thermal energy because of its higher k_T , higher charging and discharging rates, high energy storage capabilities, superior stability in many cases after several cycles of use, and small volume change during the phase transformation as compared to conventional PCM. Therefore, they can be coupled with buildings for cooling and heating needs as a way to store latent heat during melting and release it during solidification to fill the gap between the energy demand and supply by shifting peak load to off-peak times and dropping the energy necessity. These are useful for heating, ventilation, and air conditioning (HVAC) applications in the building due to their appropriate phase change temperatures (T_p).

Different integration techniques, such as direct impregnation, immersion through the material's pores, encapsulation, and shape/form stabilizing techniques, can be used to incorporate the PCM/NEPCM into the construction of buildings [6]. In the manufacturing process, the direct impregnation approach makes it simple to include PCM in powdered or liquid form in building materials including concrete, gypsum, plaster, and cellulose that serve as insulating materials. To allow for absorption by the manufactured material's internal pores, the manufactured material is added to a melted PCM bath during the immersion method [7]. But these two methods can't

be used for long-term applications because most PCM/NEPCM undergo a phase change during discharging and charging modes respectively [8]. Therefore, there is a chance of leakage to the surface and diffusion of low viscous liquid PCM/NEPCM in the building materials [9]. The encapsulation and shape stabilization methods are preferred for the long-term applications of PCM in building sectors [10]. The form/shape stabilization approach makes use of the dispersion of PCM into a different phase of a supporting substance, such as high-density polyethylene, or a stable composite made of styrene-butyl-styrene, high-density polyethylene, and graphite or carbon fibers [11]. There are two types of methods for encapsulation of PCM which are used in building such as micro and macroencapsulation. The most often utilized encapsulation method is the microencapsulation of PCM. It improves heat transfer by increasing the surface area, reducing reaction with surrounding material, and lowering the thermal resistance [12]. Microencapsulated PCM is employed in building applications, where PCM was placed into capsules shape with dimensions of less than 1 μm and up to 300 μm to avoid changes in material composition owing to environmental effects [13]. Therefore, these materials can be mixed directly in construction materials like concrete and gypsum but it may affect the structural strength of the material [14]. This approach improves cyclic thermal stability and reduces phase separation. However, corrosion (between PCM and its container) is a problem for macroencapsulated PCMs. This approach used the different shapes of containers like a sphere, tubes, and panels for encapsulation. The container size (more than 1 cm) is bigger than the microencapsulation approach [15]. In contrast, microencapsulated PCMs have higher costs and increased subcooling, which are undesirable properties for materials that change their phase for storage. Therefore, more research is needed because some studies show that it increases the subcooling effect of TES materials [16].

The performance of a commercial building for cooling purposes integrated with TES is investigated by Kim and Norford [17]. The results showed a positive effect with PCM integration. Silva et al. [18] investigated the three-wall specimen with hollow-fired clay bricks, first as a reference specimen, second with macrocapsulated PCM, and third with insulation (10 mm XPS) and macrocapsulated PCM. The study observed that there was a reduction in thermal amplitude by 80 and 50% for the third and second samples as compared to the first one. The study also observed that the samples second and third have a delay period of 3 h in achieving the peak temperature. Meng et al. [19] also tested the bricks, one using macroencapsulated PCM and the second without the use of PCM. The study used RT18 as a PCM and steel as encapsulating material. The result revealed that there was a postponement period of 3 h for achieving the highest temperature, and thermal amplitude was reduced between 5 and 10 °C. Kong et al. [20] investigated two-room systems, one with encapsulated PCM and the other without PCM. The study used the RT18 PCM for the north and south walls and SP29 PCM for the ceiling, flooring, and west side wall of the encapsulated room system. The result showed that there was a temperature reduction between 11.21 and 14.12 °C on winter days and a temperature increase between 6.93 and 9.48 °C on summer days. Therefore, microencapsulated PCM

integration in buildings improves indoor building thermal management in terms of reduction in thermal amplitude, decrease in peak temperature, and time lag.

2 Generic Challenges with the Synthesis and Applications of NEPCM in Buildings

NEPCMs can be integrated into construction materials like a structural component of lightweight or even massive buildings to boost the overall and localized thermal inertia of the building similar to PCMs. Therefore, they can be used in buildings for cooling and heating as a way to store latent heat energy at the time of melting and release it during solidification to fill the mismatch between the energy demand and supply by shifting peak load to off-peak times and lowering the energy requirement. These NEPCMs can store latent heat in a centralized or localized manner for a variety of building applications. There are many variables and unknowns with the use of NEPCM for building applications. Therefore, it is difficult to investigate and optimize the building's performance when it has been integrated with NEPCM. It is very challenging to address the problem of phase transition because of the unpredictable speed of the moving solid–liquid interface, the highly nonlinear phase change characteristics, and the interaction of nanomaterial with the base PCM.

Figure 1 represents the general framework for using NEPCMs in building sectors. With the step-by-step procedure of this framework, one can easily select the appropriate nanomaterial and PCM as per building applications. The PCM T_p must be as per the building's functioning. The commonly used nanomaterials can be metallic, non-metallic, graphene, graphite, and carbon nanotubes [21–23]. Either a one-step method or a two-step method is used to prepare the NEPCM [24]. The thermophysical properties of PCM and NEPCM are dissimilar due to the doping of different shapes, sizes, and loading conditions, i.e., volume fraction/weight fraction/mass fraction of nanomaterial [25]. In the next phase, there is a need to explore the physics of augmentation of the k_T and phase change transport mechanism of NEPCM integrated with the buildings. The atomic, molecular, and microscopic behavior of NEPCM can be understood by using advanced molecular scale and microscopic scale simulations [26–28]. The usefulness of using NEPCM in structures depends on various aspects, including the surrounding climate condition, how the PCM is integrated with the building, load management control strategies, and many others [29]. Following that, a comprehensive evaluation of the thermodynamic behavior of buildings under actual operating settings is required for the characteristics of the building temperature response and interactions between subsystems [30]. Different advanced load management control strategies are then developed by taking into account the surrounding weather conditions, thermophysical properties of the used NEPCM, load profiles of buildings, and utility rate structures. The performance of the NEPCM is then assessed with the aid of the developed control strategies of load management.

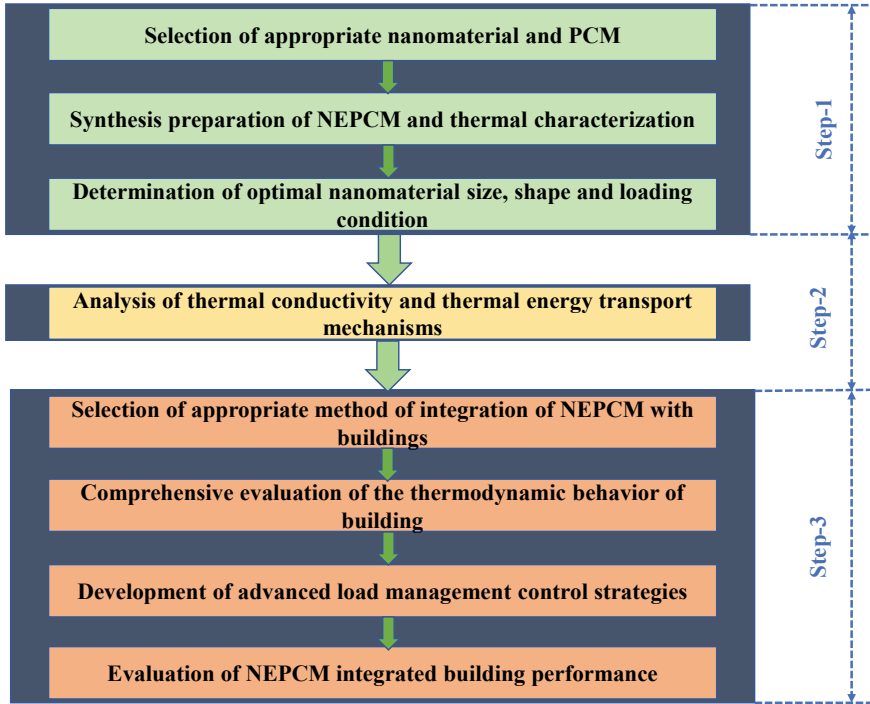


Fig. 1 General framework for using NEPCMs in building sectors

3 Current Research and Different Applications of PCM/NEPCM in Buildings

The possible building applications of PCM/NEPCM can be divided into categories like peak load shifting, free cooling, thermal comfort, and active and passive cooling systems. In the category of peak load shifting, the peak load is maximum during the daytime due to the extreme demand for electricity which creates pressure on the grid to supply the required electricity. The peak demand can be shifted to other non-load times of the day by reducing the peak load and by peak load offset using the PCM/NEPCM [31]. By this, there is energy saving or enhanced energy efficiency by the use of PCM. The PCM/NEPCM-based free cooling system stores outdoor coolness and releases it throughout the day. These systems use PCM to store latent heat while utilizing air ducts and fluid that is circulated through conducting pipes. However, this cooling is only achievable when the temperature of the system surrounding is higher at the time of day than the T_p of the PCM and lower at night [32]. Because PCM/NEPCM reduces temperature fluctuations and provides temperature uniformity, it is possible to control the indoor temperature in buildings. Therefore, it is essential to select an appropriate PCM within the intended freezing or melting temperature in order to maintain temperature uniformity within the comfort

zone. The active cooling system integrated the PCM/NEPCM storage capabilities with the heat recovery system, flooring heating system, and solar heat pump system. These systems lessen the peak load requirement on even more efficient systems, which in turn lessen the electricity requirement for HVAC systems. To increase the thermal mass for passive applications, PCM/NEPCM are coupled with buildings. The lightweight constructions often experience extreme overheating during the summer days because they have less thermal mass. The integration of PCM by storing latent heat lowers the risk of daytime overheating in the summer and lowers the need for heating at night in the winter.

Teng and Yu [33] examined the effects of TiO_2 , Al_2O_3 , ZnO , and SiO_2 nanomaterials at weight fraction (Φ_w) = 1, 2, and 3% on paraffin wax, which has a wide range of uses. The NEPCM is made using the direct synthesis technique. The k_T and TES are considered to be the main metrics to assess the NEPCM performance. The NEPCM-based TiO_2 nanomaterials is determined to have the best performance. The addition of TiO_2 nanomaterial improves heat conductivity and lowers melting onset temperature while increasing solidification onset temperature. As a result, it can be employed in building applications that have a wider temperature range and rapid changes in heat load. In terms of its k_T and heat transmission during the phase change process, Wu et al. [34] examined the performance of metallic Cu-enhanced paraffin wax which can be used in building applications. According to the study, the maximum increase in k_T was 14.2 and 18.1% in the discharging and charging states at $\Phi_w = 2\%$ of nanoparticles. The study also discovered that the most effective technique to improve phase change heat transfer is to use Cu-enhanced paraffin wax. Li [35] investigated the performance of randomly dispersed nano-graphite in paraffin wax. It is simple to create nano-graphite using exfoliated and expanded graphite. This dispersed nano graphite improves k_T and the ability for storing a large amount of thermal energy. The results of the study showed that as Φ_w of nano-graphite in paraffin increased, k_T increased while latent heat decreased.

The thermal performance of paraffin augmented using CuO at $\Phi_w = 2, 5$, and 10% was investigated by Jesumathy et al. [36]. According to the study's findings, the k_T increased with an increase in the loading condition of nanomaterial in the PCM. The highest increase in k_T is measured to be 7.8% at $\Phi_w = 10\%$ of nanomaterial. The greatest increase in dynamic viscosity is measured to be 30% at $\Phi_w = 10\%$ of nanomaterial. Therefore, the optimal fraction of the present nanomaterial in PCM has the greatest potential for TES applications, particularly in industrial waste recovery systems, solar-based power generation, and solar thermal applications. The thermal characteristics of Cu-enhanced PCM at volume fraction (Φ_v) = 0.5, 1.2, and 4% were examined by Sciacovelli et al. [37]. The performance of the NEPCM was analyzed computationally with the help of computational fluid dynamics (CFD) software, and the enthalpy approach was used for the phase transition process of PCM. The study found that the phase change phenomenon is greatly influenced by natural convection within PCM. Due to an improvement in k_T , the melting time for the $\Phi_v = 4\%$ of nanomaterial is lowered by 15%. The heat transfer rate exhibits the same patterns. Cui et al. [38] presented a study to investigate the thermophysical properties (k_T and latent heat) of PCM (soy wax and paraffin wax) doped with

carbon nanofiber (CNF)/carbon nanotube (CNT). In comparison to pure soy wax, the greatest increase in k_T was found to be 44.75% and 24.38% for CNF-soy wax and CNT-soy wax, respectively, at $\Phi_w = 10\%$ of nanomaterial. Due to better CNF dispersion in the matrix, the CNF-soy wax exhibits the greatest improvement in k_T . The highest improvement in k_T for the CNF-paraffin wax at $\Phi_w = 10\%$ was found to be 40.62% when compared to pure paraffin wax. As a result, CNF can be effectively employed as a nanomaterial in PCM to improve k_T and temperature response without lowering latent heat storage capacity.

The multiwalled carbon nanotubes (MWCNT)-deionized (DI) water NEPCM's solidification time was investigated by Kumaresan et al. [39]. The integration of NEPCM can reduce the maximum solidification time by 20.1% and 14% in bath environments with temperatures of -12°C and -9°C , respectively. This phenomenon is caused by the high heat conductivity of the MWCNTs dispersed in the PCM, which acts as a nucleation agent to initiate the solidification progression before the base PCM. When nanomaterial is loaded minimally, the subcooling effect is at its lowest and increases as the loading grows, suppressing the convection effect in the PCM. The study also revealed that the proposed NEPCM integrated with a chiller in a building can be utilized with an energy-saving potential of around 6–9%. The effectiveness of an air-conditioning system (ice storage) with Al_2O_3 dispersion in DI water was studied by Teng [40]. During the phase transition process, the dispersed Al_2O_3 facilitates heterogeneous nucleation, energy transmission, and temperature gradient elimination.

The usage of expanded graphite nanosheets enhanced paraffin (C17H36) in gypsum wallboard in a structure was examined by Biswas et al. [41]. The proposed NEPCM wallboard is tested in the natural environment of Charleston, South Carolina, USA. The performance is also investigated numerically by COMSOL Multiphysics. The 2-dimensional model based on finite elements was used for the analysis. The performance of the building is investigated in terms of saving in power consumption and building energy efficiency. The k_T of the proposed nano-enhanced wallboard was found to be 0.410 W/m-K in the solid and 0.427 W/m-K in the liquid media. Sayyar et al. [42] also examined thermal comfort and building energy-saving performance using graphite-enhanced fatty acid-based PCM. The use of the proposed NEPCM in building wallboard enhances k_T , long-term durability, and shape stability. Therefore, it is beneficial for use in lightweight buildings. The study's findings showed that buildings maintained indoor thermal comfort while saving 79% on electricity.

The application of enhanced PCM made of nanocomposites as a construction component was studied by Constantinescu et al. [43]. This enhanced PCM was made of low molecular mass epoxy resin and Al powder. Due to epoxy's ability to polymerize at room temperature, the low molecular mass of epoxy was chosen. The Al was used to provide better thermal conductive characteristics to PCM. This nanocomposite has a suitable T_p and high form stability. Guo [44] examined the study of NEPCM in the ceiling board of a building. The Al_2O_3 was used as a nanomaterial in the investigation together with paraffin wax. The thermal characteristics of integrated enhanced PCM in ceiling boards are analyzed using the enthalpy-porosity model. The study revealed that the use of it can save cooling energy in summer. In the building of

an office complex in Chennai, India, Parameshwaran and Kalaiselvam [45] examined the effectiveness of the air-conditioning system (chilled water-based with variable air volume) coupled with Ag-based NEPCM. The synthesis of the Ag nanoparticle was accomplished using the wet chemical reduction method. The study's results revealed that the suggested system in the study had improved thermal performance all around. The proposed cooling system was found to save 36–58% and 24–51% of energy annually, respectively, during on-peak and daily hours when compared to a traditional air conditioning system. Parameshwaran et al. [46] presented a study on an Ag-TiO₂ hybrid nanocomposite-based ester (organic) with a viewpoint of thermal characteristics and energy-storing capabilities. The charging and discharging rates were reduced by 8.5 and 23.9% as compared to conventional PCM. The research showed that the proposed hybrid nano-composite-based PCM had enhanced thermal characteristics and an increased capacity for energy storage, making it an appropriate option for integration in buildings. The thermal performance of the Ag-enhanced ethyl cinnamate with $\Phi_w = 0.1\text{--}5\%$ of nanomaterial was examined by Parameshwaran et al. [47]. As the loading of nanomaterial increased from $\Phi_w = 0.1\text{--}5\%$, the degree of subcooling decreased from 11.7 to 6.8%. In comparison to conventional PCM, the latent heat thermophysical property was reduced in the discharging and charging modes by 7.88% and 8.91%, respectively. As the loading conditions were increased, the k_T increased by 10–67%. As a result, it can be applied to realistic thermal interface system applications. The performance of Al and Al₂O₃ nanomaterial enhanced n-tetradecane: n-hexadecane mixture PCM for building cooling applications examined by Kalaiselvam et al. [48]. The study was conducted experimentally and analytically. The charging rate for the PCM (60% n-tetradecane: 40% n-hexadecane) dispersed with Al₂O₃ and Al nanomaterial at $\Phi_v = 7\%$ was reduced by 4.97% and 12.97% respectively. The performance of graphite-enhanced paraffin wax for district heating purposes in buildings is explored by Colella et al. [49]. The study revealed that the enhanced PCM has better energy storage density than the traditional PCM. The key findings of the reviewed literature on PCM/NEPCM integrated building structures are represented and summarized in Table 1.

Commercial uses of PCM/NEPCM are discussed in this paragraph. TermoDeck [50] (<http://www.termodeck.com/>) sells a concrete block system with hollow cores as TES in building structures. The daytime heat is stored by using the floor panels, and at the time of night, environmental/surrounding air is circulated through the cores (hollow) for discharging the stored energy. The present system was adopted by more than 300 buildings in the United Kingdom, Norway, and Sweden and showed positive results. investigated The TermoDeck [50] (<http://www.termodeck.com/>) system is investigated by different studies [51, 52]. A concrete block (hollow core) system for different applications of cooling and heating is selected. This strategy can reduce heating and cooling energy usage by 10–30%. In addition, in warm or mild climates, aero-thermal energy can minimize cooling demand by 15–30%. Products based on encapsulated PCM for radiant floor/thermally activated suspended ceiling systems are promoted by PCMProducts [53] (<http://www.pcmproducts.net/>) which can be used as an energy storage system in building structures, and for radiant

Table 1 Summary of the key findings of reviewed literature on PCM/NEPCM integrated building structures

References	PCM used and its phase change temperature (T_p)	Nanomaterial type and its concentration	Key results
Teng and Yu [33]	Paraffin $T_p = 54\text{ }^{\circ}\text{C}$	TiO_2 , SiO_2 , ZnO , Al_2O_3 ($\phi_w = 1, 2$, and 3%) ($d_n = 20\text{--}30\text{ nm}$)	The addition of TiO_2 nanomaterial in paraffin enhances heat conductivity, lowers melting onset temperature, and raises solidification onset temperature. Therefore, it can be used in applications that need a wider temperature range and fast-changing heat load
Wu et al. [34]	Paraffin wax $T_p = 58\text{--}60\text{ }^{\circ}\text{C}$	Cu ($\phi_w = 1$ and 2%) ($d_n = 25\text{ nm}$)	The maximum increase in k_T was 14.2 and 18.1% in the discharging and charging states at $\phi_w = 2\%$ of nanoparticles
Li [35]	Paraffin wax $T_p = 28.81\text{ }^{\circ}\text{C}$	Graphite ($\phi_w = 1\text{--}10\%$) ($d_n = 35\text{ nm}$)	The exfoliated and expanded graphite can be used to synthesize nano-graphite easily. This dispersed nano-graphite improves k_T and its ability to store thermal energy
Jesumathy et al. [36]	Paraffin wax $T_p = 58.2\text{ }^{\circ}\text{C}$ (freezing temperature)	CuO ($\phi_w = 2, 5$, and 10%) ($d_n = 40\text{ nm}$)	The highest increase in k_T and dynamic viscosity is observed to be 7.8% and 30% at $\phi_w = 10\%$ of nanomaterial. Therefore, the optimal fraction of the present nanomaterial in PCM has the greatest potential for TES applications, particularly in industrial waste recovery systems, solar-based power generation, and solar thermal applications
Sciacovelli et al. [37]	Paraffin wax $T_p = 37.8\text{--}44.23\text{ }^{\circ}\text{C}$	Cu ($\phi_v = 0.5, 1.2$, and 4%) ($d_n = 15\text{ nm}$)	The study found that the phase change phenomenon is greatly influenced by natural convection within PCM. Due to an improvement in k_T , the melting time for the $\phi_v = 4\%$ of nanomaterial is lowered by 15%

(continued)

Table 1 (continued)

References	PCM used and its phase change temperature (T_p)	Nanomaterial type and its concentration	Key results
Cui et al. [38]	Soy wax Paraffin $T_p = 52\text{--}54\text{ }^\circ\text{C}$	CNF (outer diameter-200 nm) CNT (length-50 μm , diameter-30 nm) ($\phi_w = 1, 2, 5$, and 10%) ($d_n = 15\text{ nm}$)	The greatest increase in k_T was found to be 44.75% and 24.38% for CNF-soy wax and CNT-soy wax, respectively, at $\phi_w = 10\%$ of nanomaterial. CNF-soy wax exhibits the greatest improvement in k_T due to better CNF dispersion in the matrix
Kumaresan et al. [39]	DI water	MWCNT ($\phi_v = 0.15, 0.3, 0.45$, and 0.6%)	The maximum solidification time can be reduced by 20.1 and 14% in surrounding bath temperatures of -12 and $-9\text{ }^\circ\text{C}$ with the integration of NEPCM. The proposed NEPCM integrated with a chiller in a building can be utilized to leverage energy savings of about 6–9%
Biswas et al. [41]	Paraffin wax	Interconnected expanded graphite nanosheets	The k_T of the proposed nano-enhanced wallboard was determined to be 0.427 W/m-K in liquid and 0.410 W/m-K in solid-state media
Sayyar et al. [42]	Eutectic type PCM made of capric acid: palmitic acid	Interconnected graphite nanosheets (surface area = 100 m^2/g)	The study's findings showed that buildings maintained indoor thermal comfort while saving 79% on electricity

(continued)

Table 1 (continued)

References	PCM used and its phase change temperature (T_p)	Nanomaterial type and its concentration	Key results
Parameshwaran et al. [46]	Ester (ethyl trans-cinnamate) $T_p = 6.8\text{ }^{\circ}\text{C}$ (melting)	Ag-TiO ₂ hybrid nanocomposite ($\phi_w = 0.1\text{--}1.5\%$) ($d_n = 10\text{--}95\text{ nm}$)	The charging and discharging rates were reduced by 8.5 and 23.9% as compared to conventional PCM at $\phi_w = 1.5\%$. Therefore, the proposed hybrid nano-composite-based PCM has enhanced thermal properties and energy storage capacity due to that it can be a potential candidate for building applications
Parameshwaran et al. [47]	Ethyl cinnamate	Ag ($\phi_w = 0.1, 0.5, 1, 2$, and 5%)	The latent heat capacity was reduced in the discharging and charging modes by 7.88 and 8.91%, respectively. As the loading conditions were increased, the k_T increased by 10–67%. Therefore, it can be applied to realistic thermal interface system applications

heating and cooling systems are promoted by ThermaCool [54] (<http://www.therma.cool/>). Emcoklima [55] (<http://www.emco-klima.com/index.html>) promoted the PCM-based plasterboards with the combination of water channels.

4 Concluding Remarks and Discussions

The integration of NEPCM into a building structure permits a more dynamic usage of thermal energy because of its higher thermal conductivity, higher charging and discharging rates, high energy storage capabilities, superior stability in many cases after several cycles of use, and small volume change at the time of phase transformation than conventional PCM. Therefore, they can be incorporated with building structures for cooling and heating needs as a way to store thermal energy at the time of melting and release it during the next phase, i.e., solidification to fill the gap between the energy demand and supply by shifting peak load to off-peak times and reducing the energy requirement. This chapter provides a discussion on generic challenges with the synthesis and applications of NEPCM in building sectors. This chapter also provides a comprehensive overview of current research on NEPCM-integrated buildings and their applications. The possible building applications of PCM/NEPCM are divided into categories like free cooling, shifting of peak load, thermal comfort, and active and passive cooling systems. A brief overview of different integration techniques such as direct impregnation, immersion through the material's pores, encapsulation, and shape stabilizing techniques of PCM/NEPCM into the construction of buildings are also provided. The following findings have been attained:

1. The TES methods for buildings that are effective and efficient include sensible and latent heat and it is worth noting that the choice of nanomaterial for a specific PCM has a significant impact on heat transfer characteristics.
2. The majority of studies have shown that adding high thermal conductive nanomaterial to a base PCM can increase the mixture's melting and solidification rates as well as its thermal conductivity.
3. NEPCM meets the ideal conditions for PCM use in buildings. Therefore, it is beneficial to save energy and fluctuation of indoor temperature while maintaining thermal comfort conditions inside desired space of the building.
4. The addition of nanoparticles has substantially shortened the time required for complete solidification. The reduced size of the nanoparticles scattered in the PCM improved energy transmission via stochastic and interparticle-type forces. Microconvection effects were created in the nanomaterial-PCM mixture. By virtue of this, there was an improvement in overall heat transfer in charging and discharging modes.
5. The thermal management in buildings can be influenced by the proper selection of PCM melting point and its type, building boundary conditions, building orientation, and different components of the building.

6. There is a change in properties like compressive, flexural strength, adhesion, microstructure, and workability when NEPCM is added to mortars, which are composed of sand, water, and cement.
7. The usefulness of using NEPCM in structures depends on many aspects such as surrounding climate conditions, how the PCM is integrated with the building, load management control strategies, and many others.
8. Different integration techniques, such as direct impregnation, immersion through the material's pores, encapsulation, and shape/form stabilizing techniques, can be used to incorporate the PCM/NEPCM into the construction of buildings.
9. Different advanced load management control strategies are developed to measure the performance of NEPCM-integrated buildings by taking into account the surrounding weather conditions, thermophysical properties of the used NEPCM, load profiles of buildings, and utility rate structures.
10. The most compatible materials utilized in structures for PCM microencapsulation for long-term use include stainless steel, high-density polyethylene, Cu pipes, Al sheets, foils, and panels. These substances provide mechanical strength to the building structure and speed up heat transfer.
11. The NEPCMs' form stability substantially simplifies their incorporation into lightweight building components. The lack of liquefaction in thermal storage in NEPCMs reduces the necessity for encapsulation, which hampers the practical application of traditional PCMs in construction sectors.

5 Future Research Directions

Future scopes are established as follows:

1. Most studies widely ignored the potential harm that nanometer-sized materials could do to both the environment and individuals. When employing NEPCMs in buildings, a thorough risk evaluation and required protective measures should be taken into account.
2. The payback periods for NEPCM-integrated buildings must also be evaluated in order to further validate the economic analysis for using the nanomaterial in PCM.
3. Future studies will entail improving the performance of the NEPCM-integrated structures using solar-thermal energy techniques. By using this combined technology, the cooling capacity and energy redistribution requirements can be supplied further, which will significantly provide assistance to improve the energy efficiency of buildings as well as sustainable development.

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Chapter 9

Application of Nano-enhanced PCMs in Electronic Devices



Imtiaz Ali Laghari, Yasir Ali Bhutto, Mohsin Ali Koondhar,
and Syed Abid Ali Shah

1 Introduction

The growing demand for performance enhancement of electronic devices has impelled manufacturers to downsize their products. As a result, the power density of electronic systems saw a gradual rise over few years. For instance, for industrial CPUs with power levels higher than 100 W/cm^2 . These larger power densities are typically confined, which crates thermal hot spots with values ranging from $(0.1\text{--}1) \text{ kW/cm}^2$ as shown in Fig. 1. The larger power densities may lead to elevated local temps, frequently above suggested limits, and significant temperature differences ($5\text{--}30^\circ\text{C}$) within the component. The extended high temperature operation may impede efficiency and, ultimately, cause the electronic devices to malfunction. Especially high risk for high switching equipment. The temperature fluctuations can trigger thermal and mechanical strains and can endanger component dependability and safety.

Similar kinds of problems may occur in high power batteries, transistors, and, electronic modules. However, most of the electronic devices involve integrated circuitry, the concept of theses integrated circuitry was given by Werner Jacobi in 1949. An integrated circuit (IC) is semiconductor material-based small size chip that can handle hundreds of millions of microstructures of electronic components like capacitors,

I. A. Laghari (✉) · Y. A. Bhutto · S. A. A. Shah

Department of Electrical Engineering, Quaid-e-Awam University of Engineering, Science and Technology, Campus Larkana, Nawabshah, Sindh, Pakistan

e-mail: laghari.imtiaz@quest.edu.pk

S. A. A. Shah

e-mail: abidshah@quest.edu.pk

M. A. Koondhar

Department of Electrical Engineering, Quaid-e-Awam University of Engineering, Science and Technology, Nawabshah, Sindh, Pakistan

e-mail: enr.mohsinkoondhar@quest.edu.pk

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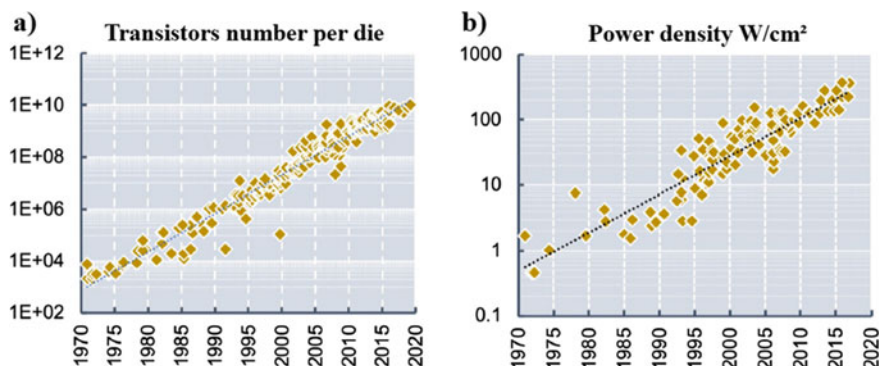


Fig. 1 a Transistors per integrated circuit b processors' commercial density over last decade [1]. Adapted with permission. Copyright 2020, Elsevier

transistors, and others. Further, ICs are utilized in nearly all electronic devices. The present society is thoroughly integrated with diverse electronic items. Similarly, as per famous Moore's law given in 1960 that suggests the transistor count contained in an integrated circuit will continue its growth in the future. Concurrently, with growing market demand, contemporary electronic gadgets are becoming smaller, thinner, and lighter. As a consequence, these situations present significant challenges to temperature control systems in order to keep activities within secure limits for electronic devices. Therefore, electronic devices thermal control problems have become increasingly essential in recent times.

The heat production is growing in line with constant development of integrated circuit manufacturing process. Consequently, IC market needs better heat control solutions that continuously improve thermal efficiency of electronic devices. The conventional air cooling system can handle heat absorption problems for some general electronics devices by improving heat sink design but other cutting-edge thermal efficient electronic devices are required in high power applications. Thermal management approaches are classified as active or inactive cooling techniques. The primary distinction between them is that a passive cooling system is usually dependent on natural airflow, whereas active cooling system requires additional energy. Further, thermal management methods are also categorized as having direct or indirect interaction with cooling fluid.

In direct cooling techniques, natural air cooling, which is a cost-effective and practical technique, is the simplest way to accomplish electronic temperature management. However, the air-cooled heat sinks to be implemented in electronic devices depends upon angle of air flow. The literature suggests that air flow with angle 90° has better results as compared to 15° [2]. However, the natural air flow is limited to low power electronic devices and for high power applications forced airflow-based electronic cooling will be required. In addition, liquid cooling has gained popularity due to its superior heat absorption to traditional air cooling. Spray cooling is one of them that has received significant importance in research. Spray cooling atomizes

drops via high-pressure compressors and nozzles and encompasses an electronic device's complete hot surface (insulating surface). Spray cooling seems to have the benefit of a large chilling surface, strong heat transmission capacity, and superior thermal consistency. Spray cooling does, however, have some drawbacks, such as high-pressure working circumstances and nozzle blockage during actual operation. There is still a dearth of knowledge regarding the heat transmission mechanisms underlying mist or film nucleate boiling. Further, one of the efficient cooling techniques with a low thermal resistance, jet impingement cooling is used regularly as thermal management option for power computing equipment and industry. Spray cooling is analogous to jet impingement cooling, but spray cooling involves particle atomization. Nonetheless, fluid transfer and thermal transmission process remain extremely complicated. However, there are some problems with jet impact cooling that must be addressed. The fact that surface temperature fluctuation owing to heat transfer coefficient substantially reduces further from the stagnation zone is a clear drawback of single-phase jet impingement cooling. Under certain circumstances, flow blockage between closely separated numerous nozzles also have an effect on cooling efficiency. In addition, Immersion cooling is considered to be among the most efficient temperature control techniques. It cools electronic devices by submerging them in a dielectric fluid or liquid with excellent temperature transmission but very weak electric conductivity. Immersion cooling is commonly used to cool things like network infrastructure and servers. Immersion cooling can effectively control heat flowing from electronic components, However, it suffers from some drawbacks that must be addressed. Like, fluff floating in coolant may be absorbed on heat exchange surface, reducing cooling effectiveness. Moreover, another method, Droplet electro-wetting is one of the most efficient techniques for controlling droplet wetting, has established lot of attention in research and commercial sectors. Gabriel Lippmann suggested the electro-wetting phenomenon as a cornerstone in 1875. The Young-Lippmann equation explained relationship between electric field impact and droplet contact angle.

$$\cos\theta = \cos\theta_{eq} + CV^2/2\gamma$$

where equilibrium contact angle is represented by θ_{eq} with exterior voltage is zero, capacitance per unit area is presented by C , direct current electro-wetting voltage is given by V , and V_{eff}^2 is effective voltage for alternating current (AC) electro-wetting. Despite the fact that droplet electro-wetting cooling technique is new and useful, it still confronts numerous challenges in terms of increasing cooling capacity and different application range. For instance, rate of droplet transport might be increased to overcome cooling capacity restriction of high-power electronic devices.

The indirect contact cooling method, in which the cooling material distributes heat coupled with exterior heat sink framework. It is worth noting that air space between the electronic device and heat sink surfaces, as shown in Fig. 2a, has a major effect on heat clearance process. Therefore, thermal interface materials (TIMs), as shown in Fig. 2b, are efficient mediums for filling space between surfaces and improving heat transmission. Several methods for increasing heat transmission of TIMs have

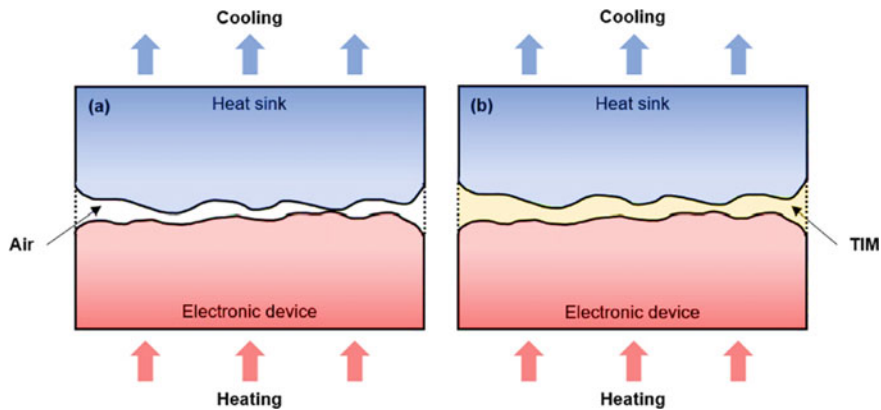


Fig. 2 a Contact thermal resistance schematic diagram [3] b thermal interface material use. Reproduced through open access, 2021 MDPI

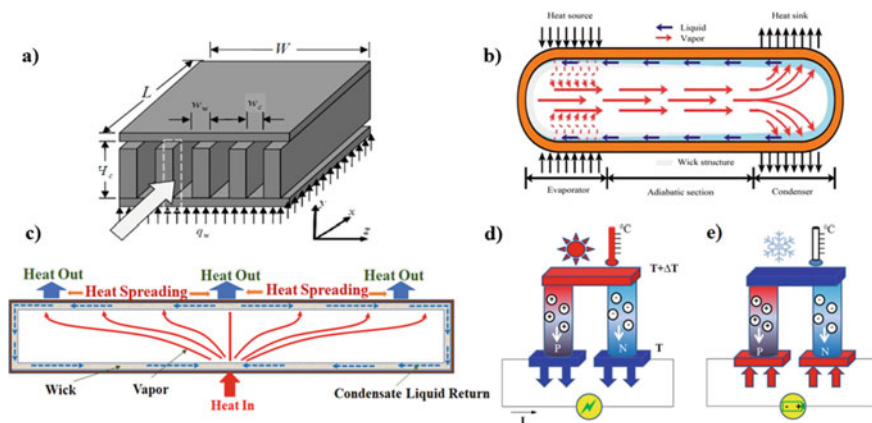


Fig. 3 Schematic diagrams a micro-channel cooling [4]. Reproduced through open access, 2018 MDPI b Heat pipe cooling [5]. Reproduced through open access, 2015 Scientific research publishing c Vapour chamber cooling [6]. Reproduced through open access, 2022 MDPI. d Thermoelectric Seebeck effect [7]. e Thermoelectric Peltier effect [7]. Reproduced through open access, 2018 Elsevier

been suggested in recent times, including the use of nanoparticles, carbon nanotube arrays (CNTs), and others.

Researchers' interest in micro-channel cooling in indirect cooling and the factors that might have an impact on its effectiveness has grown over time. Micro-channel heat sinks (MCHS) are advanced devices that are frequently used as passive cooling techniques as shown in Fig. 3a, particularly for cooling electronics devices. Due to constant development of thermal boundary layer, heated fluid collects at the channel wall and colder fluid builds along the channel center in traditional straight MCHS.

However, number of shapes for micro-channel heat sinks have been developed such as rectangular, square, trapezoid, and others. Researchers have put a lot of effort into improving basic standard MCHS's temperature performance by varying channel length, channel aspect ratio, wall thickness, and even micro-channel cross-section geometry. Further, by adding flow disruption methods such as reentrant grooves, porous medium, ribs, dimpled surfaces, and so on, the thermal boundary layer formation in micro-channel heat sinks can be disturbed. These methods disrupt the growth of boundary layers, resulting in improved mingling of flow at the leading edge and increased heat transmission. Micro-channel cooling has been demonstrated to be an extremely efficient temperature control technique for high-power electronic equipment. Every year, a significant amount of study is conducted on micro-channel cooling. Although the optimal form of micro-channel has been extensively researched but the manufactured micro-channel is still disadvantaged by machining accuracy, production expenses, and process. Micro-channel manufacturing techniques should also be improved. It is necessary to explore all of the critical elements of micro-channel heat sinks, including material, dimension, flow channel configuration, and micro-scale placement. Another indirect cooling contact method is Heat Pipe (HP)-based cooling as shown in Fig. 3b, HPs differ from other types of heat transfer devices by having a long working life, the capacity to rapidly transmit significant quantities of heat even between tiny temperature differences, and the lack of a power source. Additionally, they are progressively used in the heat management techniques of electronic devices, which are continuously getting smaller and denser, as they can transport heat away from heat sources that are situated in places where it is difficult for them to disperse. There is no question that the heat pipe is an efficient temperature control technique. But there are also some problems with thermal management that must be resolved. The wicking structure must first discover more efficient design techniques and production processes, such as hydrophilic surface preparation and multi-scale construction, to enhance capillary and heat transfer efficiency. Additionally, tendency toward folding and flexible electronic devices offers a broad variety of application possibilities for the ultra-thin heat pipe (UTHP). Therefore, the UTHP design must continuously increase structural stability and maintain the proper equilibrium between mobility and improved heat transmission. Consideration should be given to the difficulties in material choice, structural design, and general design principles. The shell material, quality of the wick, and shell combined have a major impact on the functionality and durability of heat pipes, so there are plenty of possibilities for material and packing technology improvement for Heat Pipe technology of electronic devices. Besides, electronic device thermal management has utilized Vapour chambers as a framework for heat dispersal. The Vapour chamber's benefits include favorable temperature consistency, making it ideal for devices with high heat flow, big surfaces, and high dependability. As per working as shown in Fig. 3c, Vapour chamber is typically enclosed space, with lower half of steam chamber is in close contact with heat source. Besides, working fluid is heated to allow it to evaporate and migrate to upper-side condensing surface, where it is re-condensed. Lastly, the operating liquid is taken by the wick substance and capillary force distributes it to the heat source. The heat disposal procedure of the electronic device is achieved by

performing this process regularly. As Vapour chamber and Heat pipes working are based on principles of two-phase flow and heat transfer flow mechanism of working fluid, the primary difference cannot be determined by their usage.

Heat pipe working mechanism follows the transmission of heat from hot source to cold source in straight or in one dimension flow. However, in case of Vapour chamber working mechanism it is often employed to create two-dimensional heat dispersal to outside heat sink to environment.

Further in indirect cooling of electronic devices, thermoelectric materials can transform thermal energy into electrical energy by employing temperature difference (heat transfer), which is referred to as thermoelectric cooling system. This technology was founded by Thomas Johann Seebeck in the year of 1921 and is known as seebeck effect of TE cooling as shown in Fig. 3d. Then, using Peltier effects that Jean Charles Athanase Peltier found in the year 1834. Peltier effect states that when an electrical current drifts between two connecting points, temperature differential is created as shown in Fig. 3e. The smooth plate at the thermoelectric device's cold side will receive heat while the hot side will produce heat. Benefits of the TE module cooling include zero pollution emissions, zero noise, high dependability, and gravity-unaffected heat transmission performance. Consequently, the TE module is frequently used for electrical devices thermal control. One of the efficient cooling techniques is known as TE cooling, which is considered as potential thermal management solution for electronic devices. Currently, finding novel, cheap materials with greater ZT remains the primary task in enhancing the efficacy of TE materials. Additionally, optimizing the efficiency TE modules depends on TE cooling system's optimal design, so it is important to conduct study based on various electronic device types.

Thermal management of electronic devices is founded on active and passive cooling system. Active cooling system is referred as mechanically driven system and requires extra power such as spray cooling, fan-assisted cooling, and others. Active cooling can guarantee a high capacity for heat clearance and a respectable level of control over the working environment. However, problems like increased maintenance, noise, and vibration could happen. Conversely, heat is expelled from electronic devices in passive cooling system without the aid of any exterior component. In passive cooling system, owing to their high latent heat of fusion, minimal flammability, and safety, phase change materials (PCM) and Nano-enhanced phase change materials (NePCMs) garnered lot of attention from researchers for its implementation in electronic cooling system.

2 Nano-enhanced Phase Change Material (PCM)-Based Cooling of Electronic Devices

Phase-Change Materials have drawn lot of attention from researchers and scientists due to their ability to raise thermal capacitance of the cooling system and consequently improve control of operational thermal response of electronic devices. Typically, PCMs operate by taking advantage of the material's latent heat of fusion, which causes phase-state shifts during charging and releasing procedure. The phase-change mechanism is isothermal process, which helps to lower the highest temperature. Particularly when working at high power levels, when their large thermal capacitance reduces temperature increase. Regardless of this encouraging foundation, further study is still needed to address a number of difficulties and restrictions in application of PCMs for thermal control of electronic components, such as poor thermal conductivity.

2.1 Brief Overview of PCM

Phase change materials (PCM) are a class of substances that shift from a solid to a liquid state when charged or discharged, enabling the utilization of substance's latent heat. PCMs are appealing for thermal management of electronic devices due to the possibility of using the isothermal phase shift to lessen interior temperature spikes and to control the transient temperature increase.

In common, a heat charging and discharging process in a PCM between the initial and final temperatures (T_i and T_f) can be described as shown in Eq. (1), where Q_{PCM} is total thermal energy stored or released, m denotes mass of the storage medium, a_m represents fraction melted, c_p is specific heat (kJ/kg K), Δh_m denotes heat of fusion per unit of mass (kJ/kg), and T_m represents melting temperature.

$$Q_{PCM} = \int_{T_i}^{T_m} m_{cp} dT + m_{am} \Delta a_{hm} + \int_{T_m}^{T_f} m_{cp} dT \quad (1)$$

Figure 4 illustrates how PCMs are typically broken down into three categories: organic compounds, inorganic compounds, and eutectic combinations with their advantages and disadvantages.

The working temperature range of organic substances including paraffin waxes, fatty acids, alcohols, and glycols is between 16 and 70 °C, and their energy store capacity is between 120 and 210 kJ/kg. They are typically safe, reusable, and non-corrosive. The major drawbacks of organic PCM are exemplified by their poor thermal conductivity, risk of flammability, growing thermal instability, and mild toxicity. Furthermore, the phase shift mechanism causes a significant volume change in paraffin-based PCMs.

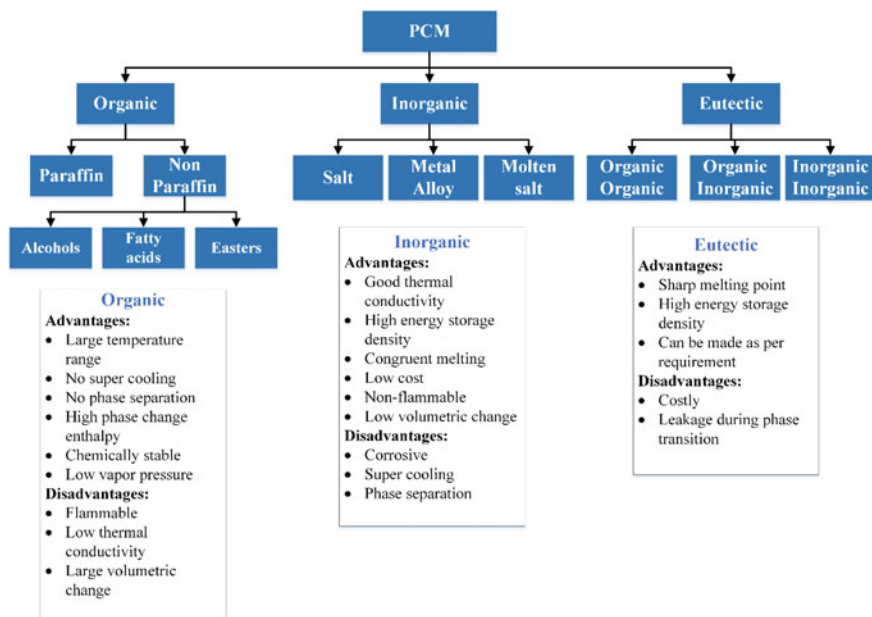


Fig. 4 PCM classifications with their advantages and disadvantages

Salt hydrates are standard PCM inorganic compounds with formula $AB \cdot nH_2O$, where the hydration and evaporation of the salt affect phase change process. The salt hydrates exhibit little volume change during the phase change and have high thermal conductivity, low corrosivity, and high volumetric latent heat capacity (if combined with polymers). However, the hydration process might not be consistent, leading to the buildup of solid residuals, temperature variations, and component-specific changes in properties. For instance, most popular salt for thermal storage, $Na_2SO_4 \cdot H_2O$, operates between 25 and 35 °C and has latent heat capacity close to 250 kJ/kg. Depending on the specific application, eutectic PCMs are typically developed to lower melting temperature and to improve thermo-physical properties of resulting compound. Eutectic PCM can include multiple combinations organic and inorganic PCMs. Despite of advantages of PCM technology for electronic devices, their inherently low thermal conductivity still remains a main obstacle in the way of implementing it in practical applications. The preferable approach to improve thermal conductivity of PCM is to add remarkably conductive nanoparticles to it, resulting material is named as Nano-enhanced phase change material (NePCM).

2.2 Brief Overview of Nanoparticles

Materials with a dimension of 1–100 nm are referred to as nanoparticles. Research into the molecular, thermal, and physical characteristics of materials that are smaller than one billionth of a meter, as well as their potential applications, is done by the field of science known as nanotechnology. The problem of low thermal conductivity can be resolved by thermal conductivity enhancers including extremely conductive micron- to mesoscale particles, fibers, and foams. Over the past several years, the science of nanotechnology has rapidly progressed and promoted the use of nanoparticles, often in the nanoscale length range in different uses. Recently, PCM became a feasible method due to the incorporation of nanomaterials, which improved its utility in energy storage devices. Nano-enhanced PCMs are also used for phase change material-based thermal control for electronic devices owing to their elevated physical and chemical characteristics, significant surface area, high aspect ratio, and potent thermal transmission.

The nanoparticles are classified as per their dimensions; 0D, 1D, 2D, and 3D as shown in Fig. 5. Further, nanoparticles are classified into three groups based on their composition: organic, carbon-based, and inorganic. NPs composed of carbohydrates, proteins, lipids, polymers, or any other organic substances fall under organic class. Carbon class includes NPs that are only composed of carbon atoms, for instance, Graphene, Carbon nanotubes, fullerene, and others. The NPs that are not composed of carbon or organic compounds are included in the inorganic class. Examples of this type that are frequently used are metal, ceramic, and silicon NPs.

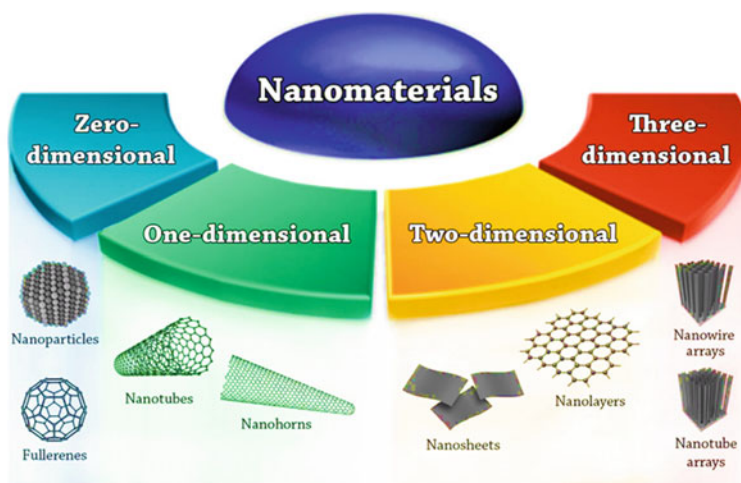


Fig. 5 Classification of nanomaterials based on dimension [8]. Reproduced through open access, 2022 Journal of Nanobiotechnology

2.3 Favorable Characteristics of NePCM for Thermal Management of Electronic Devices

NePCM must have the following qualities in order to be utilized effectively in thermal management of electronic devices.

(a) Physical Characteristics

- (i) High thermal conductivity: When storing or retrieving energy, higher thermal conductivity results in a greater heat flow rate.
- (ii) High latent heat: The amount of energy needed to fully transform 1 kg of solid matter into a liquid is referred to as latent heat. Higher latent heat implies greater energy storage per unit mass of PCM.
- (iii) Appropriate phase change temperature: To ensure adequate heat storage and extraction, the phase change temperature should be compatible with the application.
- (iv) Thermal reliability: The NePCM-based composite should have thermal cyclic reliability after being subjected to multiple cycles composite properties should remain stable.
- (v) Free from leakage: The prepared NePCM should possess form stable shape and don't leak during melting process.
- (vi) Minimal volume change: This reduces the weight needs of the NePCM storage container.

(b) Chemical Characteristics

- (i) Minimal vapor pressure: This will lower the PCM storage container's mechanical stability needs.
- (ii) Non-toxic and non-flammable: To expand its widest possible use for environmental and safety concerns, the NePCM should have non-toxic and non-flammable characteristics.
- (iii) Non electrical conductive: NePCM should exhibit insulating nature as electronic devices involve electrical current. The conductive nature of NePCM may cause short circuit in the electronic circuit.

(c) Economic Characteristics

- (i) Low price: to compete with already-available thermal technologies for electronic devices the price of NePCM should be as minimum as possible.
- (ii) Ease of availability: The NePCM material should be easily available to implement it in electronic thermal management.

3 NePCM-Based Thermal Management Technologies for Electronic Devices

To regulate the thermal control mechanism of various electronic devices, several thermal management techniques had been adopted in past decades, depending upon their working and depending upon the type of electronic device. The use of nanoparticles to improve PCMs' heat conductivity is widespread. In the meantime, it was also discovered that PCMs' latent heat could be changed. The variation in PCMs' latent heat in the presence of nanoparticles does not follow a particular pattern. According to certain researchers, nanoparticles had both positive and negative impacts on latent heat of fusion. The majority of previous research literature suggested a decrement in the amount of latent heat with the inclusion of NPs in PCM. This decrement in latent heat storage may be attributed to the amount of volume reduction in PCM due to the addition of NPs. Other researchers noticed that when the amount of nanoparticles was quite small, the latent heat of PCMs rose while it decreased when NPs amount was gradually increased. This variation in latent heat is attributed by two prime factors; one is the intermolecular between PCM and nanoparticles and the filling of nanoparticles. However, a balanced approach needs to be taken between thermal conductivity and latent heat while preparing nano-enhanced phase change material.

3.1 NePCM-Based Heat Absorbers for Electronic Cooling

The proper working of all applications requires the cooling of electronic devices. Heat removal from these systems has typically been accomplished through heat conduction/convection methods. NePCMs technology is a novel idea for cooling electronic devices. A NePCM absorbs high energy during the charging cycle and then discharges the same amount of heat to the environment. The heat of fusion basically measures how much energy is required to transform a NePCM from a solid to a liquid. NePCM materials often have high temperatures of fusion, which allows little amounts of material to absorb/store significant quantities of energy during phase transition. The introduction of NePCM technology in thermal management of electronic devices can replace completely active or assisted cooling methods for thermal control of electronic devices operating at anticipated levels. For better thermal control melting point of a NePCM is chosen so that energy from electronic devices is received while it goes through a phase shift or melts, and it can then be solidified (charged) once the ambient temperature falls below its melting point. NePCM is stored inside or connected to an enclosure in properly constructed and sealed reservoirs. During the day, an external enclosure with NePCMs will transfer heat through the cabinet sides and prevent the enclosure of electronic devices from overheating. The heat collected by NePCM throughout the day will be discharged to outside when it turns colder at night.

Yousefi et al. [9] simulated numerically to examine the effect of different enclosure materials; Aluminium (Al), Copper (Cu), and Acrylic (Acr) material on the thermal performance of lithium-ion battery using CuO NPs and n-eicosane PCM. Numerical results indicated that using Cu enclosure in BTMS retains battery surface temperature low with a minor delay in melting temperature of NePCM. Furthermore, when pure n-eicosane is combined with CuO nanoparticles and the volume percent of nanoparticles rises, the battery surface temperature and melting time of NePCMs fall and increase, respectively. BTMS with Cu enclosure and 4% NePCM (CuO and n-eicosane) are able to be an ideal solution for maintaining a low battery temperature while completely discharging at a 3 C current rate in 20 min as shown in Fig. 6a at 300 K b at 305 K. Similarly, Arshad et al. [10] numerically investigated impacts of numerous NePCM composites for passive cooling of electronic devices. Authors introduced Copper NPs with different mass fractions such as 5, 3, and 1 wt%, in addition, different types of foams like Nickel, Copper, and Aluminium foams were also included with heat sinks. Results exhibited that, heat transfer rate showed an 8.12% increment with a decrement in melting time by 18.10% with 1 wt% addition of copper NPs. Further, NPs and metal foam-based PCM compo lowered the heat sink base temperature, while enhancement of NPs volume fraction exhibited reduction in latent heat of PCM.

Ahmed et al. [11] tested the thermal performance of tablet PC using aluminized laminate film-encapsulated PCM with two-millimeter thickness. Thermal performance of tablet PC with bigger and smaller PCM package at different angles (90°, 45°, and 0°) were sustained with a varying power supply from 2 to 6 W. For instance, using PCM package with a small volume at constant operation of 2 W caused the temperature of the rear cover to drop by 8 °C even though PCM was not fully melted. The large PCM package didn't have much of an impact on the tablet PC's transient thermal response, though. The temperature of the tablet PC could not be controlled by either the larger or smaller PCM package below 85 °C at a time.

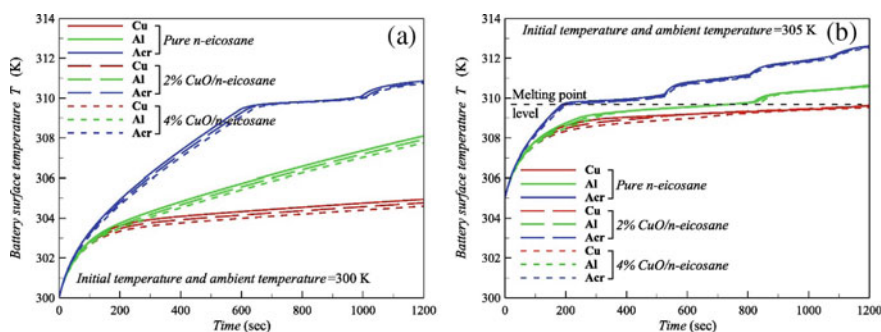


Fig. 6 Battery surface temperature for Cu enclosure with Paraffin and CuO nanoparticles at **a** 300 K **b** 305 K [9]. Adapted with permission. Copyright 2022, Elsevier

3.2 *NePCM-Based Heat Sinks for Electronic Cooling*

Conventional heat sinks used to cool devices are actually heat exchange rather than genuine heat sinks. They take in extra heat and then move it to another medium, like air or a liquid coolant. In cases where there is a dearth of heat transmission media, phase change material (PCM) heat sinks serve as real heat sinks. In the process of phase transition from a solid to a liquid form, they take in extra heat and retain it. They have a high latent heat capacity, which refers to the energy taken by a material during change in phase without increasing the substance's temperature generally. PCM are excellent at absorbing significant amounts of heat without raising the temperature, which makes them ideal for cooling of electronic devices. Besides, reliability and extended service life are thus assured by remarkable temperature regulation capabilities of NePCM packages with thickness of 1–3 mm on heat-generating sections in portable electronic devices that keep endurable temperature below 85 and 45 °C for chip and for back cover, respectively. In order to prevent burning of electronic devices like tablet PCs, laptops, and desktops, NePCM, and heat sink combinations are also a popular and affordable solution. Typically, the NePCM would be combined with other types of heat sinks, such as pin-fin, to best utilize its features and achieve superior thermal management performance rather than being used straight for the integrated circuit or packing. Pin-fin heat sink is a highly adaptable type of heat sink used when PCM is combined with other types of heat sinks to optimize its benefits. Using PCM, frequently observed pin-fin and its derivative shapes are displayed in Fig. 7a–h. Numerous researchers are working on studies to discover straightforward fixes for improving the general thermal outputs of conventional heat sinks. The link between finned surfaces and PCMs is a fascinating possibility. The goal is to develop a hybrid device that can maximize both the high thermal transmission of conventional fins and the high thermal capacity of PCMs, which are typically made of Copper or Aluminum. Phase change material can be used to enhance the heat sink's efficiency. This device is appropriate in situations where heat loads penetrate the system intermittently. In a variety of circumstances, PCM is used as a temperature control. A passive process with three stages is present in PCM-based cooling systems. The temperature of the solid material is raised to its melting point in the first stage by heat absorption through electronic devices. The second stage involves PCM beginning to melt at a steady temperature while heat is received without causing temperature to increase. The PCM is fully dissolved in the third stage, and the fluid's temperature rises as the heat input is continued. Despite the fact that the PCM can absorb a lot of heat during the phase shift, cooling by these materials may take some time before melting is complete. In circumstances where heat intake is changing, it is preferable to use nano-enhanced phase change material.

Electronic devices can be cooled using a heat sink with interior fins and PCM system. However, one drawback of this technology is its poor thermal conductivity, which can be enhanced by adding high thermal conductivity nanoparticles. As per literature various nano-enhanced PCM-based heat sinks had been adopted as in the study single wall carbon nanotube (SWCNT) was adopted with Paraffin for thermal

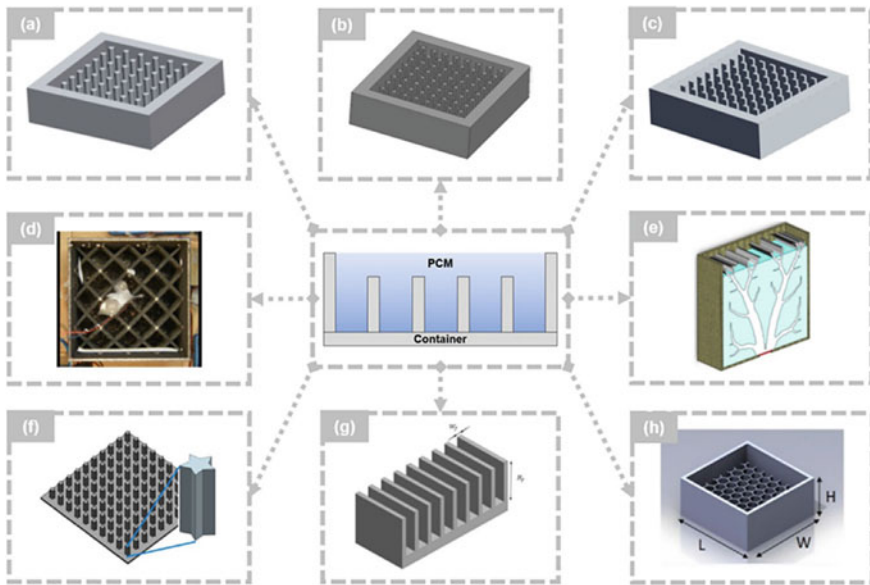


Fig. 7 Pin-fins structures for NePCM [3] **a** Circular pin-fins **b** Triangular pin-fins **c** Rectangular pin-fins **d** Pyramidal structure **e** Tree-structured **f** Star pin-fins **g** Plate type **h** Honeycomb structured. Reproduced through open access, 2021 Elsevier

management of heater [12]. The outcomes showed how crucial it is to use CNTs with Paraffin wax PCM as additive and as a TIM in order to enhance thermal efficacy of thermal control unit for resistance against intermittent heat loads in electronic devices. In other studies, different types of Heat Sinks (HS) were evaluated with copper oxide (CuO)-based NePCM. Further, Heat sink with distinct pin structures like rectangular pin fins, square pin fins, and circular pin fins were examined with plate heater. As per analysis, comparatively to other HS configurations, HS with square pin fins (HSSPF) involving PCM/NePCM shows superior thermal performance. For HSSPF using PCM and NePCM, highest temperature reduction is found to be 13 and 15 °C, respectively [13]. Similarly, comparative analysis of CuO and Aluminium oxide (Al_2O_3) nanoparticle-based NePCM using Paraffin wax for rectangular shaped heat sink made of Aluminium. The base has diameter of 4 mm with Fin thickness and height of 2 and 40 mm. Heat penetrates heat sink from bottom via a rectangle $50 \times 50 \text{ mm}^2$ surface and is transmitted through PCM via the base and fins. In the process, PCM melts by taking heat, preventing heat sink temperature from rising above allowable limit. The capacity of the PCM rises when it is melted, but not all of the area in the fins is occupied with this substance. The PCM's excess area is supplied with air. The limit of PCM will be displaced by air as it melts and expands in volume. Nanoparticles are introduced to PCM to improve heat absorber efficiency. The findings indicate that by introducing minor amount of nanoparticles (2%), heat sink efficiency can be

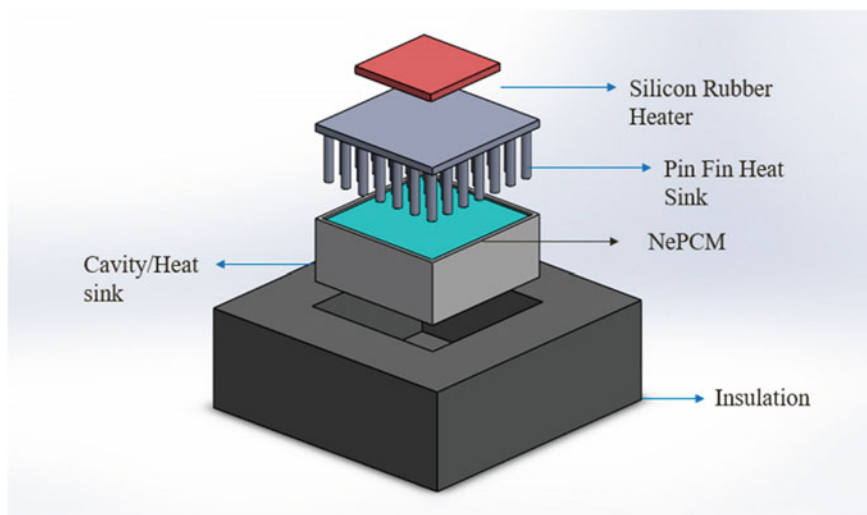
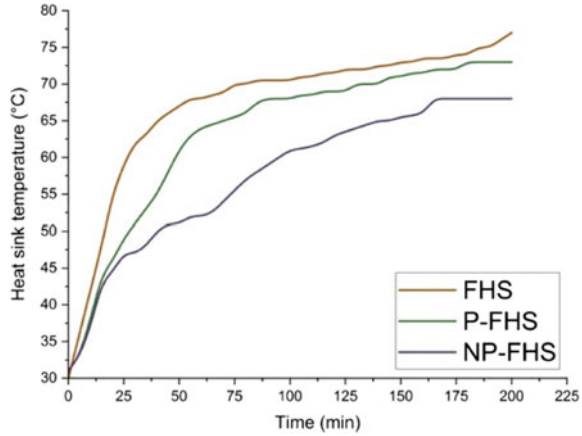


Fig. 8 NePCM-based heat sink assembly diagram [15]. Reproduced through open access, 2022 MDPI

enhanced until PCM is completely melted. Besides, raising the proportion of nanoparticles decreases heat sink efficiency. Furthermore, 2% aluminum oxide nanoparticles are added, heat sink performs better in comparison to same proportion copper oxide is added. Despite copper oxide's greater thermal conductivity, heat transmission can be decreased due to its high viscosity [14]. Further, NePCM based on multiwall carbon nanotube (MWCNT) nanoparticles of 3% weight percentage (wt%) and 6% wt% with Paraffin RT42 was prepared by utilizing two-step method for heat sink. Figure 8 shows schematic arrangement of heat sink with NePCM. As per analysis, circular fin-based heat sink with decreased base temperature by 25.83% by adding 6 wt% of MWCNT. The results demonstrate that a circular pin fin with NePCM is effective in lowering base temperature [15].

Naik et al. [16] recently investigated the influence of nano-titania nanoparticle addition on efficacy of heat reduction of PCM-based HS embedded in computer processors. Three different combinations were tried. The first combination includes plate fin HS without PCM (FHS). The HS along with PCM was the second configuration (P-FHS). The third structure added HS with a PCM combined with nanoparticles (NP-FHS). According to outcomes, addition of 0.5 wt% nano-titania nanoparticle to pure PCM increases paraffin thermal conductivity by 31%. Furthermore, at 2.5 kW/m², PCM and NePCM with finned-HS could decrease HS temperature by 3.5 and 6 °C, respectively, compared to the first scheme as shown in Fig. 9. Furthermore, at 4.5 kW/m², the NePCM-based HS increased melting time to achieve pre-set temperature by 14 min. As a result, NePCM-based finned HS demonstrated efficient cooling efficiency.

Fig. 9 Heat sink's temperature at 2.5 kW/m². Adapted with permission [16]. Copyright 2022, Elsevier



(a) Volume of PCM and Nanomaterials for NePCM-Based Heat Sinks

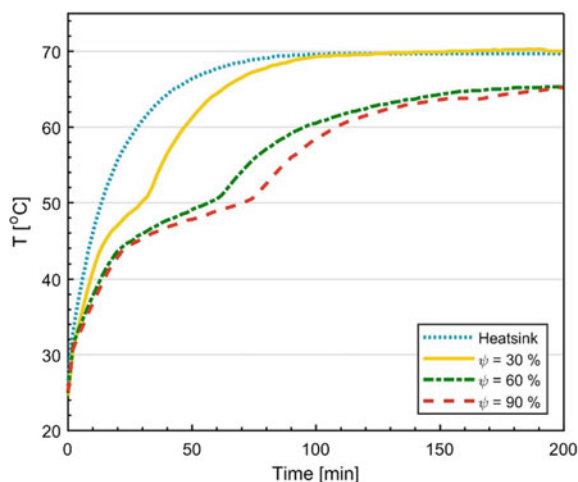
The PCM volume to heat sink's usable area ratio is known as the PCM volume fraction. As per equation, it can be written as

$$\varphi = \frac{V_{PCM}}{V_{\text{total available space}}}$$

A study [17] examined the different wt% (30–90%) of PCM for chip cooling. It can be seen that the volume percentage of PCM affects how long it takes for chip to achieve a steady temperature. When natural convection occurs, the impact of PCM on temperature fall becomes more evident with a rise in heat flux and volume fraction as shown in Fig. 10. The chip will still take longer to achieve a stable temperature under forced convection when the heat flow is low, but the stable temperature has an upward tendency.

This is because temperature does not rise to PCM's melting point when heat flow is low. Thus, heat conduction is the sole means of heat movement for PCM. The PCM utilized in the investigation is Paraffin having poor thermal conductivity. As a result, forced convection of heat sink fins becomes weaker as volume percentage of PCM rises. In particular, PCM is better suited for situations with significant heat flow, so it's crucial to increase PCM's thermal conductivity. Similarly, for nanomaterials, according to literature, 90% of the volume of PCM is typically chosen, and the remaining 10% of the volume is set apart because PCM expands slightly in conversion from its solid to liquid phase. The melting temperature and the latent heat of phase transition of paraffin-graphene nanocomposite dropped with rise in mass fraction of nanoparticles, according to measurements made by Mathew et al. [18] using a Differential Scanning Calorimeter (DSC). When graphene comprises up to 0.5% of the total volume of composite PCM, latent heat is decreased up to 12.35%. The study findings for thermal conductivity and thermal diffusivity of composite materials are

Fig. 10 Temperature–time response of chipset without forced convection of PCM at different loadings at 2000 W/m² Power [17]. Adapted with permission. Copyright 2029, Elsevier



displayed in Fig. 11a, b. It is obvious that both rise as mass percentage of nanoparticles rises. As can be seen in Fig. 11c, experimental findings, however, vary marginally from the Maxwell Equation model [18].

When the mass percentage of graphene is less than 0.4%, increase in thermal conductivity of composite material was more than expected by Maxwell model. The increase in thermal conductivity of composite material is smaller than that anticipated by Maxwell model when mass percentage of graphene is more than 0.5%. This is a result of graphene composite material's two-dimensional structure, and low Kapitza resistances at graphene-paraffin nanocomposite elevated their thermal conductivity. Thermal conductivity is hampered as graphene's mass fraction rises due to settling effect brought on by too many nanoparticles clustering. Then, it is logical to assume that keeping mass percentage of graphene high will mitigate rise in thermal conductivity. The negative growth in phase shift latent heat will also rise concurrently. As a result, the mass proportion of nanoparticles needed to create composite phase is optimum. To obtain optimum thermal efficiency, research is going on to balance thermal conductivity and latent heat for NePCM-based electronic cooling.

Therefore, NePCM-based heat sinks can be implemented in various electronic cooling applications. NePCM heat sink has some general advantages that apply to almost all uses. Firstly, NePCM heat sinks are passive, meaning they don't have any moving components that need maintenance or power to function. Second, they have a prolonged lifespan and require no maintenance. The working temperature can be reduced with a NePCM heat sink, which also increases the mean time between failures (MTBF) for electronic assemblies. This reduces the need for maintenance and expense of replacement for electronic devices. Further, putting fins into a NePCM-based HS reduced mass of PCM while increasing overall weight of the HS, reducing saved energy and adding weight, respectively, due to density of fins. However, from a design standpoint, raising the weight was unavoidable and undesirable for heat

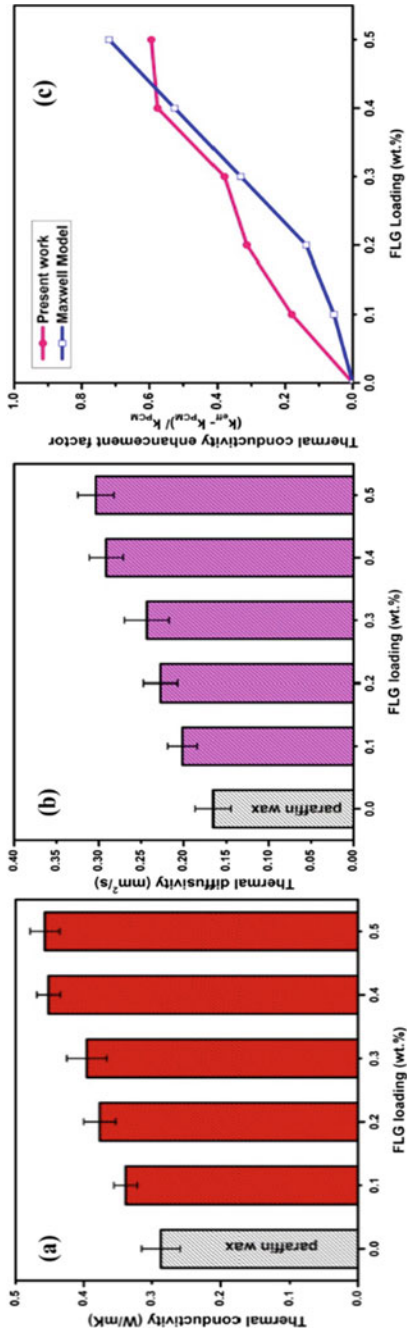


Fig. 11 a Paraffin-graphene-based composite thermal conductivity [18]. b Paraffin-graphene-based composite thermal diffusivity. c Thermal conductivity enhancement comparison to Maxwell model for paraffin-graphene model. Adapted with permission. Copyright 2019, Elsevier

control of electrical components. This issue may be alleviated by using better-performing foams, but their morphology inhibits heat transfer and decreases energy storage owing to their shape. While dispersion of nanoparticles in NePCM-based HSs appears to be better due to their light weight and demonstrated high heat transmission rate contingent on nanoparticles volume fraction utilized. Increasing their abundance, however, may result in deposition and aggregation, as well as increased viscosity, which suppresses natural flow. As a result, the suitable volume percentage of nanoparticles needs to be selected.

3.3 *NePCM-Based Heat Sink with Heat Pipe for Electronic Cooling*

The high heat flow produced by electronic components in modern electronic sectors limits the use of only PCM cooling capabilities to alleviate issue. As a result, a high efficiency heat carrier known as a “heat pipe” (HP) is a potential method that exhibits impressive performance in cooling high-power processors and is frequently utilized in computers, notebooks, and cellphones. Heat pipes can transmit more heat and have more natural flow than other heat transmission mechanisms and provide a thermal solution for passive electronic cooling. HP employs a two-phase change heat transfer method, allowing it to remove extra heat from electronic devices with a small temperature difference without extra power consumption. When incorporated in the PCM, it greatly improves the temperature reduction in electronic devices and dramatically increases the working life of device. The PCM-based HP configuration is shown in Fig. 12, the PCM can be placed at evaporator and condenser section of HP.

When compared to conduction-related configurations, the effectiveness of the NePCM heat pipe arrangement is extremely high and offers satisfactory thermal efficiency. Heat pipelines are extensively used in energy management and heat disposal uses due to their ability to transmit high heat over a narrow temperature range. Heat

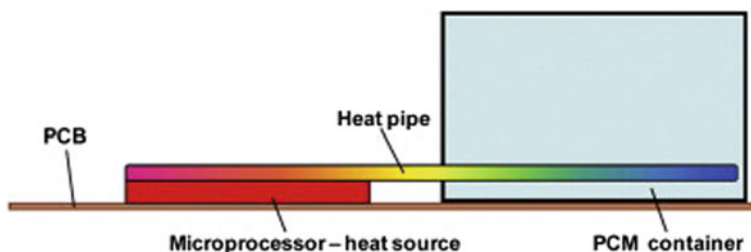


Fig. 12 Heat pipe assisted PCM heat sink for electronic devices cooling [19]. Adapted with permission. Copyright 2012, Elsevier

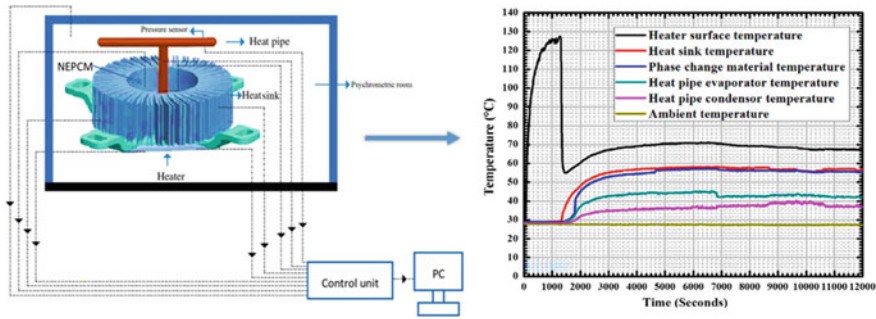


Fig. 13 Schematic diagram and transient temperature response for NePCM with heat pipe for heat sink at 20 W [20]. Adapted with permission. Copyright 2017, Elsevier

is only transmitted from the bottom to the higher portion of the heat pipe due to gravitation. When heat is given to the evaporator region, the refrigerant begins to boil and changes phase to gas before moving to the condenser region at a certain velocity. It loses heat and turns liquid in the condenser region, and the cycle persists due to gravity. Various studies have been done on NePCM-added heat pipes for heat sinks as study [20] focused heaters surface temperature. The NePCM was prepared by utilizing Capric acid PCM and CuO nanoparticles of 0.8 wt%. The test for thermal management for heater surface temperature using heat sink aided with heat pipe-based NePCM was observed at 20 W power. The schematic diagram of test setup and surface temperature reduction is shown in Fig. 13. The findings demonstrated that using a heat pipe-assisted NEPCM heat sink resulted in a 3 °C drop in the surface plate temperature of the radiator during the six-hour working time without the use of an electric fan or any other forced air flow.

Yin et al. [21] suggested an innovative passive cooling system comprised of a hybrid PCM and a heat sink based on HP. On evaporation portion of the HP, a cooling fan was fitted. The hybrid PCM was made by putting paraffin into expanded graphite and then placed in the condensation part of the HP. According to findings, under steady state power ranging from 4 to 30 W, the cooling efficacy of the cooling system with composite NePCMs was roughly 1.25–1.30 times greater than that of the cooling system without composite PCMs. Similarly, Krishna [22] examined the heat pipe-PCM cooling module's thermal efficiency. The PCM water and tricosane were applied on the isothermal portion of the cylindrical HP. To create nano-composite PCM, Al_2O_3 nanoparticles in various amounts (0.5, 1, and 2%) were distributed in tricosane. The cooling section saw a 53% decrease in fan power usage. When 1% volume of Al_2O_3 was added, the evaporation temperature was reduced by 25.75%. Different kinds of HPs with varying shapes and designs are used in electronic devices cooling in place of conventional cylinder HPs. Zhao et al. [23] examined the thermal efficiency of an oscillating HP (OHP) with PCM by changing the heating capacity and OHP's angle of tilt. Paraffin, EG/paraffin, ethanol, water, and self-wetting fluids were used as PCMs in the energy storage reservoir situated in the adiabatic portion.

HPs have remarkable thermal conductivities that involve a two-phase shift heat transmission that is over a hundred times greater than copper. A high power burden of in excess of 5 W (natural convection) or even 50 W (air-forced cooling) can be handled and the fan power usage can be greatly reduced by adding a certain quantity of NePCM to the various extremities of HP (such as the vaporization, adiabatic, and condensation portion). While this takes place, the temperature through the HP becomes more consistent.

4 NePCM Applications for Thermal Management Electronic Devices

The cooling of electronic components that are used all over the world is seen as a fundamental issue [24]. Designers and engineers both face significant problems when making electronic devices. They have to find a reliable way to solve problems like getting rid of a lot of heat and making sure the operating temperature doesn't go too high. Nanoparticles have been studied for their unique properties. Researchers have found that significant progress has been made in the cooling of electronics by utilizing hybrid nanoparticles, electronics with rough surfaces, applying phase change material (PCM), employing modified channels, and other effects [25].

4.1 ICs Chips and Boards

It is obvious that non-traditional methods are necessary for successful heat removal from high-power electronic devices and components (chips) with higher heat dissipation ratings when cooling fluid is employed as air. Electronic device performance and longevity are significantly affected by thermal management. Owing to technological progress, the power of these gadgets is rising while their physical footprint is shrinking. In the past, a wide range of strategies have been used with variable degrees of success. Using heat sinks with pin fins or channels is one approach. Micro-channels have been used for efficient heat dissipation in Multi-Chip Modules (MCMs). While designing for laminar circumstances, which leads to smaller pressure drops, heat removal rates for air-cooled micro-channels were significantly increased. High-power dissipation integrated circuits (ICs) and microprocessors have well-known heat-sinking capacities and requirements for stable operation. The majority of an electronics component's useful life, however, is spent in on-off operation because many of them operate in a transient manner. By adding PCM (Phase Change Materials) to traditional heat sinks like longitudinal plate fins and pin fins, one can lower the cooling load required or the convective flow demand for on-off operation. Moreover, PCMs are the best options where chips must be cooled by passive means solely, which requires using natural convection and radiation as the only heat transfer

modes accessible to the designers. PCM-based systems, like passive heat moderators, can incorporate the PCM into the board's structure or the heat sinks cooling the chips (such a reservoir of wax-like materials).

In addition, most chips generate more heat when they are in use than when they are idle. As integrated circuit technology advances, chip sizes continue to shrink even as the number of transistors on each chip grows exponentially, boosting the device's complexity and power density. Chip performance is hindered and its lifespan is shortened because of the correlation between power density and peak temperature. As the technology for creating integrated circuits improves, more and more of these minicomputers will be crammed into one. In other words, the density of devices increases over time. The total thermal power of the Core i7 is designed to be 140 W, and on a 270 mm² area, it aims to integrate over 731 million transistors. A rapid increase in the electronic chip's operating temperature is then to be expected as time progresses. The chip's peak temperature can be reduced by the use of heat management implemented via the PCMs latent heat storage (LHS) method. Thus, unique thermal management using nano phase change materials (NPCM) techniques, is becoming a necessity in the electronic chip industry, as standard positive air-cooling becomes inefficient. The low thermal conductivity of PCMs can be overcome through employment of nanoparticles along with PCM. Particles smaller than 100 nm in size are considered nanoparticles. The development of research has directed to discovery of a wide variety of nanoparticles, including carbon nanotubes (both single- and multi-walled), metal, and many others.

The results of an investigation by Manoj Kumar et al. [26] examined thermal performance of heat sink at different power levels (3,000, 4,500, and 5,000 W/m²) for cooling a chipset. The "simple HS," "PCM with HS," and "HS with NePCM" were used to describe the three configurations used. As per analysis, time it took the heat sink to achieve the reference temperature at a power density of 4000 W/m² was lengthened by the PCM and the NePCM. Further, at the same 5000 W/m² power output, the PCM slowed the heat sink's capacity for reaching the reference temperature by 4 min, while NePCM slowed it by 13 min. The steady-state temperature of heat sink was decreased by 6 °C by adopting NePCM, even at the lower power output of 3000 W/m². Using NePCM, experimental heat sink performed 220% better than with PCM, as measured by the time it took to achieve its reference temperature. An experimental study examines the effects of using nano-enhanced phase-change materials (NePCM) as a coolant for an electronic chipset in both free and forced convection scenarios [27]. The improvement in performance and durability of electronic equipment is primary motivation behind the pursuit of more effective cooling technologies in the field of electronic technology. The cooling systems to thermally manage electronic chipset are tested in six different scenarios, each with a different amount of heat flux. Free and forced convection are considered for the cooling setups, as are the use of a simple heat sink (referred to as HS), a heat sink including a phase change material (referred to as HS/PCM), and a heat sink containing a non-phase change material (referred to as HS/NPCM). In the research, Mn(NO₃)₂ (Salt hydrate PCM) was employed as the PCM, and Fe₃O₄ as nanoparticles (chosen by wt% of 1% in the PCM) were dispersed in the PCM with the help of ultrasonic method.

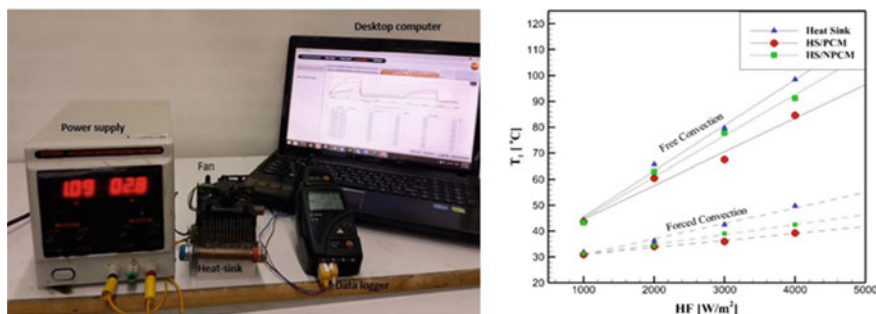


Fig. 14 Experimental setup with steady-state temperature for free and forced convection [27]. Adapted with permission. Copyright 2017, Elsevier

Researchers apply heat fluxes ranging from 4000 to 1000 W/m^2 to electronic chipset to study its steady-state and transient thermal behavior under a range of operational circumstances. As shown by the results, the chipset's steady-state temperature may be lowered by 14 and 10.5 $^{\circ}C$, respectively (Fig. 14).

A innovative approach to thermal management is explored in this work; specifically, use of phase change material (PCM) with addition of multi-walled carbon nanotubes (MWCNTs)/PCM [17]. Power levels across the spectrum are used to analyze a variety of thermal modules, such as pure heat sinks, heat sinks with phase change materials (PCM), and heat sinks with nano-PCM. Under both passive/active conditions, the system's temperature–time response is shown. Based on the findings, utilizing PCM can increase system uptime by as much as 3.34 times compared to a pure heat sink module operating in a free convection environment as shown in Fig. 15. Its utilization period can be lengthened by increasing the PCM volume fraction. Although the chipset's initial operating temperature is lowered by using PCM in a forced convection environment, the steady state temperature may rise. Using nano-PCM can extend the suggested system's lifetime in comparison to a PCM module operating in a free convection environment. Using nano-PCM, however, may not yield optimal results in comparison to PCM while operating in a forced convection environment. Nonetheless, nano-PCM thermal module seems to have benefit of quicker cooling to ambient temperature when compared to PCM, and this advantage may be further improved by using a greater weight fraction of nanoparticles. Moreover, as input power is increased, the effects of PCM and nano-PCM become more obvious.

4.2 Transistors and Laser Diodes

Due to the complexity and compactness of the latest generation of semiconductor and power electronic devices, thermal management of electronics is fetching a significant and crucial subject. When an application or environmental situation exceeds

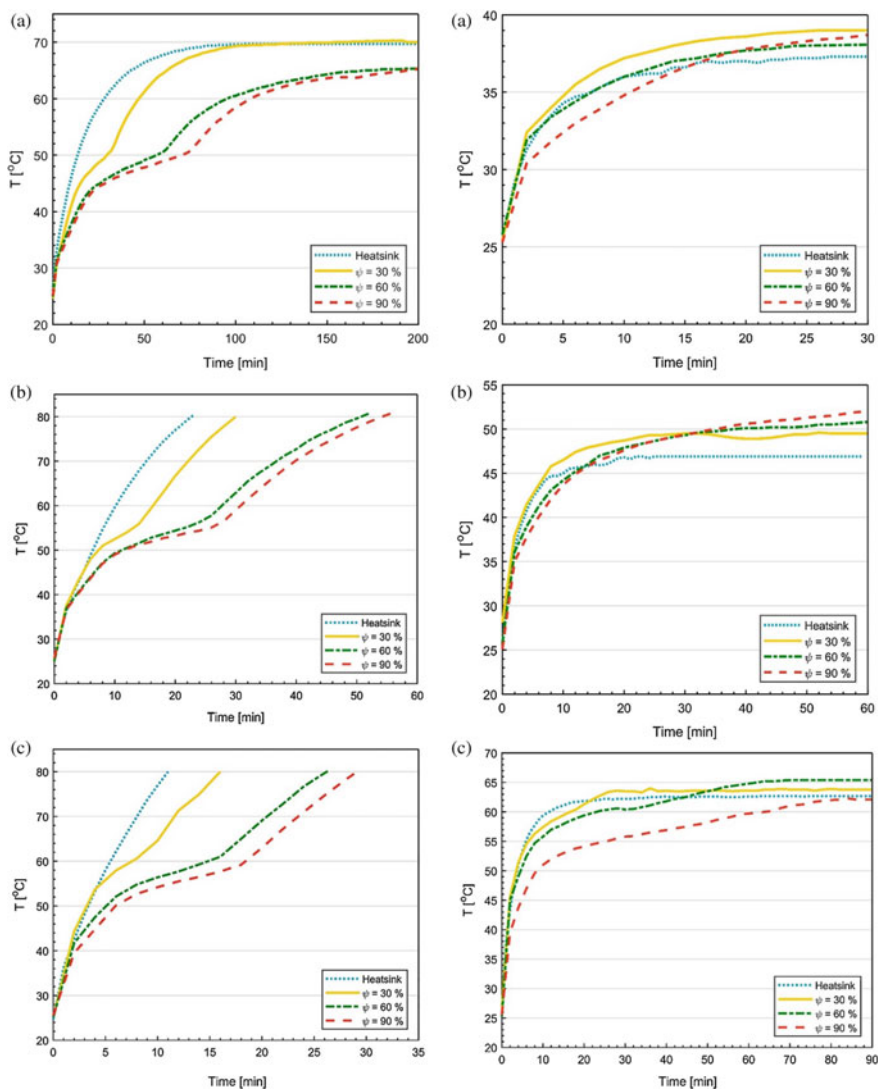


Fig. 15 The time versus temperature curve for chipset with fan in various with and without PCM volume fractions at various power levels **a** 2000 W/m² **b** 4000 W/m² **c** 6000 W/m² without PCM (right side) with PCM (left side) [17]. Adapted with permission. Copyright 2019, Elsevier

the device's application limit, the intended function of the electronic device is not performed. If a transistor, laser diode or any electronic circuitry can run continuously for a significant amount of time at the suggested operating temperature, it is said to be reliable at that temperature. The effective operating period is nonetheless decreased by an unfavorable atmosphere and atypical operation. It has been discovered that a component's failure rate can reduce by up to 4% for every 1 °C

decrease in temperature and can rise by up to 100% for every 10–20 °C increase in temperature. The demand for cutting-edge cooling systems is therefore enormous. The inverter system's thermal management is essential since switching at quite high voltage/current will happen intermittently and/or constantly, and high temperatures are extremely harmful to the useful lifetime of electronic devices, particularly for switching components like diode and bipolar transistor (IGBT). The switching stage's susceptibility to temperature cycling is widely regarded as the most common cause of inverter failure. IGBT modules are essential to the inverter system, but their lifespan is severely constrained by thermal–mechanical fatigue. In study, increasing the percentage of GNPs in paraffin PCMs affects their thermal characteristics [28], including thermal conductivity, shape-stability, and how this might be used for IGBT thermal control. Typically, 9 and 15 wt% of GNPs are used to prepare PCM composite samples. Due to increased specific surface area provided by the GNPs addition, a form stability test reveals that GNPs loading can successfully raise dropping temperature from 55 to 165 °C. Using SEM, morphology and structure of produced samples were characterized. The thermal management of a 15 kW converter (with three IGBT modules) was tested with a heat sink made of composite PCM, and results suggested that heat sink containing paraffin loaded with 15 wt% GNPs had superior heat dissipation performance as shown in Fig. 16. The proposed paraffin/GNPs PCM's excellent shape-stabilizing properties, high heat conductivity, and extraordinarily cheap production cost provide compelling justification for further study. The control of heat within power plants, solar collectors, and electronic devices are only a few examples of potential PCM usage for efficient thermal applications.

Tests and simulations studies are utilized to determine the effectiveness of PCM-integrated fin-type heat sinks in lowering the temperature increase of highly powered electronic devices consisting of two distinct IGBTs having specific hot spots of 400 W. PCM integration requires fin-type heat sinks with large base plates. The fact that thermal performance indicators such as heat sink thermal resistance and hot-spot temperatures may be quantified in terms of the thermal conductivity of the PCM section incorporated in base plate emphasizes the necessity of high embedded PCM thermal conductivity. The findings indicated that thermal resistance measurement for fin-type heat sinks added with PCM are equivalent to standardized fin-type heat sinks available. The study also conducts an experimental assessment of the thermal properties of traditional and PCM-integrated fin-type heat sinks. The study confirmed that PCM-integrated fin-type heat sinks have greater temperatures (3.9 °C) than traditional fin-type heat sinks in standard cooling conditions, NePCM heat sinks showed distinct improvements in their ability to effectively suppress hot-spot temperature upsurge till 80 °C with time delay of up to 27.3% in less-than-ideal cooling conditions, compared to traditional ones, since thermal capacitive effects brought on by high specific heats.

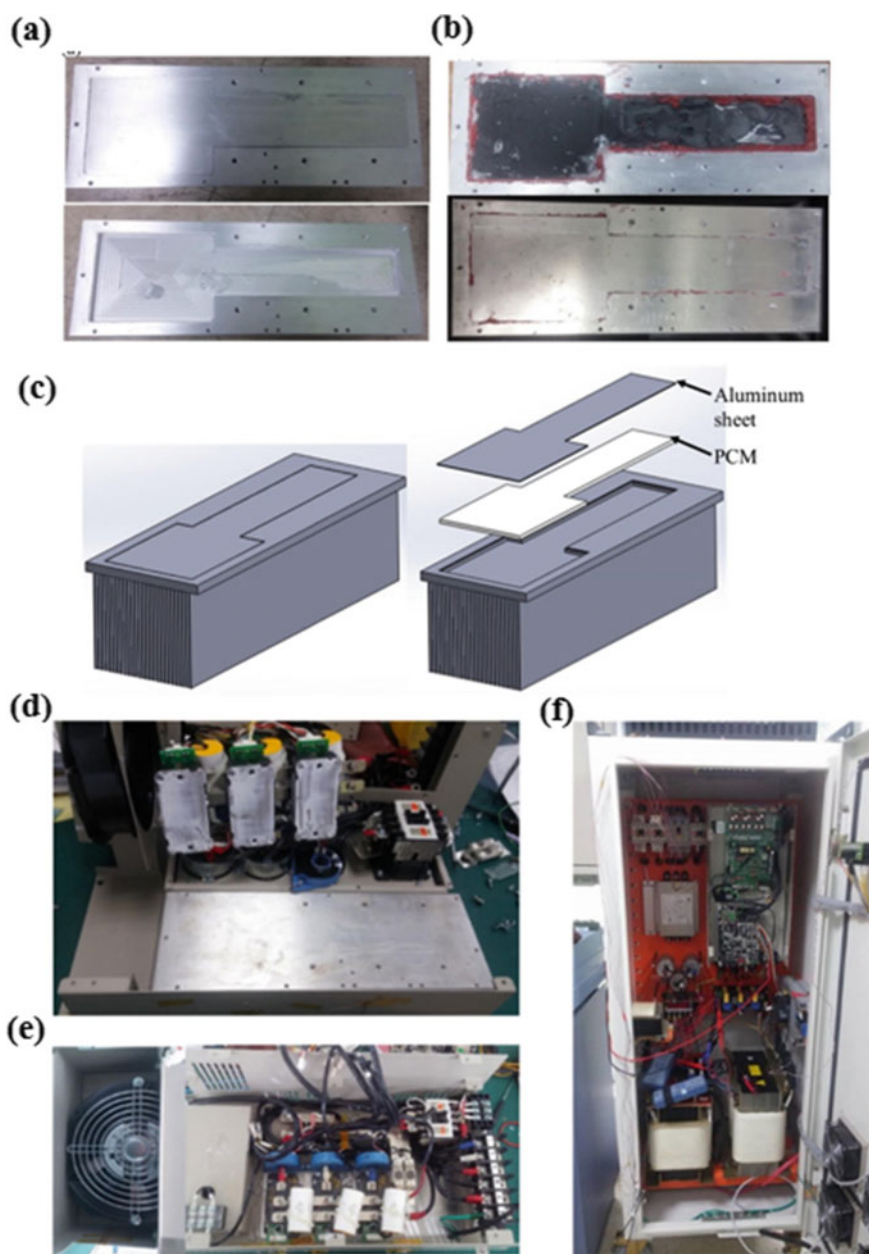


Fig. 16 Cover and straight fin **a** without PCM, **b** and with PCM. **c** Schematic showing the positions of the cover, paraffin wax, and straight fin Schematic of the heat sink **d** without IGBTs and **e** with IGBTs. **f** Schematic of the 15 kW converter [28]. Adapted with permission. Copyright 2017, Elsevier

4.3 Batteries

Temperature is recognized to have a noteworthy impact on a power battery's performance. To operate power battery inside a tolerable temperature range, battery pack needs reliable thermal management system (BTMS) [29]. Phase change material-based battery thermal management systems (BTMs) are passive thermal management technique that have the benefits of cheap running costs and superior temperature uniformity. PCM uses less energy and does not call for any additional parts than the conventional thermal management approach. The battery thermal management system (BTMS) controls terrible impacts on power, safety, efficiency, and lithium-ion battery lifecycle. The use of phase change material (PCM) to store and release energy from a battery is a typical passive technique in BTMS. The BTMS is an essential component of the battery system because its primary function is to maintain uniform and safe battery temperatures [30]. Many cells connected in series, parallel, and combinations make up a battery system. The five main sources of heat generated within Li-ion batteries are the electrochemical reaction, ohmic internal resistance, the polarization, the breakdown of the electrolyte, and the dissolution of the SEI film. Li-ion batteries present an engineering challenge due to their complex internal structure, making it difficult to correctly assess their internal heating power. The bulk of battery concerns are related to an increase in temperature and non-uniform distribution of temperature across battery, therefore these must be effectively handled before batteries may be used in extensive variety of applications. BTMS refers to process of using cooling technologies to mitigate heat produced by batteries.

Battery thermal management system (BTMS) regulates internal temperature of battery to ensure that it can function safely during its electrochemical process. The primary function of BTMS is to guarantee that the battery modules do not degrade in capacity over time, that thermal runaway is avoided, that costs are kept to a minimum, and that they discharge to the specified voltage and rate. While the market's currently available batteries can handle temperatures from 40 to 60 °C, the optimal range for these batteries, according to the researchers [31], is 20–45 °C. The PCM-based BTMS, which is viewed as a viable choice for battery cooling, employs phase-change material as a passive cooling device to retain heat. There are numerous benefits of using PCM such as the PCM-based BTMS has zero power requirements. In the PCM-based BTMS, temperature remains constant with faster temperature response. PCM-based BTMS. While comparing different cooling strategies for BTMS, it is discovered that PCM-based cooling strategy has key advantages in terms of high heat storage capacity, convenience of use, longer life, and others, however, has trouble dissipating the absorbed heat due inefficient thermal conductivity of selected materials [32]. This means that BTMS based on PCM can easily achieve thermal saturation. Furthermore, the battery's efficiency degrades in the low-temperature environment because PCM's thermal insulation capability is insufficient [33]. The thermal saturation brought on by relatively low thermal conductivity means that pure phase change material-based BTMS can't deliver reliable temperature regulation even when employed for extended periods of time in high-power applications.

Studies demonstrated that battery temperature can be greatly lowered by enhancing PCM thermal conductivity and decreasing convection thermal resistance [34].

The experimental enhancement of the local heat transfer properties of the power battery module in an unique nanocomposite PCM with strong anti-leakage and thermal conductivity was investigated [35]. Nanocomposite PCM was made by incorporating graphene, carbon tube, and EG into paraffin. The heat conductivity and leakage properties were both excellent. The composite had about the same thermal conductivity as copper foam/PCM, hence its locally enhanced heat transfer impact was similar to that of the latter. Consistent battery module temperature was achieved by decreasing the size of the improved zone. While the maximum temperature did rise somewhat, the temperature distribution was more even in the battery module with the CPCM upgrade for only four batteries, demonstrating excellent thermal management performance for the power battery module. In another similar study segregated-structure composite PCMs including binary fillers was formulated [36].

Three-dimensional heat conduction networks, such as PA-CNTs@BN30, were introduced in BTMS. As can be shown in Fig. 17, the as-prepared novel segregated-structure composite PCMs with binary fillers exhibit improved chemical stability and anti-leakage properties. The segregated-structure binary composite PCMs provide continuous heat conduction channels that are good for phonon propagation. Furthermore, CNTs introduce additional pathways for the transmission of phonons, which aids in the creation of micro-region pathways. The thermal conductivity of binary composite PA-CNTs@BN30 is the highest among composite PCMs, increasing by a factor of 176 relative to that of pure PA. Furthermore, PA-CNTs@BN30 is flexible and responsive to temperature changes while maintaining a stable form. The thermal effect of PA/CNTs@BN30 is greater in comparison to air natural cooling, and maximum surface temperature of battery module equipped with PA/CNTs@BN30 drops by 4.4 °C during lesser rate of discharge–charge cycles. Using polyaniline PCM, ethylene glycol (EG) as adsorption and thermal conductivity material, and SiC/SiO₂ as the high thermal conductivity material additive [37]. The effect of PCMs on LIBs was studied by looking at how different CPCMs affected electrochemical performance and temperature of LIBs during charge–discharge cycles. The thermal conductivity of CPCM was greatly enhanced by incorporation of SiC and SiO₂, with the created SiC/EG binary exhibiting a greater thermal conductivity than the SiO₂/EG binary, with the greatest thermal conductivity of CPCM-5 being 4.086 W/mK. With CPCM cooling, the LIBs' temperature was kept substantially lower throughout charge–discharge cycles. As compared to the other CPCMs, CPCM-5 provided the most effective cooling. Maximum surface temperatures of 39.3 and 28.6 °C for the Sanyo and Sony batteries, respectively, Fig. 18 shows that throughout charge–discharge cycles at a 2 C discharge rate, there had been drops of 7.8 and 3.9 °C, respectively, when compared to natural air convection. While discharging at 1 and 2 C, CPCM-5 cooling lowered battery temperatures by 1.4 and 3.9 °C, respectively, when compared to natural convection. The LIB temperature was successfully decreased by CPCM-5 at discharging rates of 1 and 2 C. With its long service life and high latent heat without the requirement for exterior pumping power like air or liquid cooling, battery thermal management system (BTMS) using nano-enhanced phase change

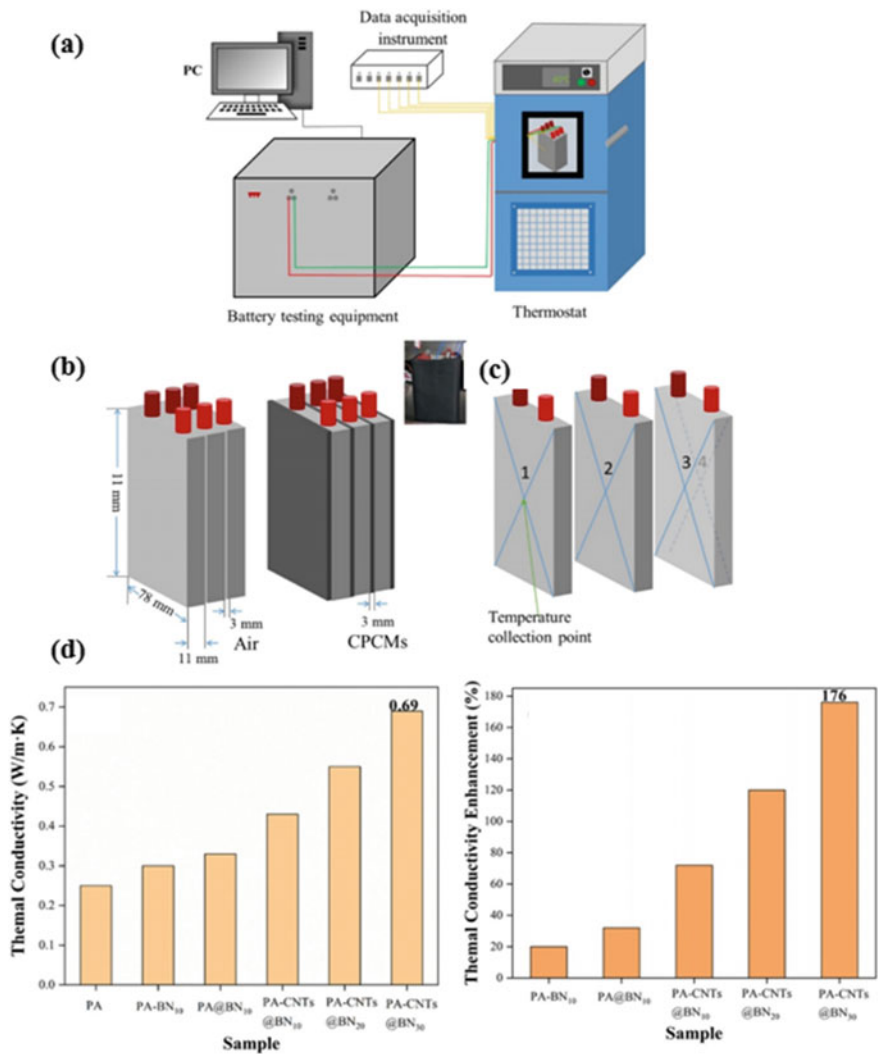


Fig. 17 The schematic diagram battery test set up module sensor positions and thermal conductivity curves [36]. Adapted with permission. Copyright 2022, Elsevier

material (NePCM) is an attractive solution. However, more work and research is required to make the system truly effective.

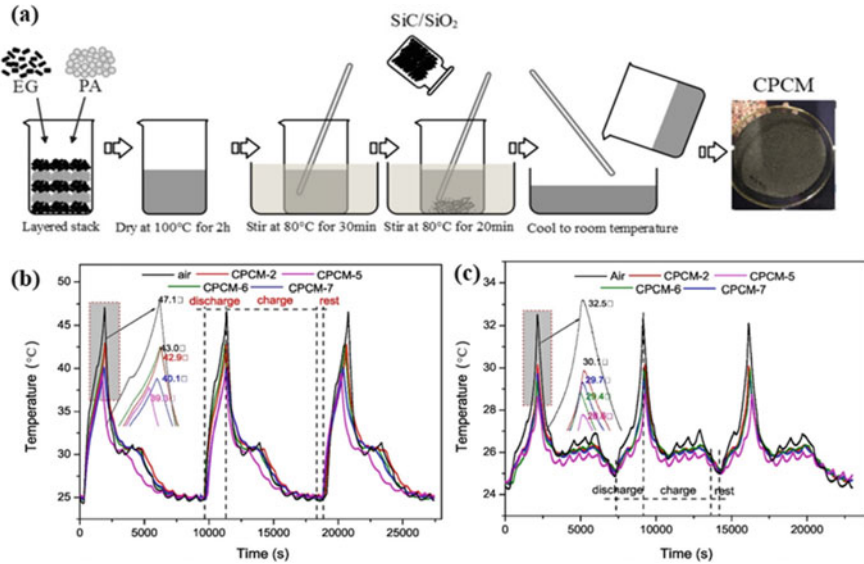


Fig. 18 a Composite PCM formulation preparation technique and charging and discharging temperature of two different company LIBS b Sanyo c Sony [37]. Adapted with permission. Copyright 2022, Elsevier

5 Conclusion

This chapter explains the basic ideas behind how Nano-enhanced Phase Change Material (NePCM) can be adopted to thermally control electronic devices temperature for different applications. A common and efficient way to lower electronic devices temperatures and prevent sudden temperature increases in electrical components is PCM-based passive cooling. However, it performs better under intermittent or low-heat power working circumstances. Otherwise, in high temperature conditions when PCM fully consumes latent heat and surpasses its melting point, temperature of electronic devices will continue to rise at faster rate. Further, another demerit associated with PCM is its low thermal conductivity, however inclusion of nanoparticles to PCM can improve its thermal conductivity. Three primary PCM-based techniques are typically used to cool electronic devices: NePCM package, NePCM with heat sink, and NePCM with heat pipe. First, it is easily achieved and possible to easily mount NePCM package on top of heating components by enclosing NePCM in a metal container. Under steady and varying heat loads of 1–5 W, the thickness of the container and various NePCM types were studied. As seen, containers with a thickness of 1–3 mm can effectively hold back-cover temperature at 45 °C for an extended length of time and electrical component temperature at 85 °C. Organic PCMs are typically held in aluminum because majority of inorganic PCMs are metal-corrosive. Further, NePCM with heat sink can show significant improvement for thermal management of devices. Besides, NePCM heat sink with fins can perform

better in thermal management of electronic devices owing to augmented thermal conductivity. Besides, HPs have extraordinarily high thermal conductivities, resulting in a two-phase shift thermal transfer 100 times larger than copper. A high-power load of more than 5 W (natural air flow) or as much as 50 W (forced cooling) can be managed by applying a certain amount of NePCM to the several edges of HP (such as the evaporation, adiabatic, and condensation portion), and the fan power usage can also be greatly reduced. In the meantime, the uniformity of the temperature along the HP increases. In conclusion, this chapter introduces new researchers to the advances in nanotechnology-based cooling solutions for electronic devices and their practical applications related to NePCM. Improved understanding of how to employ these techniques and devices for thermal management using nanomaterials in various contexts.

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Chapter 10

Applications of Nano-enhanced Phase Change Materials in Textiles



Reji Kumar Rajamony and M. Samykano

1 Introduction

The production of cutting-edge textile goods, one of the most prevalent trends currently is the use of smart materials that adapt to environmental stimuli. Smart fabrics that alter with the environment and can protect the person in harsh situations. During hot summer and cold weather conditions, people who work outside, like. Military police, traffic police, need cloths that are thermally comfortable [1]. Due to high temperature, snow, ultraviolet (UV) radiation in the environment, people need UV protecting and temperature-regulating textiles to protect their bodies. However, traditional textiles, are less effective on keeping the body temperature stable due to less heat transfer and convection heat transfer and cannot perform at high environmental temperatures [2]. This problem can be solved by using smart materials like functional materials integrating into textiles that can control or maintain the temperature. Phase change materials (PCMs) are functional materials which is an excellent material for control the temperature well during the storing and then releasing of thermal energy. The various emerging materials and the application areas were displayed in Fig. 1 [3–6].

Due to excellent properties of PCM like higher storage density, chemically and thermal stable, non-toxic, small volume change during melting, and easily available, it has been used in electronic cooling, battery thermal management, thermal

R. K. Rajamony (✉)

Institute of Sustainable Energy, Universiti Tenaga Nasional (National Energy University), Jalan IKRAM-UNITEN, Kajang, Selangor, Malaysia

e-mail: rejikumar.r2006@gmail.com

M. Samykano

Faculty of Mechanical and Automotive Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, 26600 Pekan, Pahang, Malaysia

e-mail: mahendran@ump.edu.my

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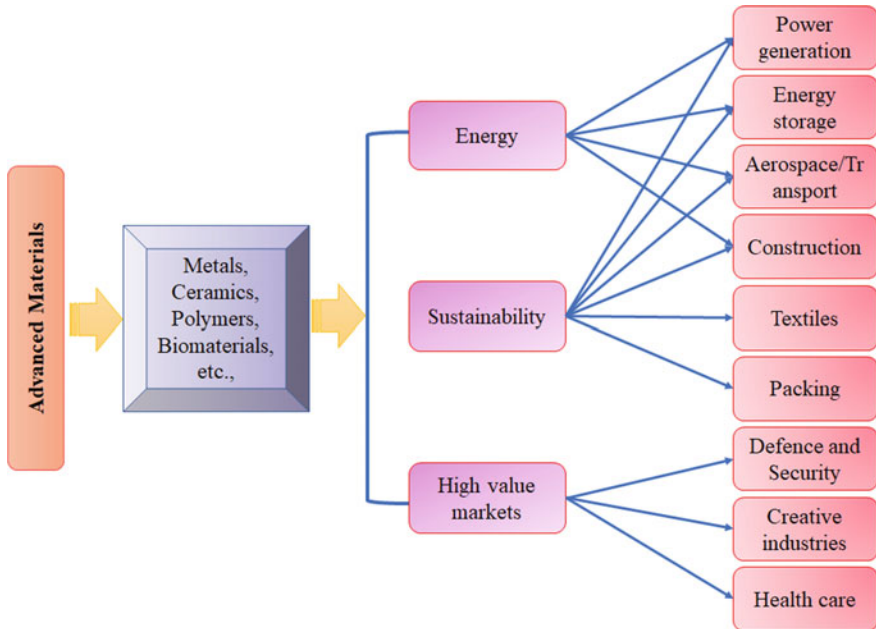


Fig. 1 Emerging materials in textiles

recovery, smart textiles, etc. [7–10]. Generally, the PCMs are combined into conventional textiles in the kind of porous supporting materials impregnation, micro electrospinning [11], microcapsules by coating [12]. Figure 2 illustrates the different methods of fabrication of PCM into textiles.

Sanchez et al. [13] developed thermal management of textiles utilising paraffin PCM. Various coatings were analysed with different binders were investigated for thermal comfort. It was found that the energy storage of 7.6 kJ/kg, adequate stability, high durability even after washing. Lu et al. [14] formulated a paraffin PCM in textiles with core-sheath structure with an encapsulation efficiency of 54.3% and energy storage of 60.31 kJ/kg. Further, the PCM-fabricated textiles have higher stability and higher latent heat at 500 cycles. Yu et al. [15] have developed corn-cob-like nanofibers incorporated with PCM for thermal comfort for textiles. These developed membranes contain varying degrees of stiffness, microscopic holes and the capability to both retain and discharge energy in reaction to shifts in its surrounding environment. It remained observed that the energy storage capability of 74 kJ/kg after 50 cycles. Besides that, the traditional ways of PCM incorporated intelligent textiles have pretty sophisticated, they still have problems. For instance, the heat regulation of PCM-integrated textiles is not enough, due its lower thermal conductivity of PCMs. Generally, the temperature transmission level is depending on the thermal conductivity of the PCMs. This made them bad at managing heat, which limited their practical use. Researchers have suggested that adding of well conductive particles like metals, metal oxides [16], carbon-based nanoparticles [17], extended

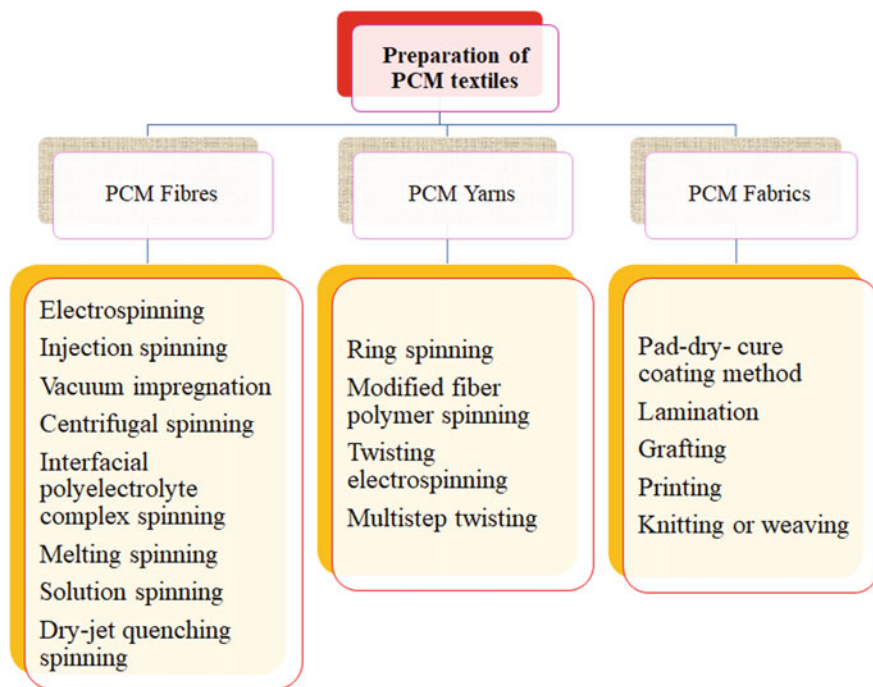


Fig. 2 Methods of fabrication of PCM incorporated textiles

surfaces [18], etc., into the base PCM significantly enhances the thermal conductivity then also alters other properties of the PCMs [19]. Many of the researchers experimentally concluded that addition of highly conductive nanoparticles improved the temperature shift ratio among the body as well as the cloth [17, 20–23]. Recently Kalidasan et al. [24] described that adding of ZnO tetrapod nanomaterials in paraffin wax enhances the thermal conductivity by 94% without compromising the melting enthalpy. Because of excellent photothermal property, higher heat transfer rate, excellent thermal and chemical stability, the novel composite can be used for thermal management in textiles, battery, etc. Another research reported that addition of binary nanoparticle (Ag; Gr) dispersed RT50 paraffin wax improved the heat conductivity by 58.8 out of 100 and the light absorption also enhanced significantly [20]. Due to the excellent thermophysical properties the developed composite is suitable material for thermal management in textiles. Recently, a researcher Fe_2O_3 dissolved paraffin was developed for thermal management purposes. It was found that adding Fe_2O_3 nanomaterial into the PCM effectively enhance the thermal conductivity by 79% and the latent heat remain decreased slightly. So the prepared high heat transfer composite is well suited for thermal management applications [25]. Similarly, Huo et al. [26], Salyan et al. [27], Liu et al. [28], Kalidasan et al. [29] and Joseph et al. [30], reported

the adding of little quantity of nanomaterials with PCM enhance the thermal conductivity without compromising the latent heat, improve the heat transfer rate and light absorption capability, so it is a potential material for thermal management in textiles.

For the production of thermal management in textiles, PCM with the range of 20–35 °C will prove to be the most powerful. The usage of PCM in underwear textiles, it is recommended to choose PCM that is close to the skin temperature. when it comes to lining material of a ski suit, the PCM temperature must be significantly lower. The following sections examine the incorporation of PCMs and their applications in the textiles industry. Also, this chapter comes to a close review of some of the difficulties that can be encountered when using PCM/nano-enhanced PCM (NePCM) in textile industry.

2 Thermal Regulation Materials

The metabolic processes that occur within a living human being consistently generate heat. During periods of inactivity, the striated muscles of the skeleton can provide as much as ninety percent of the body's total heat production, yet when the body is at rest, a major percentage of the body's heat is generated by its interior organs. The capacity of the individual's body to save heat have being restricted, yet vigorous workout for 10–20 min can raise the temperature of the body to up to 38 °C [13]. Four different systems are responsible for the transfer of heat from the human body to the neighbouring environment: they are conduction, convection, radiation and evaporation. There are different ways to regulate the temperature body by store and release the heat energy via textiles. The goal of storing thermal energy is to preserve the heat energy for use at a prior time rather than releasing it into the atmosphere, which is the traditional practise. The stored energy can achieve in a series of ways, together with physically and chemically [3]. Every possible approach to the storage of thermal energy comes with its own set of benefits and drawbacks. In the natural method of storing thermal energy, the heat transfer apparatus makes a contribution to the storage of heat energy, then the capacity of the substance to keep the energy is contingent on the thermophysical behaviour of the materials [31]. The heat energy is accumulated in the kind of latent and perceptible heat when it is subjected to the process of physical storage. In a process of sensible cooling or heating, the heat energy of a substance can be either accumulated or released, depending on whether the substance's temperature is raised or lowered. As a substance undergoes phase shifts from solid–liquid, liquid–solid and vice versa, while the temperature remains the same, this phenomenon is known as latent heat (LH) [32]. During this process, energy can be collected or released. Latent heat storage (LHS) is suggested as an efficient technique of storing heat energy owing to their high quantity of energy storage, at the same time an large quantity of heat may be accumulated in small volume. This is because LH storage can store a significant amount of energy in a tiny volume. PCMs are thermal energy storage (TES) material, often known as LHS materials, which is capable of store and release higher amount of heat energy

[33]. When a material undergoes a shifting of phase to liquid from solid at constant temperatures, heat can be stored in the material during the transition, and heat can be discharged when the material undergoes changes of phase to solid from liquid. PCMs have the ability to store anywhere from 5 to 14 times additional heat per unit volume than those that just store sensible heat. By using a reversible chemical process, heat energy can be either stored or released using the chemical storage method [34]. The phase transformations that make up the thermochemical energy are solid to solid, solid to liquid, solid to gas and solid to gas [35].

2.1 Phase Change Materials

PCMs are also known as LHS materials. Because of their sporadic and unpredictable character, sustainable energy systems make use of PCMs that can absorb, store and release heat energy. When a substance transforms from solid to liquid or from liquid to solid, a transfer of thermal energy takes place [36]. This transition from one state to another is referred to as a phase transition. Primarily, the solid–liquid PCMs act just similar to conventional storage materials as they take in heat, their temperatures rise. Unlike sensible heat storage materials, PCM absorb, store and discharge heat at almost steady temperature as shown in Fig. 3. Compared to conventional storage materials like, brick, water, rock, they can hold 5–14 times as much heat [34]. Many PCMs have been found to melt at temperatures within the range of interest. However, latent heat storage materials need to have a specific thermodynamic, kinetic and chemical properties in order to get the maximum performance. Typically, there are three distinct categories for PCMs. On the basis of the chemical composition, the phase transition temperature and the mechanism of phase transition. PCMs could remain used in different cooling, heating and thermal management applications like battery thermal management [37], photovoltaic thermal system (PVT) [38], textiles [11], electronic cooling [39], building heating and cooling [40], solar energy storage [21], solar desalination system [41], food storage [42] and so on.

2.1.1 Classifications of PCM

There are several kinds of PCMs are available and are classified based on the applications. Mainly PCMs are categorised into three kinds. Based on temperature at which the phase transition occurs; low, medium and high temperature ranges of PCM; Based on chemical identities PCMs classified organic, inorganic and eutectics; according to phase shift divided into solid–liquid, liquid–gas and solid–solid [35]. The detailed classification of PCM is displayed in Fig. 4. Organic PCMs exist between solid–liquid interface and can be divided into paraffin and non-paraffin-based PCMs. Paraffins are considered as excellent materials due to higher latent heat storage, less super cooling, self-nucleating, inexpensive and stable [3]. Several authors have examined the performance of various paraffin compounds [43–46]. The chemical formula for

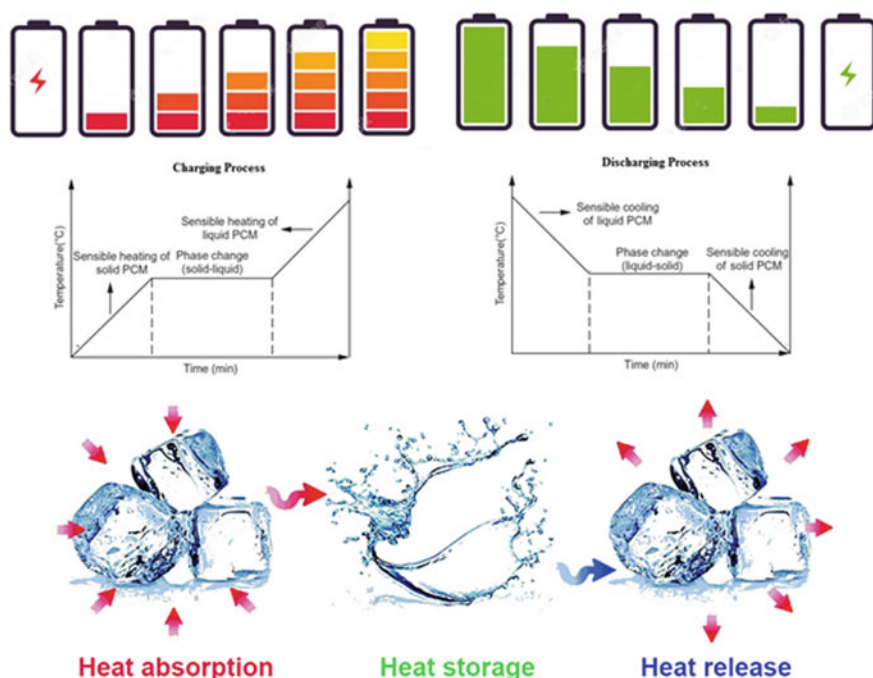


Fig. 3 Charging and discharging of thermal battery

paraffin is written as $(\text{CH}_3-(\text{CH}_2)_n-\text{CH}_3)$, where n refers to the number of carbon atoms present in the compound. Paraffins are used in a wide variety of uses. The storage capacity of paraffin is $\approx 150 \text{ MJ/m}^3$ and its thermal conductivity is around 0.2 W/mK [47]. Generally, paraffin is a solid state at room temperature. Due of their lower volatility, they pose a decreased risk of ignition when compared to other materials paraffins are well suited for thermal management and storage applications. The paraffins known as alkanes have the formula $\text{C}_n\text{H}_{2n+2}$ and belong to the category of saturated hydrocarbons known as alkanes. Alkanes all have very similar chemical properties with one another. The paraffin compounds with carbon numbers in the scale of C5 to C15 are liquids under normal conditions, whereas the remainder of the paraffin compounds in the same scale take the form of waxy solids. The melting temperature of paraffin wax ranges from 23 to 67°C , making one of the highly used and economical organic TES materials. Paraffin wax is composed of straight-chain hydrocarbons and has a melting temperature in the range of $23\text{--}67^\circ\text{C}$ [48].

Fatty acids, alcohol and polyethylene glycol are examples of non-paraffin compounds that are present in environment. For instance, the compound can be represented by R-COO-R^1 . The formation of the alkyl groups is denoted by the letters R and R^1 [49]. Corresponding to Yuan et al. [50], in order to manufacture phase transition materials, they conducted a review on fatty acids. Even though stearic acid, lauric acid, palmitic acid and myristic acid were demonstrated to be considerable,

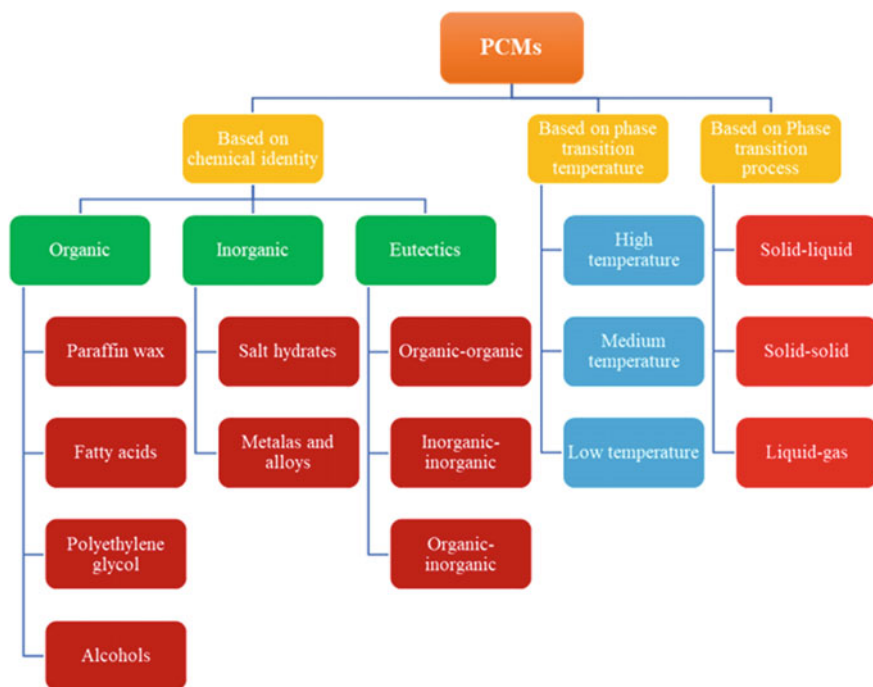


Fig. 4 Classification of phase change materials

their thermal conductivity between 0.15 and 0.17 W/mK, which indicated that these materials are not effective. Palmitic acid had the lowest thermal conductivity of the four. The general formula for fatty acids is $R\text{--COOH}$, where R signifies an alkyl group; naturally occurring fatty acids be able to either saturated or unsaturated in composition. The metallic and salt hydrates are inorganic PCMs. In thermal management and storage applications salt hydrate PCMs are an efficient material, because of the more cost-effective and higher thermal conductivity than organic paraffin PCM. In addition, the salt hydrate PCM has lesser volume change during phase transition. But the main problem with salt hydrate is supercooling behaviour [3]. In addition, the common issue of melting and segregation, salt hydrates are vulnerable to incongruent melting. These problems can be solved by mechanical stirring, adding thickening agents, stabiliser PCM encapsulation methods accelerate the chemical composition are all salt hydrates that can be used to mitigate the incongruent melting. Also, the issue of salt segregation and supercooling can be reduced by addition of surfactants and nano additives with salt hydrates [17]. Calcium chloride hexahydrate, magnesium nitrate hexahydrate and magnesium chloride hexahydrate are examples of salt hydrate PCMs.

Eutectics mixtures are composed of more than two PCMs, resulting in the melting point being less of a few of the individual ingredients. Some of the examples of eutectic PCM are organic–inorganic, organic-organic or both. According to the

phase shift temperature the PCMs are categorised low, medium and high melting temperature PCMs. The phase change temperature less than 40 °C is considered as low melting temperature PCMs. These PCMs commonly used for battery thermal management, textiles, electronic cooling and heating ventilation and air conditioning (HVAC). The phase transition temperature range of 40–80 °C considered as medium temperature PCMs. These PCMs found widespread use in a wide variety of contexts, from the textile industry, health care and energy-efficient cooling. The phase transition temperature more than 80 °C considered as a high melting temperature PCMs [35].

Further, PCMs are categorised based on the phase transition process; solid–liquid, solid–solid, liquid–gas and vice versa. Because of their modest enthalpy changes and very small volume change during phase changes the substance that phase changes from solid to liquid and solid to solid are well suited for thermal management and storage appliances. In contrast, PCMs solid-to-gas and liquid-to-gas mixtures are not suitable for practical uses due to the rapid volume change that occurs during the phase changes [51].

2.2 *Nano-enhanced Phase Change Materials*

PCMs be able to collect and release thermal energy. In the preceding chapter, a variety of PCMs and their basic working principles in textiles were discussed. When there is extra energy available, the PCM will absorb a considerable quantity of heat and store it. When the temperature of the surrounding environment drops below the PCM's melting point, the PCM will release the stored energy and begin to solidify [52]. In general, PCM are holding a lower thermal conductivity than other materials, as a result of their lower thermal conductivity, they have a reduced capacity for storing and releasing heat energy and heat transfer rate [19]. As a solution to this problem, highly conductive nanoparticles of various sizes were mixed in with the PCM components. The accumulation of nano-sized materials into the base PCM is known as nano-enhanced PCM. The impact of nano-sized particles into the PCM is described below.

Sun et al. [53] investigated the porous carbon-based nanoparticles enhanced PCM for superior thermal management applications. A hierarchical porous carbon-based nanoparticle along with huge surface area dispersed with paraffin wax. The prepared nanocomposites thermal conversion efficiency was found 89%. A PCM microencapsulation with Ti₄O₇ nanoconverter for superior thermal conductivity. The developed NePCM thermal conductivity was enhanced by 335% higher than base paraffin PCM [53]. Zhu et al. reported the garment materials composition and nanostructure underlying personal radiative thermal management techniques to control heat exchange between the human body and the environment [54]. Li et al. examined foam-based nanomaterials enhanced octadecane PCMs for thermal management purposes. It was revealed that adding nanomaterials enhances the heat conduction rate, also the higher porosity of foams is ascribed to its higher thermal conductivity [55]. Recently, Nie

et al. reported that when air is used as heat transfer fluid at a low flow rate, the potential of shape change for improving the cylinder latent heat storage unit are reduced. In particular, for the LHS unit with the conical shell, the total melting time is only decreased by 2.0% in comparison to the one with the cylindrical shell [56]. From the discussion the NePCM of potential material for thermal management like battery thermal management, textiles, buildings, electronic cooling, etc.

2.3 Incorporation of PCM/NePCM in Textiles

2.3.1 Coating

PCM/NePCM can be incorporated by coating technique. The coating includes wetted microspheres with PCM distributed throughout the polymer binder, stabiliser, nanoparticles, antifoaming agent and thickener. This can be done by applying the coating paste to the textile substrate. There are several coating methods that can be utilised in textiles such as knife over air coating, knife over roll coating, gravure coating, pad dry cure coating and dip coating.

2.3.2 Lamination

To increase thermo-physiological wear comfort of non-woven protecting clothes, NePCM could be included in thin polymer film and applied to the inner side of the fabric system via lamination, Mechanical and/or harsh climatic conditions might weaken the adherence of films to the textile substrate, lowering the quality of lamination [57]. Chemical protective clothing that utilises PCM laminated textiles is feasible. As well as chemical protecting suits, PCM laminates can be used to increase the thermo-physiological wearing comfort of other non-woven protective clothing, such as surgical gowns, uniforms and clean room clothes. PCM microcapsules can be incorporated into a water-blown PU foam mixture before lamination. In the process of water evaporation, a honeycomb structure is formed. Another benefit of the PCM-PU foam layered system is the increased passive insulation provided by the still air trapped in honeycomb form [58].

2.3.3 Fibre Technology

NePCM has the potential to be embedded into the fibres of the textile. Before beginning the spinning process, it is possible to incorporate NePCM into the polymer solution. The PCM-integrated fibers have the ability to absorb heat and store heat for extended periods of time. Zhang et al. [59] investigated the PCM composites and characteristics of sheath/core composite polypropylene fibre non-woven with varying amounts of PCM in the core. They found that these non-wovens exhibit

a diverse range of properties. The ability of the fibres to regulate temperature is impacted both by the amount of PCM present in the fibre as well as the ratio of sheath to core. Shi et al. have reported a unique method for producing sheath–core photo-thermally converted thermo-regulated fibres. In this method, the sheath of the fibres is made from a fiber-forming polymer that contains photothermal transformation ceramic, and the core of the fibres is made from a fiber-forming polymer that contains micro PCMs. In comparison to the control one, photothermally converted and thermo-regulated fibres offer superior temperature-regulating capabilities [59].

2.3.4 Other Methods

The application of NePCMs to a textile substrate can be accomplished either by impregnation or by exhaustion approach using acrylic resin. Fabrics that have been treated can then have a heat treatment applied to it in order to permanently fix the microcapsules on the substrate. It was noticed that using various procedures resulted in a considerable difference in total quantity of microcapsules that were left on the fabric [60]. When compared to the process of bath exhaustion, the impregnation method results in a greater quantity of microcapsules being deposited onto the cloth. Complex coacervation was used by Onder et al. to encapsulate PCM, and their results showed that the absorption capabilities of the coacervate-added textiles were increased by 2.5–4.5 times [61].

3 Application of NePCM in Textiles

The application of scientific principles in the manufacture of contemporary and innovative textiles is becoming increasingly widespread. One of these concepts is called energy storage using PCMs, and it can be described as a transition between two different physical states. PCMs have many applications, one of which is the textile industry, where they are utilised for clothes, blankets, prescription packaging and protection. In the following section, we will discuss using PCMs in textiles. The condition known as thermal tension develops when the heat generated by the body as a result of the activity is not dissipated into the environment to an adequate degree. PCMs can store and then release the extra heat at the right periods. PCMs can be used in mountain climbing devices, running equipment, snowboarding gloves and cycling gloves, in addition to skating boots, rally shoes, mountain climbing boots, helmets, hand gloves and golfing shoes. In addition, PCMs are used to regulate the temperature in automobiles, such as seat covers, among other things. Further applications for polymer composite materials in the textile industry include ceiling coverings for automobiles, safety helmets for firefighters and clothes for use in firefighting and scuba diving. Initially, PCMs were used to insulate space suits and gloves that astronauts used to shield them from extreme cold. Incorporating microcapsules into bedding (such as blankets, pillows and mattresses) enables active temperature management

within the sleeping environment. When the body temperature rises, additional heat is absorbed to keep the body temperature stable. After the body starts to cool down, the heat it has stored will be released and reabsorbed. Adaptive fibres and fabrics are becoming increasingly prevalent in today's society. Using PCM allows for the achievement of certain qualities and traits. PCMs are efficient and cost-effective method of storing thermal energy storage (TES). NASA pioneered the technology that allows microcapsules of phase change material to be woven or woven into temperature-regulating materials in the early 1980s. The main aim was to integrate PCM materials into space suits to protect humans from the huge temperature changes that occur in outer space. PCMs may considerably increase the thermal comfort of clothing, and textile makers now have the ability to use PCMs to do so. PCMs that go through a phase transition at temperatures below or above body temperature can be used to create textiles. Because of the dynamic nature of phase transition, the states of the materials are continually shifting in response to the level of the body's physical movement as well as temperature of the surrounding environment. The incorporation of PCM nanoparticles into the polymer solution prior to the extrusion of the man-made fibers is what gives these fibers their temperature-adjusting characteristics.

Though the use of PCM and NePCM-incorporated textiles are able to produce apparel that maintains a pleasant temperature for wear even when exposed to harsh weather conditions. PCM/NePCM have found uses in wide variety of applications, including the aerospace industry, medical field, protective clothing industry and automotive industry. The following section explains the impacts of PCM/NePCM in various textile applications.

3.1 Medical Textiles

PCMs and NePCMs have an interaction with microclimate that surrounds the human body and respond to the functions of the temperature which can be included by changes the level of physical activity as well as change of external environment. Consequently, the textiles that have been incorporated with PCM/NePCM microcapsules have the potential to be used in surgical clothing, bandages, bedding and more, in intensive care sections to help maintain comfortable temperature for patients [13, 62]. A silver nanoparticle dispersed polyester and polyamide fabrics investigated the anti-bacterial properties for medical applications. It was observed that developed composite coating act as a anti-fungal effect in textiles [63]. Sarier et al. investigated the silver-dispersed n-hexadecane composite PCM integrated fabrics fabricated for thermal comfort for human beings. The newly developed composite PCM is well suited for numerous commercial applications, including thermally enhanced garments, automobile and medical textiles and construction materials [64].

3.2 *Automobile Textiles*

The NePCMs have potential use in automobile textiles like seat cover interiors and carpeting, etc. Generally, paraffin-based PCMs are used for automobile textile applications due to its lower cost, higher heat capacity, low toxicity and absence of hygroscopic qualities, in addition to this the desired temperature range may be achieved through the use of blending. The use of NePCM-embedded textiles in textiles has potential to offer passenger greater temperature management [57].

3.3 *Aerospace Textiles*

PCMs were initially designed for usage in textiles for the purpose of being included into space suits and gloves for the purpose of shielding astronauts from the varying temperatures that they experience while operating in space. Because of their ability to regulate temperature, textiles that contain phase-change material help astronauts remain comfortable while they are in space [57].

3.4 *Active-Wear Clothing*

PCM-integrated cloths were initially developed for use in spacecraft, but they have now found widespread application in consumer garment products. The advancement of PCM-embedded textile has made it potential to make fabrics that can keep the wearer at a comfortable temperature while not adding a significant amount of mass to the bulk of the clothing. Activewear provides a heat balance between the heat generated from the body and the heat emitted into the environment while the wearer is participating in a sporting activity in order to lessen the amount of thermal stress they experience [65]. An active thermal insulation effect can be provided by PCM-integrated active wear and outdoor sports apparel. This active thermal insulation effect complements the passive thermal insulation effect provided by garment system. During moments of physical activity, excessive heat generated by the wearer's body can be absorbed by PCM-integrated clothing, and then released during rest time between movements, when the wearer's body is producing less heat. This helps maintain a comfortable state for the human body. The rise in popularity of winter activities that take place in colder climates, such as ice climbing and alpine climbing, as well as recreational skiing, has led to an increase in the need for materials that can keep the wearer dry, warm and comfortable [66]. Khosrojerdi et al. analysed the foam-stable dispersed n-nonadecane PCM composite incorporated fabrics by impregnation treatment [67]. The results show with increase in thickness of PCM composite, decreased air permeability, moisture and heat transfer. Also, DSC and heat transfer analysis show that coated PCMs fabrics temperature range depends on

its area. Lu et al. fabricated PCM-integrated textiles using coaxial electrospinning [14]. Paraffin wax is used for the core layer and polyacrylonitrile as a sheath layer. The results displayed that the core-sheath structure has a viable solution to address the leakage issues for smart textiles. The addition of an absorbent hexagonal cesium tungsten bronze has the ability to enhance the use of heat energy. In addition to this, it is quite exciting to note that the smart textile, in its as-prepared state, contains an LH of 60 J/g and a encapsulation efficacy of 54.30%. Even after 500 thermal cycles, textiles have preserved a high LH, which demonstrates the material’s excellent stability. As a result, this work offers useful direction for the production of thermo-regulated textiles and presents a novel approach for multifunctional textiles.

3.5 Firefighting Suits

Firefighting is risky job, and it is essential to wear thermal protective apparel to reduce the risk of getting hurt by the heat. A mathematical model with multiple configurations of a firefighter’s protective clothing made with PCM for use in situations requiring thermal energy storage [68]. To determine the factors that contribute to the protective qualities of fabric, researchers modelled the skin as consisting of three layers, each of which possessed a distinct set of thermal properties (the dermis, subcutaneous layer and epidermis), and then analysed the temperature of the skin’s layers at different points in time. With this information, the model may be used to estimate how much thermal protection the presence of PCM would give firefighters. According to the research findings presented above, configuration D PCM with an air gap offers the best protection against temperature in a firefighting suit (Fig. 5).

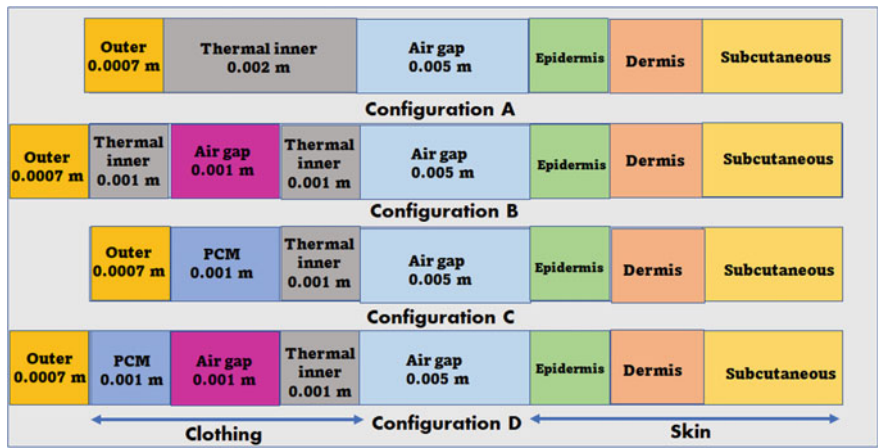


Fig. 5 Mathematical modelling of different configuration of clothing, PCM and body (The figure has been adapted/reproduced from Ref. [68] with permission from ELSEVIER, copyright 2015.)

To examine the firefighter's temperature protective garment, a researcher employed a one-dimensional model. The study used a 1D mathematical model to examine the impact of PCM thickness and clothing positioning on temperature, and the melting temperature of PCM and persistent human burns. In addition, the results showed that a thicker layer lengthened protection time while perhaps rising firefighter strain, suggesting that PCM should be placed between water-proof and inner layers [69]. Fonseca et al. ran a simulation of the thermal performance of firefighting protective material. Periods of transitional weather with a wide range of variables were typical. Including PCM in firefighter clothing has been shown to reduce the risk of heat injury during the exposure period only [70]. Niu et al. formulated by combining a sliver nanoflower and poly (styrenesulfonate): poly (3,4-ethylenedioxythiophene) as well as hydrophobic fluorocarbon resin with novel wet spun phase change fibre, in order to achieve excellent enthalpy, high flexibility, tuneable phase change temperature, outstanding hydrophobicity and shape stability. These characteristics possible to weave fabrics using the smart energy storage fibre since it possessed integrative capabilities. This new technique could be used for smart textiles in protective and wearable systems [71].

3.6 Other Applications in Textiles

PCM-embedded fabric structures can be used in bedding accessories, such as pillows, quilts, mattress covers and bed sheets, can also be made using fabrics that include PCM. Textiles with PCM/NePCM built into them could be applied to energetically control the temperature of bed by absorbing body heat and releasing stored energy only when it is necessary to do so [11]. PCMs/NePCMs are also utilised in the shoe industry, particularly in ski boots, racing boots, mountaineering boots and a variety of other types of footwear. Some examples of prospective applications of PCMs in the textile industry include fishing waders, helmets, etc. [72, 73]. Zhou et al. found that the use of polyvinyl alcohol/PCM nanofibers with core-sheath enhances thermal stability and performance [74]. So it could be a potential material for textile applications of thermal regulation. Recently, Liu et al. developed $\text{CaCO}_3/\text{Fe}_2\text{O}_3$ dispersed PCM with fabrics for thermal management of human comfort. It was found that a considerable enhancement in fluorescence emission with the rise of Eu^{3+} . Also, excellent photoluminescence properties and thermal management were noticed [75].

Yu et al. [76] presented a hybridised nano-form stable PCM using molecular chain structural selection approach and hybridisation techniques; with good heat resistance and hydrophobicity for melt-spinning polyamide-based PCM fibres. The developed composite had good washing durability and better thermal management. Song et al. introduced tri-layered nylon, polyvinylidene fluoride and polyethylene personal cooling garments that use thermal radiation to dissipate heat on hot days. The composite textile cooled the body by 277.5–279.5 K in direct sunlight by absorbing/emitting thermal radiation ($R = 3.44$) and reflecting (more than 90%) as shown in

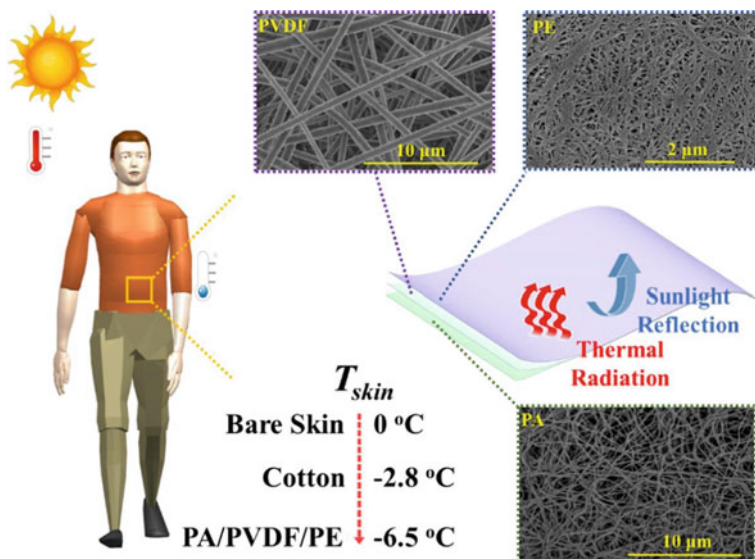


Fig. 6 Schematic and microstructure of the tri-layered nylon, polyvinylidene fluoride and polyethylene composite in textile (The figure has been adapted/reproduced from Ref. [77] with permission from ELSEVIER, copyright 2020.)

Fig. 6. Due to its less weight, efficient cooling, wearable comfort and economy, this cooling textile might be widely used by common people [77]. Table 1 displays the various PCMs, nanoparticles and their impacts on textiles.

4 Challenges

PCMs, which may now be found in a variety of consumer textile items, were first created with the intention of shielding astronauts from the severe temperature swings they would experience while working in space. There are a lot of obstacles that need to be overcome before these emerging materials may be used in consumer garment applications. In order to make advantage of these fascinating materials and incorporate them into clothes, new types of testing methods and standards will need to be developed. The poor thermal conductivity of smart material is undoubtedly one of its drawbacks. For instance, paraffin PCM has a thermal conductivity of 0.20 W/mK, whereas carbon-based nanomaterials have a thermal conductivity of up to 5000 W/mK. A low thermal conductivity slows down both the pace at which PCM stores heat and the rate at which it releases that heat during the melting and crystallisation activities, respectively. So, increasing the thermal conductivity of the core PCM microcapsules and their shell wall may be necessary in order to acquire fast response qualities of emerging materials in response to changes in the temperature

Table 1 Average transmittance and ultra-violet protection behaviour of NePCM in textiles

PCM	Nanoparticles	Size of NPs	Concentration	Observation	References
Polyester Polyamide	Ag	–	50 ppm	Increase the anti-fungal performance	[78]
Poly ethylene phthalate	TiO ₂	<100	0–2wt%		[79]
Ethanol	Ag	4.2 nm	5, 10, 20 and 30 ppm	Act as a anti-bacterial agent in fabrics, even a small quantity of Ag	[80]
Poly carboxylic acid	TiO ₂			Act as a self-cleaning property in fabrics	[81]
Acid, alkaline, inorganic salt sweat solution	ZnO		11/g/L	ZnO enhanced cotton fabrics observed worse acid resistance and inorganic salt and alkaline resistance observed much better	[82]
Silver nitrate solution	SiO ₂ loaded with Ag	20 nm	5 g with 0.8 wt% of Si	Anti-bacterial and durability performance was observed after 20 washing cycles	[83]
Polysiloxane	Ag and TiO ₂	20 and 30 nm	10,000 ppm (Ag) and 40 wt% TiO ₂	Bioactivity of TiO ₂ was enhanced with treatment of polysiloxane	[84]
Polyester and polyamide	Ag	10 nm	50 ppm	Anti-bacterial performance	[63]
<i>n</i> -Eicosane	CaCO ₃ /Fe ₂ O ₃	16 nm	–	Comfort and thermal regulation	[75]
<i>n</i> -Nonadecane	Foam	90 nm	–	Thermal comfort	[67]
<i>n</i> -Hexadecane	Ag	–	–	Thermal management in textiles	[64]

of their environment. In addition to this, the flammability of organic PCM should be investigated, as well as effective microencapsulation of PCM (which includes controlling the size, stability and shell wall thickness of microcapsules), as well as the mechanical behaviour, durability and functionality of developed garments when subjected to repeated cycles under a variety of conditions. Further study in these fields will provide chances for material scientists to develop polymer composite materials that are excellent for use in thermo-regulating fabrics.

5 Summary and Future Work

The efficiency of the TES and thermal management of textiles are influenced by thermal behaviour of the PCMs. It was concluded that inclusion of nanoparticles enhanced the thermal conductivity of the PCM even though it has a positive or negative impact on the TES capacity of NePCM. PCM/NePCM integrated textiles are smart due to their shown capacity to respond to environmental temperature changes by absorbing LH during melting and discharging energy when solidifying, this gives them a thermal regulating effect. Due to the erratic nature of PCM and enhanced properties of NePCM integrated textiles are excellent technology for regulating the temperature, so they can be used for many applications, like building materials, automotive textiles, aerospace textiles, medical textiles and sportswear. Based on the literature, paraffin-based PCMs are the most used PCMs in textile applications due to its melting temperature point being so close to the temperature of body and paraffin is a preferred kind of PCMs. Melting temperature can be tuned by using eutectic PCMs. The amount of carbon atoms in a molecule has an effect on the melting point of paraffin; specifically, the melting point of paraffin rises as the number of carbon atoms in the molecule grows. When the substance is in its liquid phase, the PCMs are protected from any potential leakage by being encased in microcapsules. PCM microcapsules can either be embedded in a coating compound and then coated onto fabrics, or they can be incorporated into the structure of foams and then laminated onto fabrics. Manufactured fibres, such as acrylic and viscose, can also have PCM microcapsules incorporated into the spinning polymer. PCMs can also be incorporated into textiles through the process of filling hollow fibres.

NePCMs are excellent materials for thermal management in textiles. Even though many of the researchers are presently concentrating their efforts on the preparation, characterisation and incorporation into the garments, there is still a need for additional research and development in order to improve the performance of PCMs and textiles in real-world settings. The following are some ideas for impending research.

Most of the research is focussed on mono nanomaterials-based PCM composites, however, need to study binary nanoparticles-enhanced PCM further to enhance the thermophysical properties. Occasionally, the nanoparticles are agglomerated after a few cycles of heating cooling operation. To solve this problem 3D carbon aerogels can be used for further analyses. The porous nature and excellent thermal conductivity of carbon aerogels can strengthen the stability of foam and heat transfer performance of PCM in textile applications. Very few works on NePCM-integrated garments for thermal regulation need to focus more experimental work on NePCM-integrated garments in textile industry.

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Chapter 11

Soft Computing Tools (Intelligent Techniques) for Nano-enhanced PCM



Prabhakar Sharma, A. K. Pandey, and Zafar Said

1 Introduction

Because of their unusual thermal properties, Nano Phase Change Materials (Nano-PCMs) have aroused the curiosity of researchers. These materials are composed of a nanostructured matrix and a phase change material (PCM) that, when heated, changes phases (liquid-to-solid or solid-to-liquid). The PCM is frequently incorporated as nanoparticles, nanocapsules, or nanofibers inside the nanostructured matrix, giving a large surface area for heat transfer [1]. Nano-PCMs have several advantages over traditional PCM materials. For starters, their surface area-to-volume ratio is higher, which boosts heat transfer and thermal storage performance. Secondly, the

P. Sharma

Department of Mechanical Engineering, Delhi Skill and Entrepreneurship University, Delhi, India

A. K. Pandey

School of Engineering and Technology, Research Centre for Nano-Materials and Energy Technology (RCNMET), Sunway University, No. 5, Jalan Universiti, 47500 Bandar Sunway, Petaling Jaya, Selangor Darul Ehsan, Malaysia

CoE for Energy and Eco-Sustainability Research, Uttaranchal University, Dehradun, India

A. K. Pandey

e-mail: adarshp@sunway.edu.my

Z. Said (✉)

Department of Sustainable Renewable Energy Engineering, University of Sharjah, Sharjah, United Arab Emirates

e-mail: zsaid@sharjah.ac.ae

Department of Industrial and Mechanical Engineering, Lebanese American University (LAU), Byblos, Lebanon

U.S.-Pakistan Center for Advanced Studies in Energy (USPCAS-E), National University of Sciences and Technology (NUST), Islamabad, Pakistan

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nanostructured matrix can act as a thermal conductor, improving thermal conductivity and heat transfer [2]. Finally, due to the small size of the PCM particles, they have a greater surface area for heat exchange, leading to faster solidification and melting rates. Finally, the tiny dimensions of the PCM particles enable greater dispersion throughout the matrix, reducing the probability of phase separation and boosting thermal stability [3, 4]. Nano-PCMs have several applications, spanning energy storage, electronics cooling, building materials, and textiles. Nano-PCMs can be used in applications involving energy storage to store thermal energy through renewable sources like solar or wind and then release it when needed, reducing the consumption of fossil fuels. Nano-PCMs can be employed in electronic cooling to remove heat from electronic devices, improving their performance and longevity [5, 6]. Figure 1 displays several typical micro PCM uses.

Nano-PCMs may be placed into architectural materials like walls and roofs to manage indoor temperatures and minimize energy usage. Nano-PCMs can be utilized in textiles to generate apparel that regulates body temperature and improves comfort. Overall, nano-PCMs are a promising family of materials that provide several benefits



Fig. 1 Applications of nano PCMs

for thermal energy storage and management [7, 8]. We should anticipate seeing additional uses of nano-PCMs in numerous sectors as research in this subject develops, leading to more efficient and sustainable energy consumption.

This ability has prompted the development of PCM-based systems for energy storage for a wider category of applications, including thermal management, building cooling and heating, and solar thermal energy storage. In the last decade, there has been a surge of interest in the creation of nano PCM, which are PCM particles or capsules with nano-scale dimensions. This review of the literature outlines current advances in the field of micro PCM and machine learning.

1.1 Nano PCM Synthesis

Various ways for producing micro PCM particles have been developed. Some examples are emulsion polymerization, the sol–gel method, and co-precipitation. The emulsion polymerization method involves first forming an emulsion that is stable of PCM droplets in a monomer solution, subsequently polymerizing the emulsion to form nano-capsules. To make PCM nanoparticles, the sol–gel method involves regulated hydrolysis and condensation of metal alkoxides. The regulated precipitation of PCM nanoparticles by mixing the PCM solution with a precipitating agent is known as co-precipitation [2, 9].

1.2 Nano PCM Characterization

Differential scanning calorimetry, scanning electron microscopy, Fourier-transform infrared spectroscopy, and transmission electron microscopy are important systems for the characterization of nano PCM particles [10, 11]. SEM and TEM were used to investigate the size and form of the micro PCM particles. DSC may be used to evaluate the solidification and melting behavior of tiny PCM particles, whereas FTIR was used to establish the chemical composition of the PCM [12, 13].

1.3 Nano PCM Performance

Nano PCM particles have shown enhanced thermal characteristics compared to their bulk counterparts, including greater melting and solidification rates, larger latent heat storage capacity, and improved thermal stability. The enhanced surface area-to-volume ratio and shorter diffusion distances for heat transmission have been linked to the better thermal characteristics of micro PCM particles [3, 14, 15].

1.4 Applications of Nano PCMs

Nano PCM particles have been employed in a variety of employment like thermal energy storage, building cooling, and heating, and solar-based thermal energy storage. Nano PCM particles have been employed in the creation of small and efficient thermal energy storage devices in thermal energy storage. Nano PCM particles have been employed in the creation of passive cooling and heating systems in building cooling and heating [16, 17].

In summary, nano PCMs have shown tremendous promise for a wide range of applications, including thermal energy storage, building heating and cooling, and solar thermal storage [18]. In recent years, significant progress has been made in the manufacture, characterization, and performance of micro PCM particles. Many challenges remain, and future research may focus on the development of innovative synthesis procedures, the optimization of nanoparticle thermal properties, and the investigation of new applications for micro PCM particles [19, 20].

Following the literature assessment, PCMs have a wide range of possible applications in energy systems. To fully realize the benefits of these systems, however, optimization and prediction of PCM behavior in combination with energy systems are required. This may be a time-consuming procedure, thus machine learning (ML) approaches can help. In optimizing and managing the behavior of PCMs in energy systems, machine learning has demonstrated considerable potential. However, there are no extensive evaluations on the issue at the moment. As a result, the goal of this study is to address that gap by giving a short assessment of ML applications in energy systems linked with PCMs. Overall, this research highlights the potential benefits of machine learning in optimizing and managing the behavior of PCMs in energy systems. It also emphasizes the need for greater study in this area, since much remains to be found and understood.

2 Applications of Soft Computing Methods for Nano PCM

Soft computing is a branch of computer science that deals with the development of algorithms and methodologies for dealing with data imprecision, unpredictability, and bias. It is a set of computer techniques aimed at simulating the human brain's ability to think through and make judgments in the face of incomplete or ambiguous information [21, 22]. The fundamental advantage of soft computing is its capacity to tackle complicated real-world situations that are difficult to solve with traditional approaches. Control systems, image processing, decision-making, optimization, and pattern recognition are all domains where soft computing methods may be applied to address issues [23–25]. The drawback of soft computing is that it may be time-consuming and has a huge cost-bearing at times. Soft computing methods frequently need huge volumes of data to be learned, which can be difficult for systems with

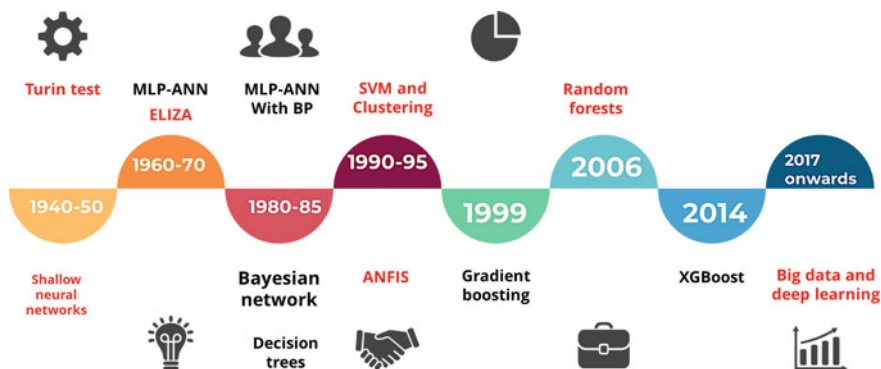


Fig. 2 Machine learning timeline

limited resources. Soft computing approaches such as gene expression programming (GEP), artificial neural networks (ANNs), support vector machines (SVM), neuro-fuzzy, fuzzy logic, XGBoost, boosted regression tree (BRT), and evolutionary algorithms are extensively employed in nanomaterial research [26]. Soft computing is an important topic in computer science with several applications, including nanomaterial research. Soft computing methods can help researchers build more effective and efficient materials and systems by allowing them to handle imprecise and unpredictable data. These methods are used to model and predict the behavior of complex systems. The section that follows explains how these strategies are utilized to improve the development of nano-PCM [27–29]. A time of main developments in this domain is depicted in Fig. 2.

2.1 Artificial Neural Networks

A Neural Network is a sub-class of ML techniques inspired by the structure and function of the human brain. It is made up of many interconnected processing nodes known as “neurons,” which work together to learn patterns and make predictions based on input data [30]. The input test data is supplied into the neural network, where it is processed by a network of interconnected layers of neurons. Each neuron in a layer receives input from the neurons above it and performs a simple computation, such as adding bias and weight. The result is then passed on to the next layer of neurons until it reaches the final prediction or classification layer [31, 32]. The process of output prediction can be summarized as:

- I. Input layer: The ANN’s input layer receives input data, which can be numerical or categorical. Each input feature is linked to a specific input neuron [33].

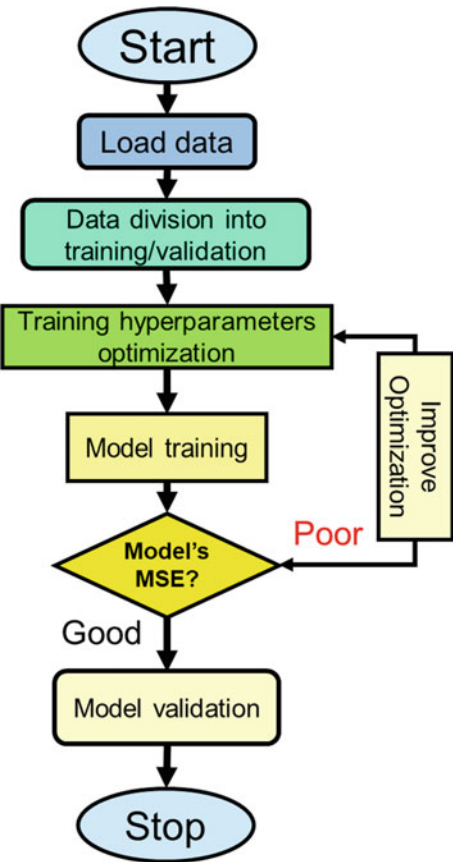
- II. Hidden layers: The ANN's hidden layers run a series of computations on the input data to extract relevant features and patterns. Each neuron in the hidden layer is linked to the neurons in the previous as well as subsequent layers [34].
- III. Activation function: Each neuron applies an activation function to the result of computing the weighted sum of the inputs. The activation function adds nonlinearity to the computation and aids the ANN model in learning complex patterns in the data.
- IV. Output layer: The ANN's output layer generates the final prediction based on the hidden layers' output. The number of neurons in the output layer is determined by the problem that the ANN is attempting to solve. In a binary classification problem, for example, the output layer would contain a single neuron with a sigmoid activation function to generate a probability value between 0 and 1 [35].
- V. Loss function: A loss function is used by the ANN to compare the predicted output to the actual output. The loss function computes the difference between predicted and actual values and feeds that information back to the ANN, allowing it to adjust its weights and biases to improve its predictions.
- VI. Backpropagation: Based on the loss function error, the backpropagation technique is employed to modify the ANN's weights and biases. The method goes backward through the hidden layers, beginning with the output layer and modifying the weights and biases of each neuron according to the error signal from the preceding layer [36].
- VII. Training: The ANN repeats the computing process until the loss function is lowered to a minimum and the ANN can reliably predict the output for fresh input data.

In essence, ANNs use a sophisticated set of calculations and feedback mechanisms to learn from input data and anticipate output. Figure 3 depicts a typical process diagram for ANN model creation.

ANNs have been shown to be a valuable tool for advancing nano PCM research and exploration. Here are several ways in which ANNs can assist in this sector [12]:

- I. Material property prediction: ANNs may be trained using existing data to estimate the melting point, thermal conductivity, and latent heat capacity of micro PCMs. This can help you save time and money that could have been spent on experiments [37].
- II. Material behavior understanding: ANNs may be used to mimic the behavior of micro PCMs under different circumstances, such as temperature and pressure. Researchers will be able to obtain a better knowledge of how these materials behave and forecast their performance in real-world applications as a result of this [38].
- III. Creating new energy materials: By using ANNs to anticipate material characteristics, researchers may utilize these predictions to guide the development of new micro PCMs with specified qualities. For example, an ANN may be taught to optimize the composition of a micro PCM to maximize its latent heat capacity [39].

Fig. 3 Schematics of ANN model development



IV. Energy efficiency: Nano PCMs have the potential to dramatically enhance energy efficiency in a wide range of sectors, including building construction and electronics. ANNs may be used to optimize the usage of these materials in certain applications, leading to greater energy and cost savings.

In conclusion, ANNs have the potential to improve the study and exploration of micro PCMs. By offering predictive capabilities, ANNs can hasten the identification of novel materials and increase our knowledge of their behavior, eventually resulting in better and more efficient applications.

2.2 Fuzzy Logic

Fuzzy logic-based machine learning approaches are a useful tool for modeling and forecasting data in a wide range of domains, including nanofluids. In essence, these

approaches employ fuzzy sets to capture the uncertainty and imprecision inherent in real-world data, allowing them to produce more accurate predictions than standard binary logic-based systems. To understand how fuzzy logic-based ML approaches function, first construct a fuzzy set [40, 41]. An element in conventional set theory either belongs to or does not belong to a set. In contrast, a fuzzy set allows for partial membership, which indicates that an element might belong to a set to some extent. FL is a mathematical method for dealing with uncertain and imprecise data. FL may be used to simulate the behavior of nano-PCM by investigating the thermal properties of PCM as well as the effect of adding nano-materials. FL can predict the behavior of nano-PCM in a variety of scenarios and may be used to optimize nano-PCM design [42–45].

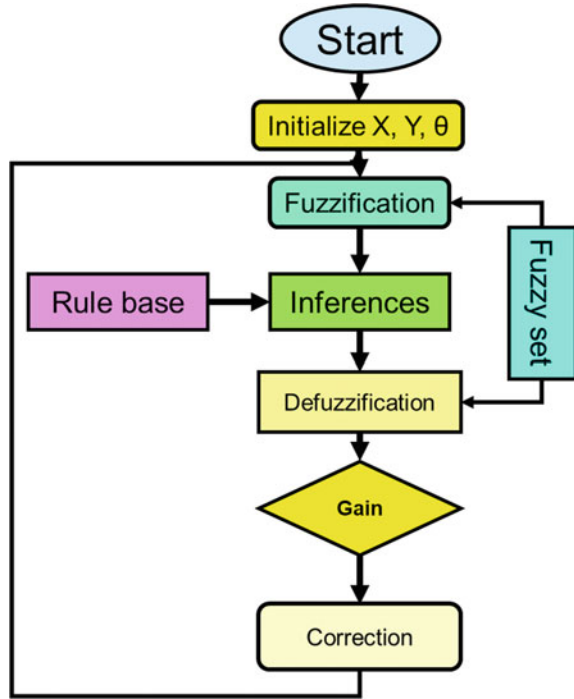
Fuzzy logic-based ML algorithms use these fuzzy sets to create predictions based on incoming data. They normally start by developing a set of rules that connect the input and output variables. These rules are often represented as “if–then” statements, with the “if” specifying the input and the “then” defining the output. Once the rules have been developed, the fuzzy logic-based ML technique applies them to the input data to provide a collection of fuzzy outputs representing the expected output values for each rule. These fuzzy outputs are then aggregated using the “fuzzy aggregation” approach to give a final output value, which is a fuzzy set indicating the projected output for the input data. Finally, the projected output fuzzy set is “defuzzified” to provide a crisp output value (a single value reflecting the expected output). Several defuzzification methods can be utilized depending on the application [44, 46, 47]. A typical flow chart is illustrated in Fig. 4.

In general, fuzzy logic-based machine learning algorithms are useful for modeling and forecasting data in a wide range of domains, including nanofluids. Because they allow for partial membership and include uncertainty and imprecision in the modeling process, these approaches can provide more accurate predictions than standard binary logic-based methods.

Fuzzy logic may be used to produce and explore micro PCM (Phase Change Material). Here are a few examples of its importance [4, 48, 49]:

- I. Fuzzy logic is extremely effective for managing data uncertainties in nano PCM research. Fuzzy logic can manage these uncertainties significantly better than standard approaches since nanoparticle behavior is typically unpredictable and varied.
- II. Fuzzy logic allows researchers to incorporate language variables such as “very hot,” “somewhat cool,” and so on, which are more intuitive and easier to grasp than numerical values. This is especially important when dealing with subjective material property evaluations and human perception.
- III. The interaction between multiple parameters in nano PCM research is typically non-linear, which indicates that the relationship cannot be modeled using a simple linear equation. For dealing with these intricate interactions, fuzzy logic is excellent.

Fig. 4 Typical flow chart of fuzzy-logic



- IV. Fuzzy logic is a rule-based system that defines a set of rules based on professional expertise and experience. Researchers may now incorporate domain knowledge into decision-making.
- V. Because fuzzy logic adapts to changing situations and can learn from new data, it is particularly beneficial in a research setting where data is continually updated and modified.

Both fuzzy logic and artificial neural networks (ANN) are helpful tools in nano PCM research, but they have unique advantages and weaknesses. Fuzzy logic excels in dealing with ambiguity, linguistic variables, and non-linear connections, whereas ANN excels at dealing with massive volumes of data and identifying complicated patterns. The research issue and the available data ultimately dictate the approach to be used. Finally, Fuzzy Logic is a valuable tool in the sphere of nano PCM development and research due to its capacity to handle uncertainty, add linguistic factors, model non-linear correlations, and adapt to changing situations. Although it is not always superior to ANN, it is a significant supplement to other approaches and should be considered during experiment design and data analysis.

2.3 Support Vector Machines

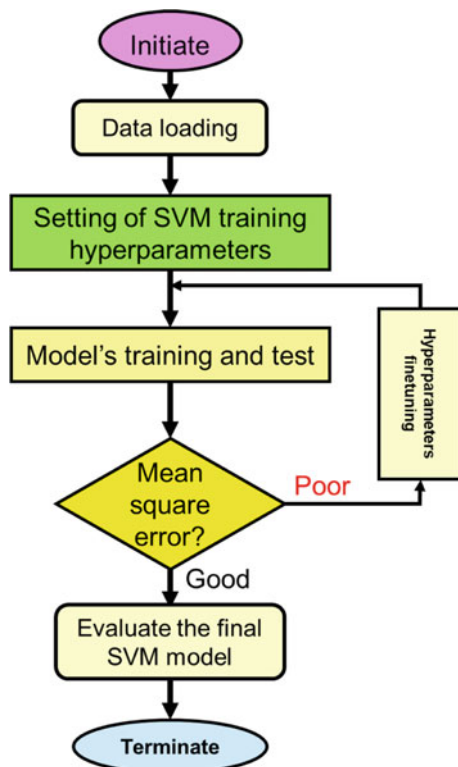
SVM is a powerful ML technique that is commonly employed used in regression and classification. The basic idea behind SVM is to find the best decision boundary (hyperplane) in a high-dimensional feature space that splits data points belonging to different classes. In model prediction, SVM follows the following general procedure [50–52]:

- I. Data Preparation: Preparing the data is the first step in any machine learning model. Cleaning the data, splitting it into training and testing sets, and transforming the data into a format that the model can use are all part of this process.
- II. Feature selection: Following that, the features that are most relevant to the problem are chosen. This is significant because irrelevant features can degrade the model's performance.
- III. Model training: SVM learns the parameters that define the hyperplane that is the finest in separating the data points belonging to different classes during the model training. The objective is to find a hyperplane that maximizes the margin, which is the distance between the data point closest to it in each class and hyperplane.
- IV. Model testing: After the model has been trained, it is put to the test on a new set of data. The model's performance is assessed by comparing its predictions to the true labels of the test data.

Once the model has undergone training and validation, it may be employed for forecasting a new set of data. A typical depiction of SVM is shown in Fig. 5.

Overall, SVM is a powerful ML technique capable of handling complex data and producing accurate predictions. However, careful parameter selection is required, and it can be computationally prohibitive for big datasets. It is being used in the nano PCM research sector for the following purposes [10, 53, 54]:

- I. SVM is a commonly used ML technique in a range of domains, including nanotechnology research and development. SVM has been used to analyze and forecast the characteristics of nano-PCM, a class of materials having potential uses in data storage, thermal management, and other areas. SVM is utilized in micro PCM development and research in the following ways.
- II. SVM may be used to forecast micro PCM features like TC, melting point, and latent heat of fusion. An algorithm may learn given a set of data that includes a material's chemical composition and physical attributes, and then apply that information to anticipate the qualities of a new micro PCM.
- III. SVM can additionally be employed to categorize distinct types of micro PCM according to their properties, such as low or high TC. This can aid in determining the presence of viable materials for certain applications.
- IV. SVM may be used to identify the key characteristics (chemical or physical qualities) which contribute to the performance of a material. This can aid in the optimization of micro PCM designs.

Fig. 5 SVM flow chart

When compared to other recent ML approaches, SVM has various benefits and downsides. SVM performs effectively with high-dimensional data, which is prevalent in micro PCM research. SVM can be more precise when applied to new data since it is less prone to overfitting than other ML methods. SVM is capable of coping with non-linear relationships between characteristics and outcomes, which may be valuable in many real-world problems [45, 54].

However, there are several downsides to using SVM in micro PCM research, including the fact that SVM may be computationally expensive when working with huge datasets or sophisticated models. SVM is hyperparameter sensitive, therefore careful adjustment may be required to attain optimal performance. SVM may not perform as well as other ML methods, such as deep learning models when dealing with particular types of data or situations [55, 56].

Overall, SVM is a useful technique in nano PCM research and development; however, its success is contingent on its implementation and the data being analyzed. It is crucial to carefully analyze the benefits and disadvantages of SVM in contrast to other ML approaches when picking a strategy for a given problem.

2.4 *Boosted Regression Tree*

The boosted regression tree (BRT) is a robust machine learning approach that combines decision trees and boosting, an approach used to increase the precision of weak learners by iteratively training them on the faults of earlier models [57]. The procedure involved in the development of BRT's model is shown as [57–59]:

- I. Initialization: The method begins by creating an initial regression tree to predict the target variable using the input characteristics.
- II. Prediction: The first tree is used to generate predictions on the training data. The residuals are determined as the difference between these forecasts and the actual values of the target variable.
- III. Third, residuals are utilized to reweight the training data. Instances with larger residuals are given more weight, meaning that they will have a bigger effect on the tree that follows.
- IV. The method then builds a new regression tree to anticipate the previous step's residuals. This new tree is trained using re-weighted training data.
- V. Tree pairing: The new tree is paired with the previous tree to form a forest ensemble. The combined model can now predict the target variable by combining the predictions of all the trees.
- VI. Iteration: The procedure is repeated by first applying the new model to the training data and then building a new tree to forecast the residuals.
- VII. Stopping criteria: When a stopping condition is fulfilled, such as when the maximum number of trees is achieved or when the model's prediction gain is no longer substantial, the algorithm grinds to a halt.

The final model is a synthesis of all of the trees formed during the iteration phase. BRT is most successful when the connection between the target variable and the input characteristics is complicated and nonlinear. It can also handle missing data and is immune to outliers. Figure 6 depicts a typical BRT model. However, if the number of trees is too great, BRT is prone to overfitting, therefore tuning the model's hyperparameters is crucial to avoid this issue [58, 60].

BRT is a machine learning approach that is used in micro PCM studies and research to model and predict the characteristics of these materials. Here are a few instances of BRT's application in this industry [61, 62]:

- I. BRT may be used to forecast the thermal characteristics of micro PCMs, including melting and solidification temperatures, enthalpy, and thermal conductivity. The BRT model may reliably predict these qualities for novel materials after being trained on a set of experimental data.
- II. Nano PCM Design Optimisation: BRT may also be utilized to optimize nano PCM design. The model can identify the optimum material property combination that will generate the desired thermal performance by inputting multiple material property combinations into it.

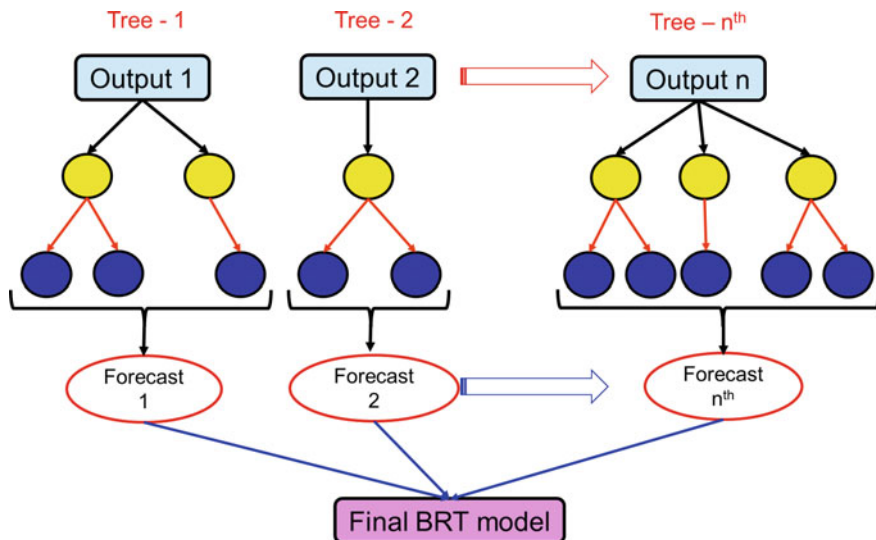


Fig. 6 BRT model's flow chart

III. BRT may be utilized to discover the key aspects of micro PCMs that influence their thermal properties. This can help researchers better understand the fundamental processes that regulate how certain materials behave.

BRT provides various benefits over recent ML algorithms like as ANN and SVM in the arena of micro PCM studies and research [63–65]:

- I. Interpretability: Because they may offer information about the relative relevance of numerous characteristics in forecasting the result, BRT models are more interpretable than neural networks. This helps researchers better grasp the fundamental mechanics of nano PCM behavior.
- II. Robustness: BRT models are less susceptible to overfitting neural networks when dealing with tiny datasets. This improves their ability to anticipate the thermal characteristics of micro PCM.
- III. Scalability: BRT models are more scalable than support vector machines because they can accommodate a high number of characteristics and observations without becoming computationally costly.

Finally, BRT is a powerful machine-learning approach for modeling and forecasting the thermal characteristics of nanophase transition materials. It has interpretability, robustness, and scalability benefits over existing ML approaches.

2.5 Other Contemporary ML Methods

In recent years, a few popular modern Machine Learning approaches have been created and used.

Decision Trees with Gradient Boosting

Gradient Boosting Decision Trees (GBDT) is a type of ensemble approach that combines many decision trees to produce a powerful prediction model. GBDT is valuable in the case of structured datasets, like time series. They have been utilized in a wide range of applications, including the recognition of images, text classification, and detection of fraud [61].

Automated Machine Learning

Automated Machine Learning (AutoML) is a group of procedures and tools for mechanizing the growth of ML models. Because it automates several time-consuming and problematic activities essential in model development construction, AutoML is extremely useful for people who are not Machine Learning experts. This ML technique showed outstanding performance in natural language processing, image recognition, and time series prediction [66, 67].

Deep Reinforcement Learning

DRL is a machine learning technology that combines reinforcement learning with deep neural networks. DRL algorithms can make decisions and take action in complex, dynamic environments by communicating with them over time. This technology has been used effectively in the domains of robotics, nanofluids, self-driving cars, and game engineering [68, 69].

Bayesian Optimization

Bayesian Optimisation is a strategy for optimizing expensive black-box ML algorithms that leverages Bayesian inference. It is useful when performing hyperparameter finetuning in ML models. Bayesian Optimisation has been utilized in a wide range of applications, including image recognition, natural language processing, and time series forecasting [70, 71].

Generative Adversarial Networks

GANs are a type of neural network architecture that may create new data samples that are comparable in a given dataset. GANs are useful in a wider range of complex technological applications, like image and video synthesis, text-to-image translation, and voice conversion [72, 73].

Random Forest

Random forest (RF) is a subclass of an ensemble-based model training system that generates several decision trees and subsequently integrates their outcomes to build a final prediction. A random selection of characteristics and a random sample of data

are used to build each tree. Random Forest is a powerful technique for handling large sets of data, and it can handle both categories and numerical data [74, 75].

Deep Belief Networks (DBN)

Deep Belief Networks (DBN) are an example of deep learning technology that learns an organizational structure of the input through unsupervised learning. Layers of limited Boltzmann machines train unsupervised layer by layer to form DBNs. Throughout RBM training, the network is fine-tuned to perform a specific task employing supervised learning. DBNs are useful for handling multidimensional data like video, images, and audio [76].

Convolutional Neural Networks

Convolutional Neural Networks (CNN) are an example of a deep learning technique that was created to cope with video and image data. CNNs extract characteristics of images by using convolutional and pooling layers, which reduce the dimensionality of the retrieved information. CNNs excel at dealing with large and complex datasets, and they may be at the cutting edge of classification and recognition of image issues [77].

Recurrent Neural Networks

Recurrent Neural Networks (RNN) are a type of deep learning algorithm designed to cope with sequential data such as written words, audio recordings, and time series. RNNs use recurrent connections to remember previous inputs and then employ that knowledge to forecast future input. RNNs perform exceptionally well with sequential data and can achieve cutting-edge results for natural language processing, recognition of speech, and time-series prediction issues [78, 79].

These can be considered only a few among several sophisticated ML methods which are currently being employed in a variety of fields. The appropriate ML technique is determined by the data type, job difficulty, and expected performance. Many more methodologies and algorithms have been developed and utilized in a variety of areas, and the field of ML is expanding all the time.

3 Challenges and Future Perspectives

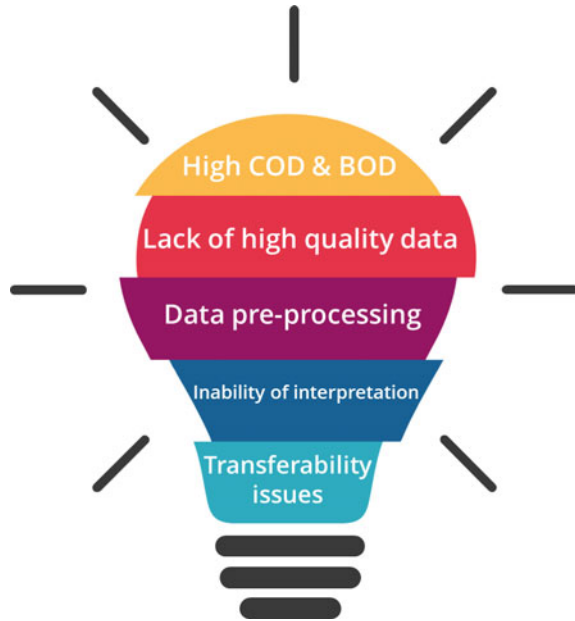
Nanotechnology has transformed several industries, including storage of energy, thermal control, and electronics. Machine learning (ML) has become known as a powerful method for analyzing vast and complicated datasets in nanotechnology research in recent years. ML, in specific, has the potential to anticipate and optimize the properties of micro PCMs for an array of applications. Nevertheless, significant challenges must be overcome before ML can be used successfully in nanotechnology research, particularly in the discipline of nano PCM [73, 80].

- I. One of the many major challenges to using ML for nanotechnology studies is a shortage of high-quality data. Given the difficulty in synthesizing and characterizing micro PCM, collecting data from experiments is a laborious and expensive task. Furthermore, the tiny size and inclination of nanoparticles to agglomerate make precise and trustworthy data difficult to gather. As a result, to obtain high-quality data for ML analysis, standardized and well-defined experimental techniques are necessary.
- II. Data Preparation: The other vital issue in ML-based nanotechnology research is the data analysis in pre modeling phase by making use of raw experimental data. The data collected through experiments frequently contain noise, missing values, and outliers, which can have a substantial influence on the accuracy and performance of machine learning systems. Owing to this, data pre-processing methods including normalization of data, feature selection, and data improvement are vital to improve data quality and assure the trustworthiness of ML models.
- III. Interpretability: ML algorithms generally create prediction models which are complicated to comprehend. Understanding the basic ideas and physical processes that support the behavior of micro PCM is essential in nanotechnology research. Nevertheless, given the complexity of ML-based prediction models, the underlying mechanisms, physics, chemistry, and material properties may be difficult to understand. As a consequence, researchers must create interpretable machine learning models that provide information on the fundamental principles that control micro PCM activity.
- IV. Model validation: Model validation is also a key difficulty in ML-based nanotechnology research. The quality and amount of test data used to learn and evaluate machine learning algorithms have a significant impact on their efficiency. The experimental information utilized for model validation and training in the context of micro PCM might not be indicative of actual settings and applications. As a consequence, to confirm the models' accuracy and reliability, researchers must test them in a range of actual settings and compare the outcomes to the results of experiments.

Figure 8 demonstrates the many obstacles associated with ML approaches.

To summarize, the use of ML in nanotechnology research, particularly in the realm of nano PCM, poses several obstacles that must be solved to assure the correctness and dependability of the models. Among these obstacles are a shortage of high-quality data, data pre-treatment, interpretability, model validation, and transferability. To overcome these obstacles, researchers from several domains, including material science, physics, chemistry, and computer science, will need to work together to construct robust and interpretable ML models that can provide insights into the physical principles that drive the behavior of micro PCM [12, 54].

Fig. 8 Challenges with machine learning techniques



Machine learning has grown into a crucial component of current nanotechnology research because of its capacity to spot patterns and predict outcomes in complicated systems. Machine learning, in particular, can alter how we discover and engineer materials with optimal characteristics in the field of nano PCM (Phase Change Materials).

- I. The creation of innovative materials with better thermal properties is one possible use of machine learning in micro PCM research. Researchers can identify trends and correlations that would be difficult or impossible to detect using standard experimental procedures alone by applying machine learning algorithms to analyse vast databases of material characteristics and synthesis variables. This could lead to improved effectiveness and affordability of synthesis procedures, as well as greater control over material properties.
- II. ML may be utilized to boost the accuracy of micro PCM simulations and models. Researchers can enhance prediction accuracy while lowering processing time by introducing machine learning algorithms into simulation frameworks. This will allow for more extensive and exact simulations of the behavior and characteristics of micro PCMs, resulting in a better understanding and design of these materials.
- III. Material processing and synthesis optimization is another possible use of machine learning in nano PCM research. Machine learning algorithms may analyze data from multiple manufacturing steps and optimize elements such as temperature, pressure, and reaction time to produce desired material properties.

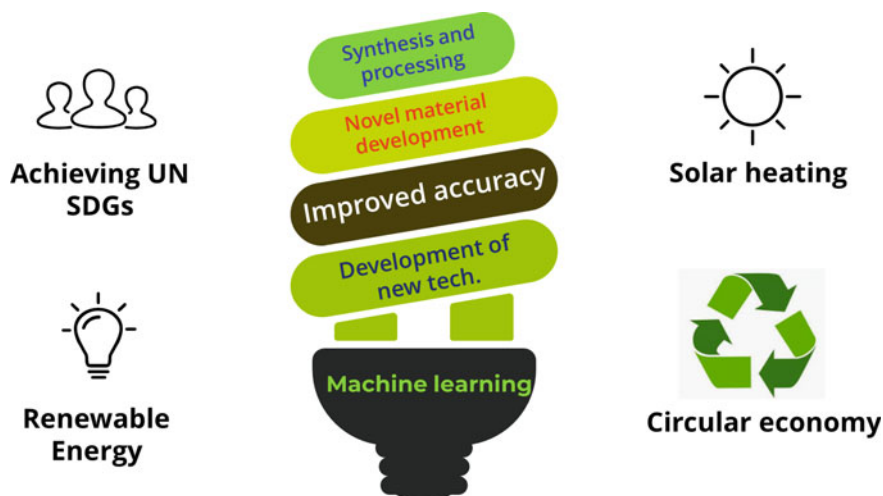


Fig. 9 Future perspectives and allocations of nano PCMs

This has the potential to result in more efficient and cost-effective synthesis procedures, as well as more precise control over material properties.

- IV. Apart from these specific applications, merging machine learning alongside nano PCM research has far-reaching effects on nanotechnology science in general. Machine learning has the potential to speed the development of new technologies and applications in a variety of sectors, including energy storage, medical diagnostics, and beyond. Machine learning may hasten the development of innovative technologies and applications ranging from energy storage to medical diagnostics as well as by enabling more efficient and effective design and engineering of nanomaterials.

As a whole, the use of ML in nano PCM research offers enormous promise for the creation of innovative materials and technologies with improved thermal properties. However, meticulous attention to data quality and interpretation, as well as continual innovation and cooperation among nanotechnology and machine learning professionals, will be essential. Figure 9 displays the viewpoints and deployment of micro PCM-based technologies in the future.

4 Conclusions

As a result, the use of machine learning in the development of nano PCM is a potential road ahead for the progress of energy storage technology. The combination of nanotechnology and machine learning enables the development, optimization, and synthesis of high-performance PCM materials. The usage of nano PCM in building insulation, thermal management, and energy storage systems is expected to become

increasingly frequent in the future because of the growing need for energy-efficient systems.

- Machine learning algorithms have proven their ability to anticipate the properties of PCM materials, improve synthesis conditions, and reduce the time and cost involved with traditional trial-and-error procedures.
- Furthermore, integrating machine learning with experimental techniques including as spectroscopy, microscopy, and thermogravimetric measurement allows for more precise and trustworthy predictions of PCM characteristics, thereby accelerating the creation of novel materials.
- However, there are several obstacles and limits to using machine learning in the creation of micro PCM. A shortage of vast and diverse datasets, the complexity of PCM materials, and the difficulty of comprehending machine learning models are some of the primary hurdles that must be solved.
- Additionally, the ethical and societal ramifications of using machine learning into energy storage technologies should be properly explored. Despite these challenges, the potential benefits of using machine learning into the development of micro PCM cannot be underestimated.

The integration of nanotechnologies, machine learning, and other emerging technologies such as 3D printing and microfluidics offers up new avenues for the design and synthesis of sophisticated materials with previously unheard-of performance. It is vital to continue investing in research and development in this sector in order to fully realize the promise of nano PCM and machine learning in solving the pressing concerns of energy sustainability and climate change.

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Chapter 12

Challenges and Difficulties in Developing Nano-enhanced Phase Change Materials and Way Forward



A. K. Pandey and Zafar Said

1 Introduction

Several incorporation methods are employed to incorporate nano-PCMs in buildings as a result of the rising worldwide energy demand. Researchers have also used nano-PCM composites in numerous other applications, such as fabrics and textiles, the thermal management of electronic gadgets, and the medical sector owing to their superior thermal conductivity and high latent heat [1]. In addition to these uses, nano-PCMs have been deployed for the cooling of PV panels, food packaging, and cold storage. The choice of PCM and the amount of nanoparticles should be taken into consideration by researchers based on the existing literature. Since a higher concentration results in a higher viscosity, which impedes natural convection, the PCM phase transition temperature should be within the range of the application temperature. Also, choosing the right PCM and nano-fillers results in long-term thermal stability, which is a crucial component that improves the performance of nano-PCMs

A. K. Pandey (✉)

Research Centre for Nano-Materials and Energy Technology (RCNMET), School of Engineering and Technology, Sunway University, No. 5, Jalan Universiti, Bandar Sunway, 47500 Petaling Jaya, Selangor Darul Ehsan, Malaysia

e-mail: adarshp@sunway.edu.my

CoE for Energy and Eco-Sustainability Research, Uttaranchal University, Dehradun, India

Z. Said (✉)

Department of Sustainable Renewable Energy Engineering, University of Sharjah, Sharjah, United Arab Emirates

e-mail: zsaid@sharjah.ac.ae

Department of Industrial and Mechanical Engineering, Lebanese American University (LAU), Byblos, Lebanon

U.S.-Pakistan Center for Advanced Studies in Energy (USPCAS-E), National University of Sciences and Technology (NUST), Islamabad, Pakistan

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in all applications. Because of this, choosing the right material is crucial, and various stability improvement techniques can also be used to increase the effectiveness of nano-PCMs.

The use of phase change materials in various fields has gained a lot of attention in recent years, especially due to their ability to store and release thermal energy [2]. They have found numerous applications in fields such as building construction, thermal energy storage, and electronics cooling. However, the effectiveness of these materials has been limited by their low thermal conductivity and low heat transfer rates, which can be improved by the incorporation of nanostructures [3]. Nano-enhanced phase change materials (NePCMs) are a type of PCM that incorporate nanomaterials, such as nanoparticles or nanotubes, to enhance their thermal properties [4]. These materials have been shown to have high thermal conductivity, high heat transfer rates, and improved thermal stability compared to traditional PCMs. Despite their potential benefits, the development of NePCMs still poses several challenges and difficulties that need to be addressed to bring them to market [5]. NePCMs are a promising solution for thermal energy storage applications due to their unique properties [6]. The incorporation of nanotechnology into PCM technology has resulted in materials with high thermal conductivity, high specific heat capacity, and improved thermal stability, making them superior to conventional PCMs [7].

The thermal conductivity of NePCMs can be increased by incorporating nanoparticles, such as carbon nanotubes, graphene [8], and metal oxides, into the PCM matrix. The high thermal conductivity of these nanoparticles improves the heat transfer rate, making NePCMs more efficient at storing and releasing thermal energy [9]. The high specific heat capacity of NePCMs allows them to store more thermal energy per unit mass than conventional PCMs. Moreover, the improved thermal stability of NePCMs enables them to maintain their thermal properties over a wider temperature range. NePCMs can be used in a wide range of thermal energy storage applications [10], such as heating and cooling systems, thermal insulation, and renewable energy systems. They can store thermal energy for extended periods, reducing the need for frequent energy input, and can be charged and discharged rapidly [11]. Despite their potential benefits, the development of NePCMs faces several challenges and difficulties, as discussed earlier. However, research and development in this field are rapidly advancing, and the potential benefits of NePCMs make them a promising solution for thermal energy storage applications [12].

Here are some of the advantages and disadvantages of NePCMs:

Advantages:

1. *High thermal conductivity:* The addition of nanoparticles to the PCM matrix enhances its thermal conductivity, which leads to a faster charging and discharging process, and improves the overall energy efficiency [13].
2. *High energy density:* NePCMs have a higher energy density than traditional PCMs, which means they can store more thermal energy in a smaller volume.
3. *Improved thermal stability:* The presence of nanoparticles can improve the thermal stability of NePCMs and prevent them from degrading over time, resulting in a longer lifespan.

4. *Enhanced mechanical properties*: NePCMs can also improve the mechanical properties of the PCM matrix, making them more resistant to cracking or breaking.

Disadvantages:

1. *Cost*: The production of NePCMs involves complex and expensive manufacturing processes, which can make them more expensive than traditional PCMs.
2. *Nanoparticle agglomeration*: The nanoparticles added to the PCM matrix can sometimes agglomerate, which can reduce their effectiveness and lead to uneven energy distribution.
3. *Toxicity concerns*: Some nanoparticles used in NePCMs may have toxic properties, which can pose health and environmental risks during manufacturing, use, and disposal.
4. *Compatibility issues*: NePCMs may not be compatible with all materials and systems, which can limit their applicability in some contexts.

Hence, NePCMs offer several advantages over traditional PCMs, particularly in terms of their thermal conductivity, energy density, and stability. However, their higher cost and potential toxicity concerns may limit their widespread adoption in certain applications [14]. There are several methods for producing NePCMs, each with its advantages and disadvantages. The following are some of the common methods for producing NePCMs.

1. *Sol–Gel Method*

The sol–gel method is a widely used technique for producing NePCMs. In this method, a sol (colloidal suspension) of the PCM is mixed with a metal oxide precursor. The mixture is then heated to form a gel, which is subsequently dried and calcined to form the NePCM [15]. This method allows for the production of NEPCMs with uniform particle size and distribution.

2. *Co-precipitation Method*

The co-precipitation method involves the simultaneous precipitation of the PCM and the nanoparticle precursors from an aqueous solution. The resulting nanoparticles are then embedded into the PCM matrix, forming the NePCM. This method is relatively simple, and the resulting NePCMs exhibit good thermal stability and homogeneity [16].

3. *In-Situ Polymerization Method*

The in-situ polymerization method involves the incorporation of nanoparticles into the PCM matrix during the polymerization process. In this method, the PCM monomer is mixed with the nanoparticle precursors, and the mixture is subsequently polymerized [17]. The resulting NePCMs exhibit good thermal stability and uniformity.

4. *Sonication Method*

The sonication method involves the use of high-intensity ultrasound waves to disperse nanoparticles into the PCM matrix. The ultrasound waves break down the agglomerated nanoparticles into smaller particles, resulting in a more homogeneous dispersion [18]. This method is relatively simple and can produce NePCMs with high thermal conductivity and specific heat capacity.

5. *Spray Drying Method*

The spray drying method involves the atomization of a solution of the PCM and nanoparticle precursors into a hot gas stream. The resulting droplets are rapidly dried, forming NePCMs with a homogeneous distribution of nanoparticles [19]. This method is relatively simple and can produce NePCMs with a high degree of homogeneity.

6. *Chemical Reduction*

Chemical reduction involves the reduction of metal ions to form nanoparticles in the presence of the PCM. This method is useful for producing metal oxide nanoparticles such as titanium dioxide, zinc oxide, and iron oxide [20].

7. *Electrostatic Atomization*

Electrostatic atomization involves the electrostatic charging of the PCM and the nanoparticles, followed by their atomization into a gas stream. This method produces fine particles with a narrow size distribution.

In summary, NEPCMs have the potential to revolutionize thermal energy storage technology. While there are challenges and difficulties associated with their development, the benefits of NePCMs make them a promising solution for thermal energy storage applications. Further research in this area is needed to overcome the challenges and develop sustainable, cost-effective, and safe NePCMs.

2 Challenges and Difficulties

1. *Synthesis and Fabrication*

One of the main challenges in developing NePCMs is the synthesis and fabrication of the nanomaterials themselves. The synthesis of nanoparticles or nanotubes with the desired size, shape, and composition is a complex process that requires specialized equipment and expertise. Additionally, the incorporation of these nanomaterials into the PCM matrix requires careful control of the dispersion and aggregation of the nanoparticles, which can affect the thermal properties of the resulting NePCM.

2. *Stability and Durability*

Another challenge in developing NePCMs is ensuring their stability and durability. The addition of nanomaterials can lead to changes in the chemical and physical properties of the PCM, which can affect its long-term stability and durability. Additionally, the high surface area of the nanoparticles can lead to increased oxidation and degradation of the material, which can further affect its performance over time.

3. *Uncontrolled Operation*

Phase change materials or NEPCMs are temperature dependent, they undergo a phase transition from solid to liquid when they are a rise in atmospheric temperature above the melting point of PCMs or NEPCMs. Likewise, PCMs transfer their phase from liquid to solid, only when the atmospheric temperature drops below the freezing point.

4. *Cost and Scalability*

The cost and scalability of NePCMs are another challenge that needs to be addressed. The synthesis of nanoparticles and nanotubes can be a costly process, and the incorporation of these materials into the PCM matrix can further increase the overall cost of the material. Additionally, the scalability of the production process is another consideration, as the current methods for synthesizing and incorporating nanomaterials may not be suitable for large-scale production.

5. *Environmental Impact*

The potential environmental impact of NePCMs is also a concern. The production of nanoparticles and nanotubes can result in the release of harmful chemicals and by-products into the environment. Additionally, the disposal of NePCMs at the end of their lifecycle may pose environmental risks, particularly if the nanoparticles or nanotubes are not biodegradable.

6. *Safety Issues*

Finally, safety issues related to the use of NePCMs need to be addressed. The small size of the nanoparticles and nanotubes raises concerns about their potential toxicity, particularly if they are released into the environment or come into contact with humans. Additionally, the high surface area of the nanoparticles can lead to increased reactivity and potential fire hazards if not handled properly.

2.1 *Synthesis Technique and Their Challenges*

The synthesis method used to create NePCMs can significantly affect their stability and durability. If a more robust and efficient synthesis method is used, it can result in

NePCMs that have fewer defects or impurities, leading to better stability and durability. A robust and efficient synthesis method refers to a manufacturing process that produces high-quality nanoparticles and NePCMs with minimal defects or impurities. Such a process should also be scalable and cost-effective.

The robustness of a synthesis method also refers to its ability to consistently produce high-quality nanoparticles or NePCMs that meet the desired specifications. A robust synthesis method should be reliable, reproducible, and capable of producing consistent results across multiple batches. Efficiency, on the other hand, refers to the ability of a synthesis method to produce nanoparticles or NePCMs with high yield and minimal waste [17]. An efficient synthesis method should maximize the production of high-quality nanoparticles while minimizing the use of raw materials and energy. Examples of robust and efficient synthesis methods include sol–gel synthesis, precipitation methods, and spray drying [21]. These methods offer precise control over the size, shape, and composition of nanoparticles, which can result in more stable and durable NePCMs. For example, if a synthesis method is used that ensures better dispersion of nanoparticles in the PCM matrix, it can result in a more stable NePCM with improved durability over multiple thermal cycles [4]. In contrast, if a synthesis method results in the clumping of nanoparticles or an uneven distribution, it can lead to a less stable and less durable NePCM. Using a more robust and efficient synthesis method can result in a higher-quality NePCM that requires less frequent replacement, leading to cost savings over time. Additionally, by improving the stability and durability of NePCMs, it may be possible to reduce the amount of PCM and nanoparticles needed, further lowering the overall cost of production [22]. It can help to overcome some of the challenges and difficulties associated with NePCM development, such as high cost and low stability. It can also lead to cost savings by reducing the need for frequent replacement and minimizing the use of raw materials and energy. A robust and efficient synthesis method is critical for the development of stable and durable NePCMs that are economically viable. Various synthesis methods have been developed for the production of nanoparticles and NePCMs, including chemical methods, physical methods, and green synthesis methods [23]. These methods differ in their ability to produce high-quality nanoparticles, their scalability, and their cost-effectiveness.

Chemical methods involve the use of chemical reactions to form nanoparticles. They are often used because they can produce nanoparticles with controlled size and shape, and can be easily scaled up for commercial production [24]. However, the use of chemicals in these methods can result in impurities and defects in the nanoparticles, which can negatively impact the stability and durability of the NePCMs [25]. Examples of chemical methods include co-precipitation, hydrothermal synthesis, and solvothermal synthesis [26]. However, they can be expensive and require specialized equipment, which can increase the cost of production. Examples of physical methods include ball milling, laser ablation, and plasma arc synthesis.

Green synthesis methods involve the use of natural or non-toxic materials to create nanoparticles. These methods are becoming increasingly popular due to their sustainability and low environmental impact. However, they often require longer synthesis times and may result in lower yields of nanoparticles. Green synthesis

methods are another class of synthesis methods that have gained attention for the production of nanoparticles and NePCMs [27]. Green synthesis methods use plant extracts, microorganisms, or other natural materials to synthesize nanoparticles. These methods are environmentally friendly and offer several advantages, such as low cost and low toxicity. Examples of green synthesis methods include biosynthesis, plant extract-mediated synthesis, and microwave-assisted synthesis. Figure 1 shows the synthesis of iron oxide Fe_3O_4 nanoparticles using an aqueous leaves extract of Artemisia plant. The synthesis process involves several steps, starting with the preparation of the plant extract. The leaves of the Artemisia plant are first collected, washed, and boiled in water. The aqueous extract is then separated and used as a reducing agent for the synthesis of Fe_3O_4 nanoparticles. In the next step, a solution of Ferric chloride (FeCl_3) is prepared by dissolving it in distilled water. The prepared aqueous leaves extract of Artemisia is then mixed with the FeCl_3 solution and stirred for a specific period to form a brownish-black colored solution. The mixing of the two solutions is important to allow the reduction of FeCl_3 to Fe^{2+} ions, which are essential for the formation of Fe_3O_4 nanoparticles. The brownish-black colored solution is then heated and refluxed for a specific period, resulting in the formation of Fe_3O_4 nanoparticles. The synthesized Fe_3O_4 nanoparticles are then collected and characterized for their size, morphology, and properties. The use of plant extracts for the biosynthesis of nanoparticles has gained increasing attention due to its biocompatibility, non-toxicity, and potential for large-scale production. The plant extract contains various bioactive compounds that act as reducing agents and capping agents, which can influence the size, shape, and properties of the synthesized Fe_3O_4 nanoparticles. This biosynthesis process is environmentally friendly, cost-effective, and relatively simple compared to conventional chemical synthesis methods. The use of green chemistry approaches for the synthesis of nanoparticles has significant potential for various biomedical, environmental, and industrial applications. Additionally, the synthesized Fe_3O_4 nanoparticles were found to exhibit antioxidant properties, indicating their potential use as a therapeutic agent.

Among the methods, the sol-gel method is an example of a robust and efficient synthesis method for NePCMs. The sol-gel method is a widely used chemical synthesis method for producing high-quality nanoparticles and NePCMs. The sol-gel method involves the hydrolysis and condensation of metal alkoxides to form a colloidal suspension, which is then used to create nanoparticles. This method offers several advantages, including precise control over the size and shape of nanoparticles, high purity of the resulting nanoparticles, and scalability for commercial production. This method involves the hydrolysis and condensation of metal alkoxides or metal salts to form a sol, which is then gelled to form a solid material. The resulting material can be further processed to form nanoparticles or NePCMs with precise control over their size, shape, and composition. The sol-gel method offers several advantages over other synthesis methods. It allows for the production of nanoparticles and NePCMs with high purity and uniformity, which can improve their stability and durability. It also offers precise control over the size and shape of nanoparticles, which can improve their thermal conductivity and energy storage capacity. Another

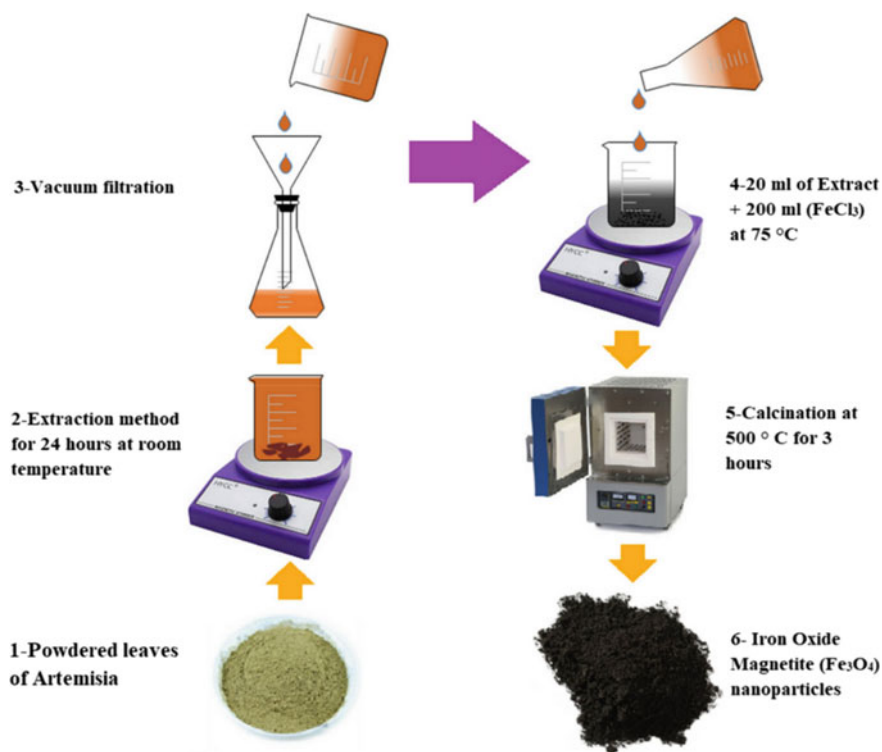


Fig. 1 Bio-synthesis for Fe_3O_4 nanoparticles [28]

advantage of the sol–gel method is its scalability. It can be easily scaled up for large-scale production, making it suitable for commercial manufacturing. Additionally, it is a relatively low-cost method compared to other chemical synthesis methods [29]. Another example of a robust and efficient synthesis method for NePCMs is the precipitation method. The precipitation method involves the precipitation of nanoparticles from a solution by adding a precipitant [30]. The resulting nanoparticles can then be incorporated into a PCM matrix to form NePCMs. The precipitation method offers several advantages for NePCM synthesis. It is a simple and low-cost method that can produce nanoparticles with high purity and uniformity [31]. Additionally, it is a scalable method that can be easily adapted for large-scale production. Therefore, it is important to consider the synthesis method used when developing NePCMs to ensure that they are stable and durable over time. This can lead to cost savings and increased economic viability in the long run.

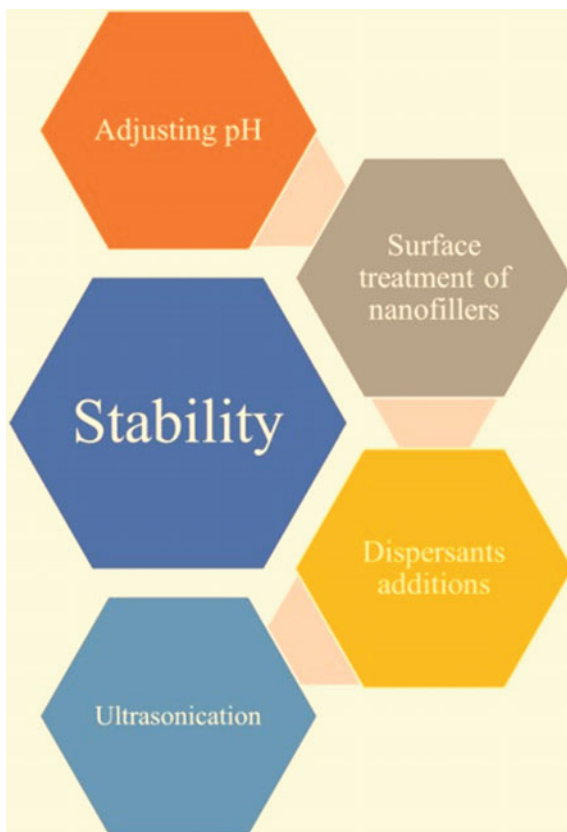
Though many synthesis techniques discussed above are scalable; there exists a greater void in NePCMs-based commercial applications. This is also due to the lack of commercial units and business investors in exploring the benefits of PCMs. There is a predominant need for technologies involving effective sonication of nanoparticles

with PCMs, which are a challenging activity specifically when dealing with low-temperature salt hydrate PCM. Any loss in hydrate molecules of the inorganic salt hydrate PCM will subsequently deteriorate the energy storage performance and is more likely to vary the phase transition temperature.

2.2 *Stability and Durability*

At the moment, most nano-enhanced phase change materials (NePCMs) based research is focused on enhancing the thermal properties and specific applications intended for thermal regulation. According to the existing studies, NePCMs has a greater thermal conductivity than basic PCMs, as well there are certain studies discussing on the effect of nanoparticle in overcoming the subcooling or supercooling issues [32]. In addition, it is important to investigate the energy storage and energy release behaviour of NePCMs. To explore the latent heat behaviour of NePCMs, more research is likely required. Although the majority of investigations demonstrated that adding nanoparticles reduced the latent heat, certain studies also showed that there is an ideal particle loading that generates the most latent heat. The findings' inconsistency has to be addressed by researchers. Further investigation is needed, particularly on the thermal stability of phase-change materials. To identify the optimum concentration that access to superior in both thermal conductivity and latent heat properties, optimum particle concentration in the PCM should be further analysed. PCMs boosted by nanotechnology may change as a result of repeated melting and solidifying operations, which could ultimately impair the material's overall thermal properties. NePCMs are designed to store and release thermal energy during phase change cycles, and they undergo repeated heating and cooling cycles during operation. As a result, they are subjected to various stresses, including thermal, chemical, and mechanical stresses, which can degrade their performance over time. One of the primary stability challenges of NePCMs is the tendency for nanoparticles to agglomerate or aggregate during the synthesis process or during storage. This can result in the non-uniform dispersion of nanoparticles in the PCM matrix, which can reduce their thermal conductivity and energy storage capacity. Agglomeration can also lead to the formation of hotspots and cold spots during the phase change process, which can affect the thermal stability of NePCMs. In the PCM, the forces of attraction and van der Waals play a role in particle aggregation. The Van der Waals force (attraction force) of nanoparticles weakens during the heating process, whereas the repelling force increases [33]. When the reverse happens (cooling of liquid PCM to become solid), there is a tendency for nanoparticles to aggregate and settle out. The solidification time needs to be shortened or reduced to minimize this issue. The gravitational pull prohibits nanoparticles from migrating downward or towards one another if the solidification time is short [34]. Researchers ought to take this issue under consideration for in-depth examination. Figure 2 lists the most influencing parameters affecting the stability of NePCMs.

Fig. 2 Factors influencing stability of NePCMs [1]



Another stability challenge is the tendency for NePCMs to undergo degradation or decomposition during repeated heating and cooling cycles. This can lead to changes in the phase change temperature, latent heat, and thermal conductivity of NePCMs, which can affect their performance [35]. Additionally, the thermal expansion coefficient of nanoparticles can differ from that of the PCM matrix, leading to the formation of internal stresses that can cause cracking and delamination of the NePCM. These can be improved through the use of appropriate materials and synthesis methods. For example, the use of high-quality nanoparticles with uniform size and composition can improve the stability and durability of NePCMs. Additionally, the use of appropriate surfactants and dispersants can improve the uniformity of nanoparticle dispersion in the PCM matrix, reducing the tendency for agglomeration. The choice of PCM matrix material can also affect the stability and durability of NePCMs. Stability and durability are critical factors that can impact the effectiveness and economic feasibility of NePCMs. In general, NePCMs are expected to have high thermal stability, meaning they can withstand repeated thermal cycling without undergoing significant degradation. They should also have good chemical stability, which refers to their ability to resist chemical reactions and maintain their

structural integrity. On the other hand, given that the particles being employed are nanoscale, researchers should also emphasise the safety component of NePCMs to human health and the environment. The use of NePCMs should be justified through techno-economic analysis as well.

The challenge with stability and durability in NePCMs is that the addition of nanoparticles can sometimes decrease the stability and durability of the PCM. The nanoparticles can agglomerate, leading to reduced thermal conductivity and PCM phase change properties. They can also cause chemical reactions that degrade the PCM, leading to reduced stability and durability over time. To address these challenges, various approaches have been developed to improve the stability and durability of NePCMs. One approach is to use surface-modified nanoparticles that are more stable and compatible with the PCM. The surface modification can reduce agglomeration and improve the dispersion of the nanoparticles, leading to improved thermal conductivity and phase change properties. Another approach is to use encapsulation methods to protect the NePCM from external factors that can degrade its stability and durability. Encapsulation methods can prevent the leakage of nanoparticles from the NePCM, which can cause unwanted reactions and reduce stability. Encapsulation can also protect the NePCM from external factors such as moisture, which can cause degradation over time. Additionally, as mentioned above the synthesis method used to produce the NePCM can also impact its stability and durability. As mentioned earlier, the sol-gel method and precipitation method are examples of robust and efficient synthesis methods that can produce high-quality nanoparticles and NePCMs with improved stability and durability. Overall, the challenge of stability and durability in NePCMs can impact their effectiveness and economic feasibility. However, by using surface-modified nanoparticles, encapsulation methods, and robust synthesis methods, researchers and manufacturers can improve the stability and durability of NePCMs, making them more viable for commercial applications.

Figure 3 consolidates the thermal stability of organic and inorganic PCM dispersed with a variety of nanoparticle for thermal performance enhancement over a repeated number of thermal cycles. Overall, the inclusion of most nanomaterials in a PCM causes a decrease in latent heat and an increase in thermal conductivity. Due to their high conductivity values, the carbon-based nano-fillers improved thermal conductivity more than other particles. In addition, carbon-based nanoparticles are stable due to their higher surface area and lower density. Nevertheless, due to their hydrophobic nature, CNTs do not distribute into the PCM properly, which causes agglomeration [36]. The surface treatment of CNTs can solve this problem. In contrast, metal oxide particles, such as TiO_2 particles, displayed only a modest improvement in thermal conductivity due to the poor thermal conductivities of metal and metal oxide particles, despite possessing stronger intermolecular interactions with the PCM. As a slight decrease in the energy storage capacity of PCMs with carbon-based fillers is adequate for a large improvement in thermal conductivity, researchers typically prefer these particles. However, the cost of the carbon-based particles is a major drawback when compared to metal and metal oxide particles. The overall cost of the particles can be limited while also boosting the thermophysical properties of the

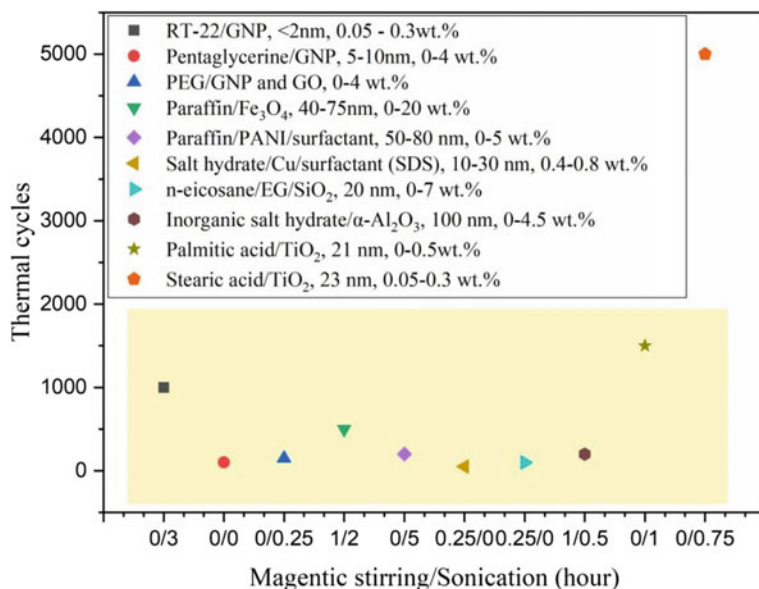


Fig. 3 Stability of NePCM synthesised via magnetic stirring/sonication [1]

nano-PCM with hybrid nanoparticles (i.e., carbon and metal or metal oxide particles) that have a small proportion of carbon particles and a large concentration of metal or metal oxide particles [13]. This hybrid nanoparticle also supports effective dispersion of the nanoparticle within the PCM by having an effect on the density of the base PCM and nanoparticle. Nonetheless, the aforementioned stability improvement techniques lead to the following conclusions.

- Surfactants can be used to increase the stability of nano-PCMs, but doing so reduces their thermal performance because they breakdown at higher temperatures when added in significant quantities. Because of this, the surfactant concentration in the nano-PCMs is a crucial element [37].
- In comparison to pristine nanoparticles, the surface-treated nanoparticles with acids showed good dispersion in PCMs.
- Whilst some studies lack mixing settings, ultrasonication of the nano-PCM improves particle stability. By adjusting the numerous factors, such as the ultrasonication frequency, temperature, and time, it is possible to further analyse the stability of nano-PCM.
- While small-size particles promote Brownian motion, which increases particle-to-particle interaction, it has been observed that smaller particles with bigger surface areas exhibit superior stability.
- The optimal pH value raised the electrostatic repulsive forces, which minimized the influence of particle agglomeration and increased the nanofluid stability duration, and this resulted in higher stability findings. There has been extensive

research on the effect of pH on the pH of nanofluids, but there is still room for more study of mono and hybrid nano-PCMs.

2.3 Uncontrolled Operation

Phase change material and nano-enhanced phase change materials are commonly applied for thermal regulation systems and for thermal energy storage unit. PCM absorbs and stored energy within when the ambient temperature of the operating location raises above the melting point of PCM; and this process is termed as charging. Likewise, for the next charging to occur, it is necessary for the PCM and NePCM to dissipate the stored energy and regain its phase from liquid to solid. On a keen observation, it is noticed that the charging and discharging of PCM and NePCM aren't operated via smart devices; and its completely temperature depended of the operating atmosphere. On the contrary, charging and effective heat storage of NePCM would be in trouble, if the liquid phase NePCM fails to freeze back to solid state, owing to any external factors like temperature, issue of supercooling, phase separation and instability of PCM.

In general, NePCM is actively used for thermal regulation of buildings, electronic gadgets, battery thermal management systems (BTMS), heat dissipation from photovoltaic panels, thermal energy storage in solar thermal systems and in smart fabrics. Let's discuss the issues associated with NePCM for each application in terms of uncontrolled operations. NePCM is integrated with building walls, ceiling, windows and roofs for thermal management. During daytime, NePCMs absorb sunlight and effectively undergo phase transition from solid to liquid phase, during night time in the absence of solar power, NePCM tends to release the stored energy. However, on a keen analysis, it's been noted that integration of NePCM with buildings located at the region with difference in temperature of the day by minimum of 15 °C is effective on integrating NePCM without any external aid. At this location the discharging of the PCMs is passive in nature, and doesn't need any external source; where building located in the region with a difference in temperature of the day below 15 °C, doesn't support complete discharging of the PCM and complete transition of PCM from liquid to solid phase. Thus there is a need for an active source to ensure a complete discharge phase transition of PCM, which can be achieved by PCM filled in a thermal system integrated with thermic fluid passing by. These added thermal units tend to increase the cost of the NePCM unit, as well as make the operation too complicated which hinders the commercialization of NePCM for building applications. Whereas, this is too severe when the opted NePCM is a base of organic PCM, which has higher degree of supercooling (ability of the material to not freeze at its freezing temperature). In addition, the severe problem associated is that there is no control system to switch ON and switch OFF NePCM charging and discharging as applicable for electrical batteries. This has been a major hindrance as they are temperature depended, and there is a greater void for research to be explored in uncontrolled operation of the PCMs on integration with thermal applications. Likewise, for other thermal applications like

BTMS and electronic gadgets the operating temperature is 60–70 °C at peak operation and during rest they are at an ambient temperature of 25–30 °C which undergoes complete phase transition without external aid. However, in this system, NePCM is packed or filled within the system which is assisted by heat transfer fluids passing within tubes. The flow of thermic fluid is controlled and the charging and discharging of the NePCM is controlled. Owing to too many mechanical systems, the efficiency of the system drops and makes the system too complicated for commercialization.

2.4 Cost and Scalability

NePCMs have the potential to revolutionize thermal energy storage applications due to their high thermal conductivity, high specific heat capacity, and improved thermal stability. However, the economic viability of NePCMs is a significant challenge that needs to be addressed for their widespread adoption.

The cost of raw materials, processing, and production is a significant factor that affects the economic feasibility of NePCMs. The cost of nanoparticles used in NePCMs is high, which increases the overall cost of production. Moreover, the manufacturing process of NePCMs is complex and requires specialized equipment and processes, which further increases the cost. The cost of raw materials, processing, and production is a critical factor that affects the economic feasibility of NePCMs. NePCMs require the use of nanoparticles, which are significantly more expensive than traditional materials. These nanoparticles, such as graphene, carbon nanotubes, or metal oxides, are used to enhance the thermal properties of the PCM, such as thermal conductivity and specific heat capacity [38]. The high cost of nanoparticles is primarily due to the complex synthesis process and the high purity required. Nanoparticles are typically synthesized using expensive chemicals and require specialized equipment to produce, which drives up the cost of raw materials. Additionally, the synthesis process must be carefully controlled to ensure that the nanoparticles are uniform in size and shape, which is essential for optimizing the thermal properties of the NePCM. The manufacturing process of NePCMs is also complex and requires specialized equipment and processes, which further increases the cost of production. For example, the nanoparticles must be mixed uniformly with the PCM, which is challenging due to their high surface area and tendency to agglomerate. Various techniques, such as ultrasonication, co-precipitation, or in-situ synthesis, are used to ensure uniform mixing of nanoparticles with the PCM, which adds to the complexity and cost of the production process.

Furthermore, the production of NePCMs requires careful control of the processing parameters, such as temperature, pressure, and reaction time, to ensure the desired properties of the NePCM. This requires skilled personnel, specialized equipment, and rigorous quality control measures, all of which add to the cost of production. In conclusion, the high cost of raw materials, processing, and production is a significant factor that affects the economic feasibility of NePCMs. The cost of nanoparticles, the complexity of the manufacturing process, and the specialized equipment and

processes required all contribute to the high cost of NePCMs. Future research and development efforts must focus on finding cost-effective production methods and improving the efficiency of NePCMs to enhance their economic viability.

To evaluate the economic feasibility of NePCMs, a cost–benefit analysis can be performed. The cost–benefit analysis involves comparing the cost of producing NePCMs with the benefits they provide, such as reduced energy consumption and increased efficiency. The analysis should consider the lifetime cost of the NePCM, including production, installation, and maintenance costs, and compare it with the cost of conventional thermal energy storage solutions.

The high cost of producing NePCMs has a direct impact on their economic viability, as it increases the payback period for the initial investment. The payback period is the time it takes for the NePCM's cost savings to equal the initial investment cost. Since the cost of producing NePCMs is higher than traditional PCMs, the initial investment cost is also higher. As a result, the payback period for NePCMs is typically longer than that of traditional PCMs. This longer payback period can be a barrier to their widespread adoption in many applications.

To improve the economic feasibility of NePCMs, efforts must be made to reduce the cost of production and improve their performance. Reducing the cost of production can lead to a shorter payback period, making NePCMs more attractive to potential users. Additionally, improving the performance of NePCMs, such as increasing their thermal conductivity and specific heat capacity, can lead to increased cost savings, further improving their economic viability [39]. To further illustrate the cost challenges associated with NePCMs, we can perform a cost analysis using a mathematical equation. The cost of producing NePCMs can be estimated using the following equation:

$$\text{Total cost} = \text{Raw material cost} + \text{Processing cost} + \text{Overhead cost} \quad (1)$$

$$\begin{aligned} \text{Raw material cost} = & (\text{Mass of PCM} \times \text{Unit price of PCM}) \\ & + (\text{Mass of nanoparticles} \times \text{Unit price of nanoparticles}) \end{aligned} \quad (2)$$

$$\text{Processing cost} = \text{Labor cost} + \text{Equipment cost} + \text{Energy cost} \quad (3)$$

$$\text{Overhead cost} = \text{Maintenance cost} + \text{Quality control cost} + \text{Miscellaneous cost} \quad (4)$$

The raw material cost includes the cost of PCM and nanoparticles, which are the main components of NePCMs. The processing cost includes labor, equipment, and energy costs, which are associated with the production process. The overhead cost includes various other costs, such as maintenance, quality control, and miscellaneous costs.

Example 1

Let's assume we are producing 1 kg of NePCM using paraffin wax as the PCM and silica nanoparticles as the nanoparticle. The unit price of paraffin wax is \$1 per kg, and the unit price of silica nanoparticles is \$50 per kg. We can estimate the raw material cost as follows:

$$\text{Raw material cost} = (1 \text{ kg} \times \$1/\text{kg}) + (0.01 \text{ kg} \times \$50/\text{kg}) = \$1.5$$

Assuming that the labour cost is \$20 per hour, and it takes 5 h to produce 1 kg of NePCM. The equipment cost is estimated to be \$5000, and the energy cost is estimated to be \$0.50 per kg of NePCM. We can estimate the processing cost as follows:

$$\begin{aligned} \text{Processing cost} &= (\$20/\text{hour} \times 5 \text{ h}) + \$5000 + (1 \text{ kg} \times \$0.50/\text{kg}) \\ &= \$102.5 \end{aligned}$$

Lastly, we can estimate the overhead cost as \$50, bringing the total cost to \$154.

$$\begin{aligned} \text{Total cost} &= \$1.5(\text{raw material cost}) + \$102.5(\text{processing cost}) \\ &\quad + \$50(\text{overhead cost}) = \$154 \end{aligned}$$

As we can see from this example, the cost of producing NePCMs can be quite high. In this case, the cost of producing 1 kg of NePCM is estimated to be \$154, which is significantly higher than the cost of producing traditional PCMs. Therefore, to improve the economic viability of NePCMs, efforts must be made to reduce the cost of production. This can be achieved through the development of more cost-effective production methods, the optimization of the manufacturing process, and the reduction of raw material costs. These efforts can lead to a shorter payback period, making NePCMs a more attractive option for thermal energy storage applications.

Therefore, finding ways to reduce the cost of producing NePCMs while improving their performance is essential for enhancing their economic viability. This can be achieved through research and development efforts focused on developing new and more cost-effective production methods, improving the synthesis process of nanoparticles, and optimizing the manufacturing process. Ultimately, these efforts can lead to a shorter payback period for NePCMs, making them a more attractive option for thermal energy storage applications. Overall, the economic viability of NePCMs depends on several factors, such as the cost of raw materials, production, and installation. However, several studies have shown that NePCMs can be economically feasible for various thermal energy storage applications. Further research is needed to develop cost-effective production methods and improve the efficiency of NePCMs to enhance their economic viability.

2.5 *Environmental Impact*

The development of NePCMs raises concerns about their potential environmental impact, which is an important challenge that needs to be addressed. The environmental impact of NePCMs can be assessed at different stages of their life cycle, including production, use, and disposal. One of the primary environmental concerns associated with the production of NePCMs is the potential release of nanoparticles into the environment. During the synthesis of nanoparticles, there is a risk of releasing toxic substances and harmful chemicals, which can have adverse effects on the environment and human health. For example, the use of solvents and surfactants in nanoparticle synthesis can contribute to air and water pollution, which can lead to adverse effects on aquatic and terrestrial ecosystems [40]. Therefore, it is essential to develop and implement environmentally friendly production processes for NePCMs. Another environmental challenge associated with the use of NePCMs is their potential impact on energy consumption and greenhouse gas emissions. While NePCMs have the potential to reduce energy consumption and greenhouse gas emissions by improving the energy efficiency of buildings and other applications, their production and use also require energy and contribute to emissions. It is essential to conduct a life cycle assessment (LCA) to evaluate the environmental impact of NePCMs comprehensively and identify opportunities for reducing their environmental footprint. Disposal of NePCMs is another environmental challenge that needs to be addressed. NePCMs can be difficult to dispose of, as they can contain toxic materials, which can be harmful to the environment and human health. It is essential to develop safe and effective disposal methods for NePCMs to minimize their environmental impact. Also, the main environmental impact associated with NePCMs is the use of nanoparticles in their production. Nanoparticles can be toxic to the environment and human health if not handled properly. The production of nanoparticles also requires significant energy inputs, which can contribute to greenhouse gas emissions and other environmental impacts. In addition to the environmental impact of nanoparticles, NePCMs also have the potential to contribute to electronic waste. NePCMs can be incorporated into various products, such as electronic devices, which can create a significant amount of waste when these products reach the end of their life cycle.

To address these environmental challenges, several strategies can be employed. First, the use of green synthesis methods for NePCM production can reduce the environmental impact of nanoparticle synthesis by using non-toxic and renewable materials. Second, the adoption of sustainable practices in the production and use of NePCMs, such as reducing energy consumption and being more reliant on renewable resources. Figure 4 depicts the two primary approaches for synthesizing silver nanoparticles: Top-down and Bottom-up approaches. The Top-down approach involves the reduction of bulk materials such as silver sheets or wires to produce nanoparticles through mechanical or chemical methods. This approach is widely used in industries and commercial applications due to its cost-effectiveness and scalability.

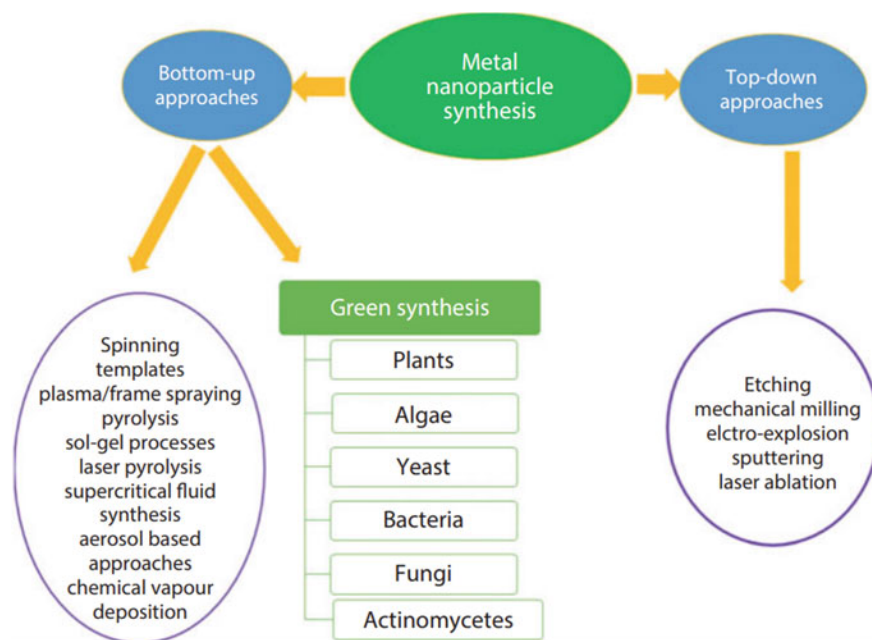


Fig. 4 Techniques for synthesis NPs [41]

However, it often results in the production of a wide-size distribution of nanoparticles, making it challenging to control the size and shape of the nanoparticles. On the other hand, the Bottom-up approach involves the nucleation and growth of nanoparticles from smaller precursor molecules or ions. This approach is commonly used in research settings and allows for precise control over the size, shape, and composition of the nanoparticles. However, it is often more challenging to scale up for industrial production, and the cost can be relatively high.

2.6 Safety Issues

Safety is a critical issue that needs to be addressed in the development and use of NePCMs. NePCMs can pose risks to human health and the environment if not handled properly. The potential risks associated with NePCMs can arise from various stages of their life cycle, including production, transportation, use, and disposal.

One of the main safety issues associated with NePCMs is the potential toxicity of nanoparticles used in their production. The inhalation, ingestion, or skin contact of nanoparticles can cause harm to human health. The toxicity of nanoparticles can vary depending on their size, shape, and chemical composition, which makes the risk assessment of NePCMs a complex task. Another safety issue associated with

NePCMs is the potential fire and explosion risks. NePCMs can undergo phase transitions from solid to liquid or vice versa, which can release large amounts of thermal energy. If not managed properly, this energy release can lead to overheating and potentially cause a fire or explosion. To address these safety challenges, various approaches have been developed to minimize the risks associated with NePCMs. These approaches include the use of personal protective equipment (PPE) when handling nanoparticles, the development of safer synthesis methods for nanoparticles, and the use of fire-retardant materials in NePCM-containing products. Furthermore, the transport and storage of NePCMs must also be managed properly to minimize the risks associated with their phase transitions. This can include the use of proper packaging and transportation methods, as well as the incorporation of safety features, such as pressure relief valves, in NePCM-containing products. In addition to the challenges mentioned above, there are other safety concerns associated with the use of NePCMs that need to be addressed. One such concern is the potential for NePCMs to release hazardous materials during their life cycle. This can occur during the production process or as a result of their eventual disposal. The release of hazardous materials can pose risks to the environment and human health, particularly if they enter the food chain or water supply. Another safety challenge associated with NePCMs is the potential for them to cause thermal instability. NePCMs are designed to store and release large amounts of thermal energy, which can cause rapid temperature changes. This can be problematic if the NePCMs are not designed to handle these temperature changes, as it can cause thermal stresses in the surrounding materials, potentially leading to mechanical failure or even explosions. To mitigate these safety challenges, various safety protocols and standards have been developed to guide the development and use of NePCMs. These include guidelines for the safe handling and transport of NePCMs, as well as the use of appropriate protective equipment to reduce the risk of exposure to hazardous materials. Furthermore, efforts are being made to develop new and safer NePCM formulations that can minimize the risks associated with their use. For example, researchers are exploring the use of biodegradable materials in NePCM formulations to reduce their environmental impact and improve their safety profile.

Overall, safety is a critical challenge that needs to be addressed in the development and use of NePCMs. The proper handling, transport, and disposal of NePCMs, as well as the use of appropriate safety measures and fire-retardant materials, are some of the approaches that can be used to minimize the potential risks associated with NePCMs and enable their safe and sustainable use. While NePCMs offer significant advantages over traditional PCM systems, they also pose unique safety challenges that must be addressed to ensure their safe and sustainable use. Through ongoing research and development, as well as the implementation of appropriate safety protocols and standards, these challenges can be overcome, paving the way for the widespread adoption of NePCMs in various applications.

2.7 Way Forward in Economical Aspect

Despite the challenges and difficulties associated with the development of NePCMs, there are several ways forward to overcome these obstacles and promote the widespread adoption of these materials in various applications. In this section, we will explore some of these ways forward.

1. *Research and Development*: One of the key ways forward for the development of NePCMs is continued research and development. Through ongoing research and development, researchers can work to overcome the challenges and difficulties associated with the development of these materials, including the high cost of production, environmental impact, and safety concerns.

Research can focus on a range of areas, including the development of more efficient synthesis methods, the optimization of NePCM formulations to improve stability and durability, and the exploration of new applications for these materials. By investing in research and development, we can continue to push the boundaries of what is possible with NePCMs and drive innovation in this field.

2. *Collaboration and Partnership*: Another way forward for the development of NePCMs is through collaboration and partnership. Collaboration can occur between researchers, industry partners, and other stakeholders to pool resources, expertise, and knowledge to overcome the challenges associated with the development of NePCMs.

Partnerships can also be formed with government agencies, NGOs, and other organizations to promote the use of NePCMs in various applications. By working together, stakeholders can leverage their strengths and expertise to drive progress in this field and promote the adoption of NePCMs in various applications.

3. *Standardization*: Standardization is another way forward for the development of NePCMs. By developing standard protocols and guidelines for the production, handling, and use of NePCMs, stakeholders can ensure that these materials are produced and used safely and efficiently.

Standardization can also help to promote the widespread adoption of NePCMs by providing a framework for stakeholders to work within. By adhering to standardized protocols and guidelines, stakeholders can ensure that NePCMs are produced and used in a consistent and predictable manner, which can help to build trust and confidence in these materials.

4. *Scale-Up and Commercialization*: Finally, scale-up and commercialization are critical ways forward for the development of NePCMs. By scaling up production and commercializing NePCMs, stakeholders can drive down costs and increase accessibility to these materials.

Scale-up and commercialization can also help to drive innovation and spur the development of new applications for NePCMs. By demonstrating the potential of these materials in various applications, stakeholders can build momentum and support for the adoption of NePCMs in various industries.

In conclusion, while the development of NePCMs is not without its challenges and difficulties, there are several ways forward for the advancement of these materials. Through continued research and development, collaboration and partnership, standardization, and scale-up and commercialization, stakeholders can overcome the obstacles associated with the development of NePCMs and promote their widespread adoption in various applications.

2.8 Way Forward for Environmental Aspect

As discussed earlier, NePCMs can have a significant environmental impact due to the high energy consumption required for their manufacturing process. However, several ways forward can minimize this impact and make the technology more environmentally friendly.

1. *Use of renewable energy sources:* The use of renewable energy sources such as solar, wind, or hydropower can significantly reduce the carbon footprint associated with the manufacturing process of NePCMs. The adoption of such sources of energy can lead to a sustainable and eco-friendly process of manufacturing NePCMs.
2. *Recycling and reuse:* Recycling and reusing the raw materials used in the manufacturing of NePCMs can significantly reduce the environmental impact associated with their disposal. The waste generated during the manufacturing process can be reused or recycled, leading to a more sustainable process.
3. *Life cycle analysis:* Performing a life cycle analysis (LCA) of NePCMs can help identify the environmental impacts associated with their production, use, and disposal. The analysis can identify ways to minimize these impacts, such as reducing the use of non-renewable resources or adopting more sustainable manufacturing practices.
4. *Use of biodegradable materials:* The use of biodegradable materials in the manufacturing of NePCMs can reduce the environmental impact of their disposal. Biodegradable materials can decompose naturally, leading to a less harmful impact on the environment.
5. *Development of eco-friendly manufacturing processes:* Research can focus on the development of eco-friendly manufacturing processes for NePCMs, such as the use of green solvents or non-toxic nanoparticles. These processes can significantly reduce the environmental impact of NePCMs and make the technology more sustainable.

Overall, the development of NePCMs can lead to a significant reduction in energy consumption and greenhouse gas emissions in various industrial and residential applications. The adoption of eco-friendly manufacturing processes, the use of renewable energy sources, and the recycling and reuse of raw materials can make the technology more sustainable and environmentally friendly.

3 Conclusion

In conclusion, the development of NePCMs presents significant opportunities for energy-efficient applications in various fields, including thermal energy storage, electronics cooling, and solar thermal energy conversion. However, several challenges and difficulties hinder their widespread adoption, including high cost, stability, durability, environmental impact, and safety concerns. Despite these challenges, several ways forward can improve the feasibility and adoption of NePCMs. For example, the use of advanced synthesis methods can improve the stability and durability of NePCMs while reducing the cost of production. Similarly, the use of renewable energy sources, recycling and reusing raw materials, performing life cycle analyses, using biodegradable materials, and developing eco-friendly manufacturing processes can make NePCMs more sustainable and environmentally friendly. Furthermore, the ongoing research and development in the field of NePCMs provide promising opportunities for future advancements. Researchers are working on developing novel nanoparticles, improving thermal conductivity, enhancing stability and durability, and adopting green and sustainable manufacturing processes. As the demand for sustainable and energy-efficient solutions continues to rise, NePCMs will play a crucial role in meeting these demands. In summary, NePCMs present significant opportunities for energy-efficient solutions, but their widespread adoption faces significant challenges. Overcoming these challenges will require continued research and development, the adoption of advanced synthesis methods, and the implementation of sustainable and eco-friendly manufacturing processes. With these efforts, NePCMs can become a viable and sustainable solution for various thermal energy storage and conversion applications.

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