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RECENT ADVANCEMENTS IN LATENT HEAT PHASE CHANGE MATERIALS AND THEIR APPLICATIONS FOR THERMAL ENERGY STORAGE AND BUILDING

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ABSTRACT

This review explores the latest developments in latent heat phase change materials (PCM) and their diverse applications in the realms of thermal energy storage and building technologies. PCM, known for their ability to store and release large amounts of thermal energy during phase transitions, have gained significant attention in recent years due to their potential to enhance energy efficiency and sustainability. The paper discusses advancements in PCM synthesis, encapsulation, and incorporation into various matrices to optimize their thermal properties and stability. Furthermore, it examines the wide-ranging applications of PCM in thermal energy storage systems for residential, commercial, and industrial sectors, emphasizing their role in peak load management, renewable energy integration, and overall energy conservation. The review also delves into innovative approaches and emerging technologies that leverage PCM for building envelope materials, contributing to improved thermal comfort and reduced energy consumption in buildings. Overall, this comprehensive analysis highlights the promising advancements in PCM research and their transformative impact on the fields of thermal energy storage and building technologies.

Key words:
Emphasizing, sustainable energy, depletion

INTRODUCTION

The phrase "energy crisis" describes the combination of traditional resource depletion and rising energy demand. In addition to having negative consequences such air and water pollution, ozone layer depletion, habitat degradation, and climate change, conventional resources are widely exploited worldwide because they are an affordable way to meet energy demands [1]. Therefore, it is essential to do research on green energies and renewable energy sources as nuclear, solar, biomass, geothermal, and wind energy [2]. The usage of fossil fuels has increased due to the quick development of cities and industry, which has exacerbated pollution. The globe is shifting away from fossil fuels by utilizing renewable energy sources and innovative strategies to increase energy system efficiency and increase the use of innovative and sustainable energy sources.One of the innovative methods is to use latent heat Thermal energy storage (TES) using PCMs.

Phase change materials (PCMs) are categorized as clean energy sources and are an affordable form of energy conservation [3]. PCMs are seen to be a respectable option for TES because of their promising qualities, which include the ability to store and release significant amounts of latent heat during the phase change process. Because of its unique properties, including low cost, high heat capacity, high density, dependability, thermal stability, capacity to melt consistently, non-segregation, non-corrosiveness, less toxic, and minimal or no super-cooling, PCMs are being explored for a wide range of applications. Additionally, the PCMs can retain latent thermal energy without altering their characteristics even after hundreds of phase change cycles [4,5].

According to their chemical makeup, PCMs are divided into three groups: eutectic, inorganic, and organic, as shown in Fig. 1. On the other hand, paraffin-based organic PCMs are the most widely utilized in a variety of applications. Unlike organic PCMs, inorganic PCMs are non-flammable,

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extremely cost-effective, and have a high latent heat per unit mass and volume. Despite certain disadvantages including isolation and subcooling, these materials are being researched and used due to their high thermal conductivity [6, 7].

Even though PCMs have better thermal properties than water, the mechanism of thermal enhancement is still unknown due to inaccuracy in research findings. Nanoparticles[9–12],expanded graphite [13,14], micro-encapsulation [15], macro-encapsulation [16], extended surfaces [17], multiple or cascaded PCMs [18,19], eutectic PCMs [20], porous metal foam [21–23], geometric modifications [24,25], heat pipe [26], and different finned tube structures [27,28] have been used in PCM research to improve thermal stability, thermal conductivity, and heat transfer rate for TES applications.

Safaei et al. [29] utilized graphene oxide with various concentrations

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Fig. 1: Phase change materials

Dispersed in Paraffin PCM for solar still efficiency improvement. Solar still productivity enhanced by 25% by incorporating GO/Paraffin as compared to simple PCM case. By increasing concentrations of nano particles, efficiency of solar still improved considerably. Sarafraz et al.[30] experimentally tested the thermal performance of heat pipe filled with binary mixtures of n-pentane-methanol and n-pentane-acetone together with pristine acetone, n-pentane and methanol. According to findings the n-pentane-acetone mixture exhibited highest thermal efficiency while the value of filling ratio and tilt angle was small for binary mixture compared to pure liquids. Ahmadi et al. [31] compared several machine learning techniques for modelling the dynamic viscosity of CuO /water nanofluid. Variables such as concentration, temperature and size of nanoparticles were explored in terms of their influence on dynamic viscosity. By relative importance of input variables, size of nanoparticles displayed lowest influence whereas concentration of nanoparticles showed highest impact on dynamic viscosity. Bahiraei et al. [32] explored the graphene-silver based hybrid nanofluid in a microchannel heat sink along with secondary channels and the ribs for improving cooling performance. The results depicted that with the nanoparticles concentration from 0 to 0.1% and Reynolds number of 100, the convective heat transfer coefficient enhanced by 17% and the bottom surface temperature of heat sink reduced by 13.88 K by increasing Reynolds number from 100 to 500 at 0.1% nanoparticles concentration.Bahmani et al. investigated numerically the thermal characteristics of Al_2O_3/H_2O nanofluid in parallel and counter flow double pipe heat exchangers. The effect of nanoparticles concentration, flow direction and Reynolds number were explored for thermal characteristics evaluation. According to results, the increase in nanoparticles con- centration and Reynolds number gave maximum enhancement of average Nusselt number and thermal efficiency by 32.7% and 30% respectively. Optimal concentration of nanoparticles was noticed to be 5% and counter flow heat exchanger was recommended at higher Reynolds number. Giwa et al.investigated the electrical conductivity and effective viscosity of hybrid nanofluids of Al_2O_3/Fe_2O_3 (25:75 mass%) with base fluid of deionized water and ethylene glycol (50:50 vol%). The influence of parameters like nanoparticles concentration, temperatures and base fluid was evaluated. It was revealed that effective viscosity of hybrid nanofluid with deionized water as base fluid was much lower compared to deionized water-ethylene glycol based nanofluid. While electrical efficiency enhancement was more in case of deionized water-ethylene glycol based nanofluid. Bagherzadeh et al.numerically studied the flow and thermal behavior of microchannel heat sink with slip boundary condition and water/Al_2O_3nanofluid jet for heat transfer enhancement in the presence of homogenous magnetic field. The performance of heat sink was explored by varying parameters of Reynolds number, nanoparticles concentration and magnetic field strength. Results showed that the magnetic field lowered the vertical velocity gradient but at creeping flow the magnetic field showed no influence on Nusselt number enhancement. Using homogenous magnetic field, Reynolds number of 50 and nanoparticles of 0.06 vol% in water enhanced the Nusselt number which caused better cooling of heated wall. Bagherzadeh et al. developed a novel approach of enhanced ANN for sensitive analysis of hybrid nanofluid functionalized- MWCNTs-Fe_2O_3/Ethylene Glycol. Analysis was done by ANN analytically, gave authentic results with less computation time and cost. Akbari et al. used two-phase mixture model to analyze the heat transferand fluid flow characteristics of laminar Cu/H_2O nanofluid in a 3-Dcurved microtube. The results were illustrated for coefficient of friction, Nusselt number patterns, dimensionless axial velocity and dimensionless temperature profiles. Results showed that the due to centrifugal and buoyancy forces, the axial velocity profiles showed no symmetry. As the number of nanoparticles enhanced, isotherms attained the desired temperature quickly.

Goshayeshi et al. dispersed various types of Fe_2O_3 NPs into the Kerosene to investigate the closed-loop pulsating copper heat pipethermal behavior. The influence of magnetic field, NPs type and size were evaluated for thermal attribution of heat pipe. Results showed that the addition of NPs enhanced the thermal performance of pulsated heat pipe, magnetic field reduced the thermal resistance by 12% packed with gamma Fe_2O_3 NPs. Gamma Fe_2O_3 NPs of 20 nm size were observed to be best candidate for attaining better thermal performance.

The addition of high conductivity nanoparticles (NPs), porous metal foam, expanded graphite, and encapsulation are promising methods for improving the thermophysical, and chemical characteristics of PCMs, hence enabling wider applications of PCM at improved system performance. These advanced PCMs are researched for extensive applications such as thermal energy storage, solar heating [3], auto- mobiles, textiles, refrigeration, waste heat recovery, air conditioning applications. These researches are mainly concerned with the rate of energy consumption, energy storage capacity, energy savings, efficient heat charging/discharging and PCM thermal conductivity enhancement. Similarly, PCM usage for solar cooking, drying, power generation and desalination ap- plications has been studied. PCMs usage in textiles enhance their thermal and cooling properties. Methods to introduce PCM in textiles are covering, spraying, and encapsulation. The use of nanofiber technologies for stability of PCMs is also one of the most recent approaches to the study of these materials. Researchers have proposed and studied the use of PCMs for cooling of electronic equipment and batteries. Their findings revealed that the heat sink performs well before the PCMs fully melts. After PCM has fully melted, the heart sink's productivity begins to deteriorate rapidly. The latent heat capacity of PCMs with suitable transition temperature can be used to provide thermal comfort and minimize building loads. In recent years PCMs use in building heating–cooling systems and hot water supply has received a lot of attentiondue to diverse variety of melting temperatures of PCMs. Accumulating solar thermal energy during daytime and supply it during night for heating application may be a practical option for lowering the building's energy costs.

Extensive experimental and numerical studies have been conducted to improve the efficiency of energy storage materials to date, but no definitive conclusion has been reached. Fig. 2 depicts the number of publications on advanced energy storage materials from 2010 to 2020, based on “Web of Science” results. It is apparent that the number of publications is steadily growing, indicating that the world is increasingly focused on this domain.

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Fig. 2. Web of Science stats regarding number of publications during (2010–2020) when searched with keywords “advanced energy storage materials”.

Advanced phase change materials have been broadly used in various applications. Zhu et al. investigated the trombe wall packed with PCM for indoor thermal comfort in Wuhan climate conditions. The author utilized the TRANSYS heat transfer model and GenOpt optimization tool to determine the best value of critical parameters and energy consumption rate. Trombe wall optimization findings indicated that the ideal air gap thickness was 0.05 m, optimal wall thickness was 0.68 m, optimal vent area was 0.6 m^2, and optimal melting temperatures of lower and higher temperature PCM layers were 16.5 C and 27.75 C respectively. The annual building load was lowered by 13.52% in optimized PCM packed trombe wall as compared to conventional trombe wall. Kozelj et al. analyzed the thermal storage tank with encapsulated PCM for building heating purposes. Paraffin was used as PCM and represented 15% of total volume of water thermal storage tank. Results showed that use of encapsulated PCM in water tank, the heat storage was enhanced by 70% compared to conventional case of water based thermal storage system. Further, author did numerical simulation using TRANSYS and validated the experimental results.

Wonorahardjo et al. studied the passive cooling system comprising of coconut oil and water PCMs as internal thermal mass coupled with stratum air ventilation under tropical climatic conditions. Author defined storage panel filled with coconut oil or water with inlet and outlet openings for indoor air and conditioned air respectively. Results showed that the coconut oil-based storage medium gave 0.5 C lower peak temperature in middle zone and more temperature re- ductions in upper zone. Passive cooling system led to a uniform temperature throughout the day and revealed low-cost and energy-efficient solution for ever increasing building energy demand challenge. Li et al.explored the thermal and optical performance of window unit filled with NPs enhanced PCM. NPs of different types, different volume fraction and sizes were dispersed in PCM for thermal and optical characterization of window. Results revealed that the NPs volume fraction and size influence was significant during dawn and dusk times. CuO NPs of volume fraction below 1% and size below 15 nm were proposed for better thermal and optical performance.

Wang et al. investigated the Al_2O_3/paraffin nano PCM thermal radiative properties for the harvesting of solar energy. The parameters of volume concentration, NPs size, temperature and optical path were adjusted to improve the solar energy absorption ability of nano PCM. The absorption coefficient of nano PCM at 0.01% was found to be 15.5 times greater in relation to paraffin. With NPs size reduction from 30 to 10 nm, the reflectivity of nanofluid dropped by 37.04%. Similarly, the increase in temperature raised the Al_2O_3nano PCM absorption coefficient and decreased the reflectivity. Li et al. performed thermo economic and environmental analysis of PCM loaded walls in rural residence of Northeast China by Energy Plus tool. The parameters examined related to PCM were PCM layer position, PCM wall orientation and PCM melting point. Results indicated that energy saving of 12.9% was achieved by PCM filled in wall near the interior surface. Compared to baseline case, PCM filled wall in the south facade decreased 12.8% heating load. The optimum PCM melting temperature was reported as 16 C for interiordesign temperature of 18 C Carbon footprints were reduced by 52.7 kg/ m^2 by utilizing the appropriate PCM wall throughout its lifecycle.

According to review of recent literature, the phase transition temperature, phase transition enthalpy, and thermal conductivity are three significant criteria for selecting a suitable PCM for use in potential ap- plications. PCMs retain thermal energy during heating before undergoing phase transition and emit heat when cooled. The ability of PCMs to store and release thermal energy has prompted researchers to investigate PCM's thermophysical properties for possible applications. Owing to low thermal response rate of most of PCMs, various heat transfer improvement techniques are employed to increase energy storage and retrieval rates of PCMs. In this article, the studies for advancement in thermal properties of PCMs are extensively explored. Also, recently a lot of PCM based review papers have been published in which PCM specific application is discussed or specific improvement in thermal properties of PCM is discussed. Ahmed et al.reviewed fatty acids and their eutectics PCMs enhanced by carbon based fillers. Authors reported that the latent heat storage capacity of PCMs reduced by increasing concentration of carbon-based fillers. Christopher et al. studied the cascaded PCM arrangement for latent heat TES systems. It was shown that using multiple PCM improved the TES system in terms of energy and exergy efficiency, charging/discharging rate, energy storage, power density. Tariq et al. discussed NEPCM preparation techniques and discussed
different NEPCM applications related to TES and thermal management.

Alehosseini and Jafari reviewed the nano encapsulated PCMs preparation techniques and discussed the applications of nano- encapsulated PCMs in various fields. Shen et al. reviewed the thermal management performance enhancement techniques of lithium ion batteries and discussed the improvement in heat transfer and TES capacity of PCMs. Preet reviewed the thermal management of PV panels using PCMs and NEPCMs. Author discussed the numerical models of PV thermal systems coupled with PCMs and NEPCMs and stated the PCM selection criteria and determination of phase change temperature of PCM. Mahian et al. evaluated the building integrated PCM based PV systems, and systematically discussed the PCM-PV experimentalnumerical, optimization and economics studies. Farooq and Zhang discussed the basics, materials, and approaches of the smart textiles and also analyzed the usage of PCMs in smart textiles for personal thermal management. Most recent reviews on PCMs have explored specific enhancement method and specific applications of PCM based systems. Therefore, a comprehensive review covering major PCM enhancements techniques and applications of PCM based systems needs to be addressed. This review presents a comprehensive overview on the advancements in the PCM and the use of advanced PCM in energy storage and thermal management applications. In first section, different thermal performance enhancement techniques of PCMs are discussed which includes addition of nanoparticles, fins, metal foams, encapsulation. In second section, various PCM applications are discussed thoroughly through recent literature. In third section major challenges and future recommendations related to PCM advancements and applications are discussed. The surveyed literature was collected from Google Scholar, Elsevier's ScienceDirect, and Web of Science with several keywords. The keywords included phase change materials, PCMs, NEPCMs, porous metal foams, fins, encapsulation, shape stable PCMs, thermal energy storage, latent heat TES, thermal management, thermal comfort, PV cooling techniques, solar energy, battery thermal management, buildingthermal management, solar collector, solar heating and cooling, heatexchanger, smart textiles, electronic devices, thermo electric generator, food. This is the novelty of this review paper that it encompasses major thermal performance enhancements in PCMs and extensively discusses diverse PCM applications. So, overall, the current manuscript will help researchers to provide a valuable insight into recent developments in latent heat thermal energy storage along with thermal management as well as their thermal energy storage applications.

VARIOUS ADVANCEMENTS IN PCMS

PCMs have drawbacks like low thermal conductivity, leakage, volume change during phase transition, flammability, super cooling, corrosiveness, and poor stability. Thermal conductivity is a critical property of PCM that influences heat transfer capacity and its low value reduces thermal response rate. A variety of techniques have been investigated in literature to improve the performance of PCMs that include addition of NPs, adding expanded graphite, and pre- paring eutectic PCMs, porous metal foams, heat pipes and capsulation of PCM as represented in Fig. 3. Encapsulation, or microencapsulation, is the process of completely covering and isolating the core from its surroundings. The thermal stability and leakage resistance of PCMs increased significantly after encapsulation, greatly expanding the application domains of PCMs. The emulsion polymerization, suspension polymerization, and coacervation encapsulation techniques are primarily used to synthesize PCM encapsulated in organic polymers. Interfacial polymerization and in situ polymerization techniques are used to synthesize PCM encapsulated inorganic coatings. PCM encapsulated in inorganic coatings is usually produced by the sol–gel technique.

Therefore, the above discussed are some ways to increase PCM thermal performance that recently gained significant attention.

The addition of high thermal conductivity NPs improves the heat transfer within PCMs. NPs function as a link for thermal energy transfer since they have a low thermal resistance. Nano enhanced PCMs (NEPCMs) are being studied due to high thermal conductivity of NPs and their effect of enhancement of heat storage and retrieval rate of PCMs. There are a lot of studies which explore the influence of NPs parameters like size, shape, materials and concentration on the PCM thermal properties. It is reported that the heat transfer rate and thermal reli- ability of PCMs have improved with the addition of NPs. The nonme- tallic NPs have better influence on thermal characteristics of PCMs than metallic NPs.

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Fig. 3: Various Advancements In PCMs

Thermal conductivity of NEPCMs is reported to enhance by 20% to 100% as compared pristine PCM. The NPs addition in salt hydrates PCM improve their sub cooling, phase segregation and thermal conductivity properties.Nizetic et al. critically reviewed studies of NPs enhanced fluid interms of preparation, applications and thermal properties. Findings showed that the use of NPs in PCMs increased the thermal conductivity but marginally lowered latent heat. In TES and cooling systems, NEPCMs are mainly used. Authors concluded that literature does not provide the optimal preparation process for nanofluids, economic and environ- mental assessments, safety concerns and handling guidance.Wu et al. explored the thermal conductivity of paraffin by dispersing graphenenanoplatelets

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(GNPs) and carbon nanotubes (CNTs) NPs. The dispersant WinSperse3050 was added for stable dispersion of NPs in PCM. Dispersion of 5% GNPs in PCM enhanced the thermal conductivity by 37.1% than pristine PCM. Melting/freezing rates and thermal stability of PCM were improved by the addition of CNTs and GNPs. Kalidasan et al. prepared nanocomposite of polyaniline and cobalt NPs and mixed it with paraffin wax in various proportions (FESEM image shown in Fig. 4). According to the findings, enriching the PCM with polymer nanocomposite increased the latent heat of fusion and thermal conductivity by 15.9% and 20.4%, respectively and improved thermal stability for 200 thermal cycles.

Daneshazarian et al. numerically inspected the thermal performance of halogen graphenenanoplatelets (xGNP) enriched PCM packed in vertical cylindrical cavity at different xGNP concentrations. Results showed that with 0.5 wt% of xGNP in the PCM, melting rate decreased by 9.7% and heat storage rate improved by 12.6%. Authors further noted that the inclusion of NPs in PCM by more than 0.5 wt% decreased melting rate and heat storage rate, as well as increased the dynamic viscosity. Liu et al. prepared hybrid NPs through coating carbon layer on aluminium NPs and dispersing them in sodium sulphatedecahydrate for thermal efficiency enhancement. According to the findings, the use of 3 wt% hybrid NPs increased thermal conductivity by 26.41%, decreased the freezing latent heat enthalpy by 5.13%, and strengthened the stability of PCM.

Raj et al. [93] studied thermal characteristics of shape-stabilized
polyethylene glycol dispersed with 1 wt% MWCNTs and GNPs. Various thermal, structural, and chemical analysis demonstrated that the NEPCM possessed better thermal response, good chemical and thermal stability. Results concluded that addition of MWCNTs and GNPs in PCM enhanced the thermal conductivity of PCM by 61.73% and 84.48% respectively and lowered the heat sink base temperature by maximum of 9.77%. Benbrika et al. numerically analyzed the melting/solidification characteristics of a latent heat TES unit of horizontal cylinders by diffusing GNPs in PCM. According to the findings, with the addition of 3 wt% GNPs in PCM, solidification time was reduced by 50%, melting time slightly reduced and energy storage ca- pacity was reduced by 14%.

Sun et al. [95] investigated melting process of TES system utilizing
Paraffin PCM and graphite and nano coconut shell charcoal. The con- centration of NPs was 0.02, 0.06, and 0.10 wt%. It was found that the melting time shortened by 21% with 0.06% graphite nano particles in PCM with 2 wt% oleic acid dispersant. Qu et al. studied the face stabilized paraffin with the hybrid nano additives of expanded graphite (EG)/MWCNTs and EG/carbon nano fillers (CNF). The shaping material for paraffin was polyethylene and the concentration of NPs and EG was varied. According to findings, PCM thermal conductivity enhanced by 60% and 21.2% for MWCNTs/EG and CNF/EG for mass ratio of 4:1 respectively compared to case of5% EG.

Shahsavar et al. performed experimental and numerical study to evaluate the effect of temperature and concentration of NPs on viscosity and thermal conductivity of paraffin/Fe_2O_3 PCM. For improving NPs dispersion, oleic acid was utilized. According to findings NPs concentration augmented both “k” and viscosity of nanofluid while the increase of temperature enhanced the “k” and decreased the viscosity. Furthermore, the artificial neural network (ANN) model was utilized to simulate the “k” and viscosity of nanofluid using experimental data. It was observed that the developed ANN model provided accurate results.

Arici et al. explored the melting of PCM with various arrangement of fins, various wall orientations, and CuO NPs. As compared to the no fin case, the integration of fins in the cavity shortened the melting time by maximum value of 52% and 68% based on fins length and fins position, respectively, with short fins performing better with NPs. While it was observed that the combine use of fins and NPs augmented the melting rate by 54%. Sarani et al. examined the effect of discontinuous fins configuration and CuO NPs on PCM solidification rate enhancement. Findings showed that the inclusion of discontinuous fins increased the discharging rate by 89%. Maximum enhancement in discharge rate of 77.8% and 59.5% was observed for the combination of CuO NPs with copper and aluminium discontinuous fins respectively. Sheikholeslami et al. explored the melting/freezing of

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RT35 PCM with triangular fins and CuO NPs in triple tube heat exchanger. The use of triangular fins increased freezing rate by about 40.75%, and the addition of CuO NPs lowered freezing time by 44.88%. The combine use of fins and NPs in the system lowered the solidification time from 20.2 min to 11.13 min. Alizadeh and colleagues investigated numerically the solidification process of latent heat TES device with curved fins and numerous NPs. The results revealed that with 4% single walled carbon nanotubes, increased solidification rate of PCM by 40.9% and optimized fin shortened the freezing time of PCM by 61.54%. The
combine use of optimized fins and NPs increased the rate of solidification by 68.81 %.

USE OF FINS ALONG WITH BASE PCM

PCMs have good energy density, and constant phase change temperature but the major drawback of PCMs is weak heat transfer during melting/freezing cycles especially in case of organic PCMs. So for accelerating the PCM responsiveness for heat transfer, increasing con- tact area by utilization of fins is widely researched technique due to favorable outcomes compared to no fin case. Different types of fins i.e. rectangular, longitudinal,radial, annular, tree, plate, spiral, triangular, trapezoidal, corrugated, perforated, helical, and some others shapes have been studied for optimizing the geometric shapes, size, orientation and materials of fins. In recent studies, various types of fins along with NEPCMs and metal foams are utilizing for thermal performance enhancement of latent heat thermal energy storage systems. By using various type of fins with base PCM, the effect of heat transfer is increased due to large area availability.

Fig. 4: Nano composite Of Polyaniline And Cobalt

Zhang et al. designed and investigated the PCM based TES system with novel shape fins. Topology optimization technique was used to optimize the PCM and fins layout in TES system. Results showed that the optimal volume fraction of fins to be 20%, while charging and dis- charging rate of PCM enhanced by 46.8% and 47.1% respectively compared to longitudinal fins case. Huang et al. investigated the charging and discharging behavior of fractal tree shaped fins based latent heat TES system. Results showed that inclination angle influence melting process more than freezing process. The vertical fractal latent heat system gave 52.5% reduction in melting time while horizontal fractal latent heat system gave 94.7% and 101.5% improvement in melting and freezing rate respectively.
Yang et al. [135] studied the thermal performance of irregularly

Liu et al. investigated the solidification ability of latent TES system using novel triangular shaped longitudinal fins depicted in Fig.5(a). Aside from fin geometry, the impact of initial temperature and fin material on solidification rate was also investigated. The results showed that the novel fin shortened solidification time by 38.30% as compared to the simple longitudinal fin case. The optimal temperature gradient between the inner wall and the PCM was over 20 K for a quick solidification rate.

Kothari et al. studied the effect of varying the inclination angles of paraffin base heat sinks with plate fins. According to the findings, for critical temperature of 75 C, three finned heat sink at a 0° inclination angle increased operating time by 74%, while a decrease in inclination angle from 90° to 0°

enhanced operating time by 66%, 46%, and 43% for no fin, one fin, and two fin PCM based heat sinks, respectively.

PCMS SATURATED WITH POROUS MATERIALS

Metallic and non-metallic porous foams saturated with organic paraffin type PCMs are being explored for their thermal performance enhancement of PCMs and their possible usage in diverse applications. The integration of porous materials and PCMs results in shape-stabilized PCMs which have better thermal conductivity and no leakage issues Yao and Wu explored the thermal characteristics of composite PCM of copper metal foam and paraffin by varying the foam porosity and pore density. The low porosity and high pores density were observed as ideal for the uniform distribution of temperature and low temperature maintenance. Copper foam with porosity of 0.935 and pore density of 7 pores per inch (PPI) augmented the melting rate by 2.1 times and maximum temperature drop of 30 °C was achieved. Zhang et al. explored the charging behavior of paraffin saturated with copper foam under varying centrifugal accelerations. By the centrifugal acceleration, the heat transfer coefficient and the PCM convection have been improved. The melting rate of PCM increased asymmetrically in the direction of centrifugal acceleration, resulting in phase interface with a curve pattern. Hu and Gong investigated the thermal regulation of RT 62HC PCM infiltrated with 3D printed porous aluminium material. The research used a variety of porosities and heat fluxes with various thermocouples (TC) positions. The results revealed that for 80% porosity of porous material, the highest increase in PCM melting time and temperature reduction of 78% relative to the case without porous material was achieved (charging/discharging figure shown in Fig.5(b).

Fig. 5: Shape-stabilized PCMs

Shape-stabilized PCM is another process in which molten PCM is held in place by capillary action in porous material. Shape-stabilized materials include mineral materials like diatomite, vermiculite and perlite, as well as polymeric materials such as polyethylene, polyurethane, or acyclic resins.

MAJOR CHALLENGES AND FUTURE RECOMMENDATIONS

The use of phase change materials (PCM) in energy storage applications has received a lot of attention. Following are some challenges recommendations for careful consideration based on this study. These suggestions can be summed up as follows:

- Even though a great deal of research is being conducted on the thermophysical and chemical properties of PCMs for their use in different applications, there is still no international standard for PCM testing and analysis. Furthermore, the thermophysical properties of PCMs are the subject of much debate in the literature.

- The materials with the best thermal properties, such as paraffin wax or fatty acids, are highly flammable.
- Organic PCMs have major drawback of low thermal conductivity which negatively effects its utilization in applications.
- The cost of nanomaterials, instability, and agglomeration are all significant obstacles to the widespread use of nanomaterials based PCM.
- In recent studies, nanoparticles have demonstrated to have promising as a PCM additive. However, there is a shortage of studies into hybrid nanomaterials' implementations. As a result, further research into the thermal properties and performance analysis of hybrid NPs based PCM is needed.
- NEPCM preparation is time-consuming and expensive processes. Although studies have shown that NEPCMs have higher thermal conductivity than single PCMs, it has also been found that the phase enthalpy of PCMs decreases when nanoparticles are added. Their long-term stability is also difficult to maintain compared to initial stabilization.
- Encapsulation of PCMs is costly and time consuming, give poor thermal characteristics. Further research needs to be done to optimize the PCM encapsulation process.
- Although most PCMs and NEPCMs have defined melting points, but thermophysical properties of liquids and solids vary amongst studies. A standard test procedure and database should be established to yield correct results and records.
- For several years, researchers have tested and analyzed the thermal conductivity of PCMs using a variety of techniques. The usage of various values of PCM thermophysical properties revealed a major problem with research criteria.
- To maintain stable performance of the storage systems, future work must avoid phase separation and supercooling of PCMs.
- It is suggested that the use of PCMs in various sectors should be assessed in terms of their effect on the atmosphere and human health

. • The fundamental feature of an energy storage system is phase transition enthalpy. So, detailed examination of the existence of interactions between PCM and nanostructures, as well as their potential impact on the performance of these systems is needed

. • Techniques for preparing composite PCMs are complex and sensitive, and they have a direct effect on performance improvement. As a result, it is strongly advised to report the preparing procedures .

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