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Contribution of Nanoparticles in Elaborating the Thermal Performance of Phase Change Materials: Up-to-date Review Study

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Abstract

Phase change material (PCM) is an example of thermal mass, which has many advantages in store the heat for peak time through a conversion process. This material is in demand for energy saving in conditioning applications and electrical appliances. The PCMs can be used to save thermal energy for heating or cooling, in many applications depending on the design and characteristics of the system and limitations of transformation change. They are generally used for space heating in residential buildings on a short-term or seasonal basis. For boosting their heat capacity, such materials could be enhanced through adding nanoparticles (NPs). Nanomaterials, including metal- or carbon-based NPs, have shown to be the most effective additions for thermal energy storage units. In charge and discharge modes, they enhance the properties of PCMs in both sensible as well as latent heat. In general, the following NPs are being considered: SiO2, Ag, graphene, CuO, and Al2O3. Where, the content was between 0.5-15%. The content should be less than 5% for paraffin PCM and can be higher for salts and other classifications of PCMs.

Introduction:

A phase change material is an object that oscillates between liquid and solid; thus absorbing or releasing heat depending on the ambient condition. Many substances, such as paraffin and salt hydrates, can serve as transfer materials. This material can be used in hot arid climates where the ambient air is warm during the day and cool at night. On hot days, the material absorbs heat from the indoor air and liquefies. On cold nights, the material radiates heat into the air and vice versa. By repeating this process, the indoor air is still pleasant.

Phase change materials (PCMs)-based thermal energy storage systems have drawn attention as a research issue in recent decades. Thermal energy is stored in PCMs for a variety of uses, primarily space heating in residential buildings. A PCM is one that undergoes a change in state from solid to liquid by gaining thermal energy and subsequently losing heat to return to solid state. This technique allows the material to store extra heat for long time. Paraffin waxes and salt hydrates are examples of these materials. The PCMs store both sensible and latent heat energy [1, 2]. Yet, because of their low thermal conductivity characteristics, such materials have little heat transfer rates during processes of melting or solidification. Low thermal conductivity is the primary drawback of paraffin as well as fatty acids, which are utilized as thermal storage materials in solar heating and cooling systems. It decreases heat recovery throughout solidification and holds onto heat during melting. Consequently, it was indicated that a variety of materials, including carbon and metallic bases with micro- and macro-encapsulation, are combined with PCMs to boost their values of thermal conductivity [3–7]. Low thermal conductivity is the primary drawback of paraffin and fatty acids, which are utilized as thermal storage materials in systems of solar heating and cooling. It decreases heat recovery throughout solidification and holds onto heat throughout melting. **Table 1** shows common PCMs and corresponding properties in average.

Table 1: Thermal properties of common PCMs [8-11].

Material	Density (kg/m^3)	Specific heat (J/kg.K)	Thermal conductivity (W/m.K)	Melting point (^oC)	Latent heat of fusion (kJ/kg)
Paraffin	1000	2150 (solid) 2550 (liquid)	0.35	40	180
Black beeswax	1100	4750 (solid) 4950 (liquid)	0.45	65	260
Fats	900	2100 (solid) 2200 (liquid)	0.15	35	150
Glauber's salt	1500	1950 (solid) 3350 (liquid)	0.7	30	250

Researchers could improve PCMs' thermal conduction and other thermal properties by incorporating common or novel nano-materials into organic phases [12–14]. Table 2 shows common NPs and corresponding properties in average.

Nano-enhanced phase change material (NE-PCM) is a mixture of liquids and solids. A common way to prepare NE-PCM is to mix nanoparticles with PCM and disperse them in the PCM structure using an ultrasonic or magnetization process. The mixture must have a uniform and sufficient distribution of nanoparticles (See **Figure. 1**).

Table 2: Thermal properties of common NPs [15-18].

Material	Density (g/cm^3)	Specific heat (J/kg.K)	Thermal conductivity (W/m.K)
Graphene	< 1	> 750	~ 2500
Alumina	> 3	~ 600	~ 20
Silica	< 2	> 500	~ 0.1
CuO	> 5	~ 600	~ 30

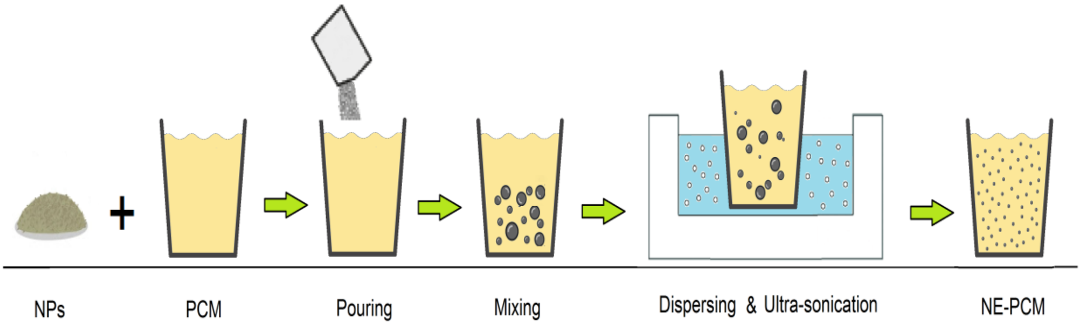

Fig. 1 ***Common method to prepare NE-PCM.***

However, the aim of the current study is to introduce the recent contribution of nanoparticles in elaborating the thermal performance of phase change materials as a review study. The study investigates the most updated PCMs and NPs that involved in the improvement with their limits and features. This study can be useful investigations that seek to practice the development in PCM with innovative ideas.

Interest of available literature:

By reviewing the available studies within this field for the last 5 years, it can be noticed that majority of the works were experimental with an amount of numerical and theoretical studies, as well. However, numerous of review studies [19-34] have been conducted to introduce a general overview upon the development of PCMs with nano-materials by giving some examples of the current applications and available data. The review studies focus upon various configurations, such as:

- Production of PCMs.
- Select suitable nano-materials and better loadings and sizes.
- Seeking for homogenous combination and dispersion.
- Encapsulation techniques.
- Technical challenges in the systems.
- Phase-change behaviors.
- Measuring general thermo-physical characteristics of the PCM.
- Enhance thermal conductivity of PCM.
- Enhance the specific heat of PCM.
- Enhance the latent heat storage of PCM.
- Applications of PCMs.

Nano-PCM to improve heat transfer:

Regarding the nature of the studies, that are either numerical or experimental researches, they are currently focused on adding NPs to PCMs in order to enhance the heat transfer, either conduction or convection, due to the super ability of nano-particles in elaborating the heat transfer rate. **Figure 2** shows common applications and corresponding details about NPs to improve heat transfer.

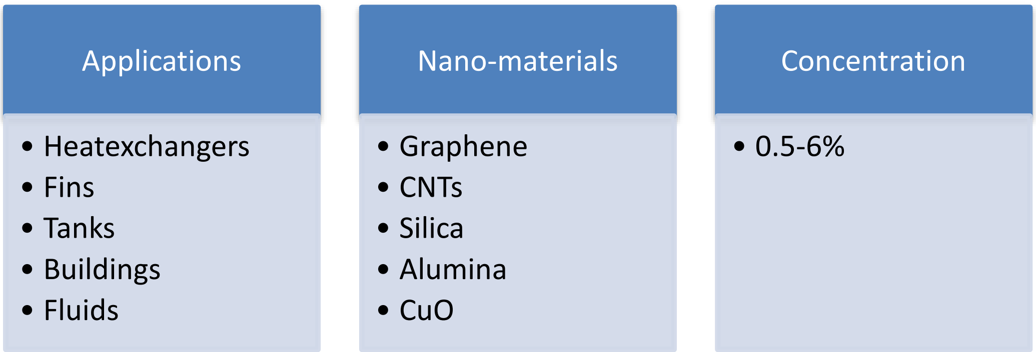

Fig. 2 ***Applications and common nanoparticles used to improve heat transfer.***

In order to improve PCM heat transfer, Kant et al (2017) [35] have studied the incorporation of graphene NPs into both non-organic and organic PCMs. To observe the impact of composite PCM melting, graphene NPs are combined in three distinct volumetric ratios (1, 3, and 5%) in this work. There has been a detailed discussion conducted regarding ensuing transient isotherms, velocity fields, and melting fractions. Those findings unequivocally show that the addition of the nano-particles of graphene result in speeding up melting, in addition to having a potential for impeding the convection heat transfer in the large cavities. In addition to that, the research showed that such enhanced PCM could be successfully applied to a variety of applications and industries.

Martin et al (2019) [36] have researched 2 fatty acids, which are capric acid (CA) and capric–myristic acid (CA–MA) eutectic mix in building application temperature range. In such cases, PCM were nano-enhanced by adding 0.5wt.% , 1wt.% , and 1.5wt.% of silicon dioxide (nSiO2) NPs. The main resulting NEPCM (i.e., nano-enhanced phase change materials) features have been evaluated through the scanning electron microscopy (SEM), rheological tests, differential scanning calorimetry (DSC), thermos-gravimetric analyses (TGA), and hot wire method. In addition to that, the cycling stability tests have been utilized for the assessment of their long-term performance after 2,000 cycles. The high values of specific heat capacity and thermal conductivity have been shown by developed NEPCM. In addition to that, both PCMs ensure the long-term performance and are thermal stability within their range of operating temperature.

If there is Rayleigh-Benard convection, Parsazadeh & Duan (2020) [37] have carried out an experimental analysis for the determination of the way that nano-particles affect NePCMs melting time. Variations in factors that affect heat transfer have been researched for the purpose of comprehending NP impacts on the rate of phase changes that are reported in many studies. Scaling analyses on NePCM heat transfer in bottom-heated enclosure has been utilized for the identification of such factors. Al_2O_3NPs have been scattered at various concentration levels in PCM (coconut oil). These samples have been utilized in multiple tests for the purpose of determining whether NP impacts on the rate of phase changes vary with the variation of the experimental settings. Findings have demonstrated that, based upon the way that the conditions of heat transfer change, the introduction of specific NP concentration might result in melting rate's increase, decrease, or remain the same. Because of the larger Grashof number reduction, adding NPs to a PCM in enclosure that is heated from the bottom at high Grashof number values is not advised. However, because of the increased thermal conductivity, adding NPs to PCM might shorten melting time at low Grashof numbers. In presence of Rayleigh-Benard convection, correlations are created to quantify impacts of NPs on melting rate and position of solid-liquid interface using experimental data as well as scaling analysis.

A novel class of fluids including NEPCMs, in which NPs consist of a shell and a core, was presented by Seyyedi et al (2021) [38]. The research looks into the properties of NEPCM heat transfer in an enclosure, entropy generation, and free convection flow. The enclosure consists of a porous medium-filled annulus positioned between concentric horizontal circular as well as square cylinders. The energy, continuity, and momentum governing equations are expressed in the non-dimensional form and are subsequently numerically solved with the use of the CVFEM (i.e., control volume finite element method). We study how factors impact entropy generation number as well as average Nusselt number. The results showed that, for any value of Stefan number, there’s a maximum value for Nusselt and a minimum value for entropy generation at temperature difference of 0.40.

In Adebayo and Yehya's (2022) [39] study, the influence of applying a consistent magnetic field on the rate of Octadecane PCM melting has been examined, both in the presence and absence of high-conductivity NPs, and in enclosures with different aspect ratios. They found that in the case when the Lorentz force is directed in the opposite direction regarding the buoyant force and Hartmann number is 100, a 43% reduction in the liquid fraction and, subsequently, the melting rate may be achieved. They have demonstrated that the PCM's magnetic susceptibility is affected by the enclosure's aspect ratio. Additionally, the Lorentz force increases with the inclusion of NPs, although an overall drop-in melting rate isn’t noticeable due to increased conductive heat transfer. Therefore, their application could be promising in situations where it is necessary to increase the melting rate. Therefore, the magnetic field strength, form of enclosure, and material conductivity must be carefully studied for a significant effect on phase-change material’s rate of fusion.

The natural convection as well as heat transfer of NEPCM suspensions within a boundary layer along a heated flat surface were explored theoretically by Ghalambaz et al (2022) [40]. The NPs have a core-shell structure, with a solid shell covering a core made of PCMs. To address the phenomenon, the finite element method (FEM) is combined with a similarity solution strategy. The results show that temperature at which particles of NEPCM go through phase transition is a critical element in increasing the heat transfer. In comparison with the scenario without any NEPCM particles, the parameter of heat transfer could be increased by roughly 25% with only 5% of the NEPCM particles added.

Teja et al (2022) [41] reported a study to enhance PCM's characteristics by including NPs and altering the enclosure's orientation. The impact of Grashoff numbers (5,000, 13,000, and 20,000), types of nanoparticles (Al2O3, CuO, and MWCNT), volume concentrations (0%, 1%, 3%, and 5%) added in RT42 PCM, and square enclosure orientations (30, 45, and 60°) on the rate of heat transfer is studied using 2D transient numerical analysis. An assessment and presentation of nano-PCM's thermo-physical characteristics are made. Findings confirm that, up to an optimal threshold, the melt fraction of PCM increases as Gr and the volume concentration of nano-particles increase. MWCNT-based nano-PCM achieved the highest melt fraction, succeeded by pure PCM, Al2O3, and CuO. It is observed that more pure PCM and nano-PCM will be converted to liquid fraction at an orientation of 60° and 45°, respectively. In comparison to (3% Al2O3/RT42 PCM), (1%CuO/RT42 PCM), and pure PCM, (3% MWCNT/RT-42 PCM) placed in a 45° orientated container achieved the maximum melt fraction by 3.4%, 2.04%, and 2.94%. The change in thermo-physical characteristics of nano-PCM is the cause of the fluctuation in maximum melt fraction of the nanomaterial.

The mechanism of heat exchange of LHTES (i.e., latent heat thermal energy storage system) that is fitted with compact finned tube heat exchanger has been studied by Passaro et al (2022) [42]. There have been quantitative models created for investigating impacts of the fin pitch and PCM thermal characteristics on energy discharge process under fully turbulent conditions in HTF (i.e., heat transfer flow). Samples of the commercial paraffin wax A-53 that are doped with the graphene-based nano-particles have been tested and characterized. Various types of the nano-platelet varieties that weigh in the range of 0.50% to 6.0% have been utilized. Thermal conductivity, specific heat, and fusion latent heat measurements are reported. Simulations have been created with 3 values of the fin pitch—5mm, 10mm, and 20mm—as well as with loads of 1% and 6% weighted nanoparticles. In order to determine the amount and caliber of heat produced, the system's performance has been assessed with the use of the HTF outlet temperature. The findings demonstrate that the inclusion of high aspect ratio graphene NPs considerably increases the PCM thermal conductivity. Solid phase PCM thermal conductivity doubled with only 1%wt addition, and increased by a factor of 3.5 with 6%wt load. In the meantime, the samples' specific and latent heat values remain mostly unchanged. Numerical findings further demonstrate that improving the discharge performance of LHTES systems by installing thin fins is a successful strategy. The increase of fin number improves heat transfer rate and temperature at which the HTF discharges during solidification. It also increases the useable discharge heat capacity and produces higher-quality heat. Fins and NPs work better together to enhance the process of discharge, although as the number of fins grows, the function of NPs becomes less important. The findings show that low thermal conductivity of the common PCMs could be effectively overcome by standardized compact finned heat exchangers, which are widely utilized in the HVAC industry, without sacrificing their useful heat discharge capacity or needing to use NPs to shorten the time of discharge between 60 and 77% when the fin number is sufficient.

The impact of ultra-sonication on the heat transfer efficiency as well as particle agglomeration regarding NP-embedded PCMs throughout the discharging and charging operations was examined by Sundaramahalingam and Jegadheeswaran (2023) [43]. Cu NPs imbedded in paraffin wax at weight percentages of 0.5wt%, 1wt%, 2wt%, and 3wt% are used in melting and solidification investigations. The shell and tube module is equipped with 2 ultra-sonic transducers at bottom face to produce power ultra-sonic waves. The findings suggest that power ultrasonography could improve phase change rates and reduce particle agglomeration. There is 18% reduction in the time of solidification and a maximum 30% reduction in melting time when compared with the system without ultra-sonication. While the melting rate rises with the particle fraction, the rate of solidification only improves up to a point of 2 weight percent because the 3 weight percent nano-PCM composite takes longer to solidify than the 2 weight percent nano-PCM composites. Ultrasound only has a noticeable impact on phase change when natural convection is dominating. Therefore, it is advised to optimize the ultrasound's activation time and period.

The magneto-hydrodynamic mixed convection of NEPCM inside lid-driven trapezoidal prism enclosure with hot-centered elliptical obstruction was studied by Younis et al (2023) [44]. The remaining walls are insulated; however, upper cavity wall moves at steady speed. Both inclined walls are cold. The governing equations of the system have been solved with the use of the Galerkin finite element method. The elliptical obstacle orientation has been between 0 and $3\pi/4$, the volumetric fraction of NEPCM was no more than 8%, the Reynolds number was no more than 500, and the Hartmann number was no more than 100. An introduction and analysis are given to the thermal fields and flow patterns. According to the results, in the case where hot elliptic obstacle is oriented at a 90° angle, the largest rate of heat transfer is observed; compared with other orientations, such orientation leads in a 6% increase in the Nusselt number. 14% more Nusselt number was obtained by reducing Hartmann number from 100 to almost 0.

The coupling between advanced 2-phase model for NP-enhanced PCM (NePCM) and enthalpy-porosity formulation with regard to transient behavior of phase change was represented numerically by Amidu et al (2023) [45]. Thus, in order to account for particles' frozen state in areas filled by solid PCM, a source of porosity component is introduced to NP transport equation. There are three primary ways that NPs can slip in this two-phase model: sedimentation, Brownian diffusion, and thermophoresis diffusion. The study examines a 2D model of a triplex tube heat exchanger and examines various configurations for discharging and charging. Results indicate a significant enhancement in heat transfer throughout the discharging and charging cycle when a homogenous distribution of the NPs is assumed as initial condition, in comparison to pure PCM. In this instance, the predictions made by 2-phase model outperform those made by traditional single-phase model. When discharging and charging in multiple cycles, the two-phase model shows a notable decline in heat transfer rate; in contrast, the single-phase mixture model's formulation leads to absurd results when attempting to analyze the same. Based on the two-phase model results, melting performance throughout second charging cycle is 50% lower than the first for NePCM with a high concentration of NPs (> 1%). The significant non-homogeneous distribution of nano-particles at the start of 2^{nd} cycle of charging is blamed for this performance decline. In this case, the migration mechanism of NPs that predominates is caused by sedimentation effects.

An innovative method for improving heat recovery capacities of nano-PCM composites was presented by Nsofor and Mahdi (2024) [46]. This involves grading concentration of NPs along direction of heat flow. The shortcomings of conventional uniform-concentration nano-PCMs, show a decreased heat rate when they are far from heat transfer surface. With the use of RT55 as well as water as the basis PCMs, computational fluid dynamics simulations were utilized to study solidification in cylindrical shell-and-tube configuration and a hexahedron enclosure. Three different configurations of NP concentration were investigated, all of which kept the total volume fraction at 0.10: no-degrading concentration, 3-concentration grading, and 5-concentration grading. The findings show that, in comparison to uniform concentration, degraded concentrations speed up solidification, increasing heat recovery rate by up to 12% and 27% for hexahedron and cylindrical examples, respectively. In comparison with conventional nano-PCMs, graded concentrations improve nanoparticle-PCM communication, promoting homogeneous temperature distribution and diffusion.

Nano-PCM to improve thermal energy storage:

Thermal energy storage can involve nano-particles to improve the thermo-physical properties of the PCMs that consider the reservoir for both: sensible and latent heats. The investigations centered on how adding different kinds and concentrations of NPs to PCMs affected the materials' thermal capacity, thermal conductivity, and thermal stability. **Figure 3** shows common applications and NPs used to improve thermal energy capacity of PCMs.

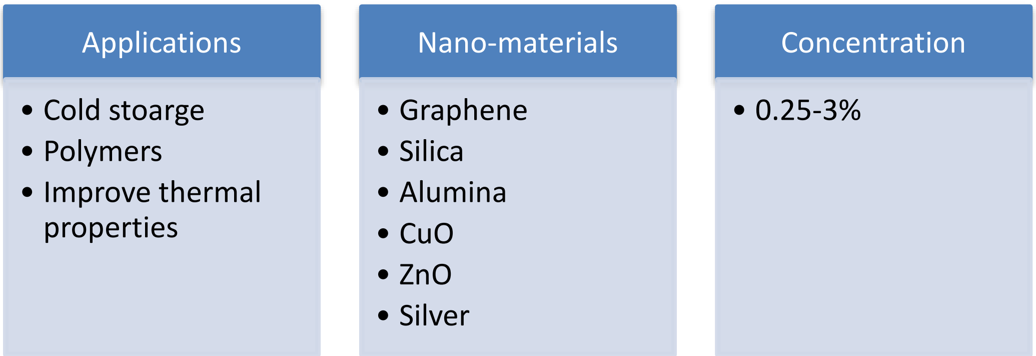

Fig. 3 ***Applications and common nanoparticles used to thermal storage.***

Sidik and Kean (2019) [47] have studied the thermal efficiency of the NEPCM with the nano-particles in the CTES (i.e., the cold thermal energy storage). They have worked on PCM phase change after being scattered with several kinds of NPs has been given, both numerically and experimentally. In 25 mm x 25mm square enclosure, the rate of phase change of the paraffin wax as the PCM dispersed with 3 distinct NP types, which are —alumina (Al2O3), copper oxide (CuO), and zinc oxide (ZnO)—in addition to wall heating side effects as well as dispersed NP concentration in PCM had been examined. ANSYS Workbench 17.0, which featured mesh generating tools, and FLUENT software were employed for the purpose of simulation. Enthalpy porosity method has been used in numerical analyses. According to results, adding low volume fraction of the NPs has resulted in increasing heat transfer rate.

Agner et al (2020) [48] had developed an innovative approach for the thermal energy storage by nano-encapsulation of the n-hexadecane in high MW value of polystyrene. This study involves mini-emulsion of the polymer with the use of IL (i.e., ionic liquid) depending upon imidazolium with the iron as catalyst. PCM-containing nano-particles have undergone a number of tests, which include differential scanning calorimetry, gel permeation chromatography, TEM, and thermal performance and molecular weight. Typical spherical nano-particles had restricted distribution in a range of particle size between 138nm and 158nm. When n-hexadecane amount increased from 20wt% to 50wt%, melting enthalpy for the nano-encapsulated PCM has been increased from 19J/g to 72J/g. In addition to that, after a 100 thermal cycles, NPs have shown thermal reversibility. The high molecular weight of the polymer could positively influence the thermal performance.

The improvement of the performance of finned cylindrical thermal energy storage (FC-TES) utilizing the PCMs boosted by the nano-technology which served within a system of water heating has been researched by Aichouni et al (2020) [49]. The stud included theoretical and experimental investigation carried out for the purpose of determining the impacts of CuO and Al_2O_3 NP addition to the PCM on thermal conductivity, specific heat, as well as rates of charging and discharging performance. Paraffin wax has been utilized as PCM in experimental equipment and it has been filled in the FC-TES. Comparing experimental results to the conventional PCM had shown to have a positive impact.

Ghalambaz et al (2021) [50] Have proposed layer of metal foam and PCMs reinforced with nano-particles for the purpose of boosting shell-and-tube LHTES (i.e., latent heat thermal energy storage) thermal performance unit filled with the capric acid. Each of Graphene oxide and CuNPs had been studied as additions. A higher degree of composite thermal conductivity could result in enhancement of heat transfer by metal foam use. It might, on the other hand, limit heat transfer in the molten areas and impede natural convection flows. Partial differential equations for the conservations regarding heat and momentum were used to represent the heat transfer. The partial differential equations have been solved with the use of the finite element method. It was discussed how LHTES unit's thermal performance and energy storage were affected by the eccentricity, porosity, and volume percentage of NPs in the metal foam layer. LHTES unit's response time is significantly enhanced through the metal foam layer, and it was found that a 10% eccentricity regarding porous layer toward the bottom increased unit's response time by 50%. LHTES unit's response time (melting time) can be lowered through 12% with the existence of nano-additives, and copper NPs performed marginally better in terms of heat transfer enhancement compared with the graphene oxide particles. Consequently, an LHTES unit's thermal charging time might be practically shortened by combining the enhancement approach without requiring a large size increase.

To maintain the flexibility and stability of solar-energy-based cooling and heating systems, Han et al (2022) [51] suggested the PCM as a unit for the thermal energy storage. A mathematical model that takes under consideration the impact of NPs on heat transfer is created to assess the PCM melting process. In order to improve melting process regarding phase change materials, we assess the contribution of NPs (copper, Al_2O_3, and graphene-based nano-fluids). The findings demonstrate that, even in early stages of the PCM melting process, natural convection driven by buoyancy effect controls flow behavior. The melted PCM is moved upward from the lateral by strong natural convection at the annular tube's bottom, which pushes liquid-solid boundary downwards. PCM melting performance has been improved through the addition of 3% vol. Al_2O_3 NPs, which reduce PCM melting time by approximately 15%. A comparative analysis of copper, Al_2O_3, and graphene NPs shows that the increase of the thermal conductivity (36W/m.K – 5,000W/m.K) doesn't result in a significant enhancement of the PCM melting ability.

A numerical analysis was conducted by Nehari and Benlekkam (2022) [52] to enhance PCM for LHTESS (i.e., latent heat thermal energy storage system). To increase PCM's thermal conductivity, a small mass fraction of hybrid NPs TiO_2-CuO (50%–50%) has been dispersed in 5 mass concentrations: 0%, 0.25%, 0.5%, 0.75%, and 1%. Hybrid nano-PCM (HNPCM) utilized in the LHTESS has been the subject of a study centered on its thermal performance. An enthalpy-porosity based numerical model is created for solving the energy as well as Navier-Stocks equations. The HNPCM's processes of melting and solidification in a shell and tube latent heat storage device were calculated. Experiments from the literature were used to successfully validate the created numerical model. Results have demonstrated that distributed hybrid NPs had enhanced the HNPCM's density as well as effective thermal conductivity. As a result, average time of charging had improved by 12.04%, 19.90%, 23.55%, and 27.33%, respectively, in the case where mass fraction of an HNPCM raised by 0.25%, 0.50%, 0.75%, and 1.0 mass %. Additionally, there is a decrease in stored energy of 0.83%, 1.67%, 2.83%, and 3.88%, in that order. Additionally, there were reductions in the discharging time of 18.47%, 26.91%, 27.71%, and 30.52%, in that order.

Artificial neural network (ANN) was constructed by Jaliliantabar et al (2022) [53] in order to predict latent heat of NEPCM. In the development study, various kinds of paraffin-based PCMs as well as nanoparticles have been employed. Density of NP, NP size, density of PCM, latent heat of PCM, concentration, and latent heat of PCM were the properties that were utilized as input for the model. These properties fell into the following ranges: 1–60nm, 100–8960kg/m^3, 89–311kJ/kg, 760–1520kg/m^3, 0.02–20wt%, and 60–338kJ/kg, individually. The outcome suggests that latent heat of nano-enhanced PCM may be satisfactorily predicted using ANN model.

The impact of nano-material loading on a few significant thermo-physical characteristics of PCMs, such as the melting enthalpy and thermal diffusivity coefficient, was investigated by Jafarian et al (2022) [54]. Paraffin wax has been modified with the addition of the silica (SiO_2) and CuO NPs as PCM for improving its thermal properties. The most accurate approaches have been utilized for creating samples, and FE-SEM has been utilized for examining their morphology. A laser flash apparatus (LFA) in addition to DSC have been used for the determination of thermal diffusivity and melting enthalpy, respectively. The percentage of weight of NPs (3 levels), NP type (2 levels), and NP size (3 levels) have been the 3 key factors tested in factorial arrangement with the use of an entirely randomized design. Pure Paraffin wax has been utilized as control sample with 3 replications. Results have shown that while NP size did not have noticeable impacts, the nano-composite's melting enthalpy has been decreased as NP weight percentage increased. In addition to that, Ne-PCMs' thermal diffusivity coefficient has been strongly affected ($p<0.01$) by NP type and size. It could be concluded that the NPs of the silica are more successful compared to CuO at the enhancement of PCM's thermo-physical properties, as it has been shown by the fact that those nano-particles had enhanced the nano-composites' thermal energy storage properties.

The impact of NP addition to PCMs and adding copper fins to both finned and un-finned triplex-tube thermal energy storage systems on the rate regarding PCM solidification has been studied quantitatively by Bazai et al (2023) [55]. In order to increase the solidification time, a number of parameters have been examined, including the kind of NPs (Ag, Al2O3, Cu, and CuO), concentration (1 & 3%) and diameter (20nm and 80nm). The obtained results showed that up to 67.11% of the solidification time could be saved by simultaneously adding fins and 3% of nano-Al2O3 with an average diameter of 20 nm.

Srinivas et al (2023) [56] main focus has been on the thermal conductivity of SiO2 nano-PCM in various reference materials. The sodium thiosulfate pentahydrate, paraffin wax, Zn(NO3)6H2O, and Na2S2O3·5H2O thermal energy storage capacity values have been measured in the PCMs. Temperature and SiO2 NP concentration impacts on heat emission rate from the polychlorinated biphenyls (PCMs) have been studied through the analysis of outcomes of those tests. Temperature degrees within the range of 20^o to 65^{o}C have been utilized for testing nano-PCM based upon volume fraction concentration and temperature. Thermal conductivity values of SiO2/Paraffin Wax, SiO2/Na2S2O3·5H2O and SiO2/Zn(NO3) 6H2O, have increased with the increase of the temperature and concentration.

Nano-PCM to enhance the electronics:

Phase change materials can be incorporated in order to increase the capacity of the coolers used for electronics, and to ensure their stable operation. Studies reveal the necessity to make changes to traditional cooling systems of electronic equipment. Benefits of PCMs include the enhancing of the device cycling and strengthening the components.

Through the use of numerical analyses, Hamza et al (2019) [57] have reached heat transfer boosting within rectangular adiabatic enclosure filled completely with the nano-enhanced PCM. A micro-processor, serving as heat source of the enclosure, is placed in the middle of the motherboard. This approach is dependent upon the dispersion of the metallic NPs and with the use of the PCMs for improving the heat dissipation for electronic component's passive cooling. Through the approach of enthalpy-porosity, a 2D model has been created numerically. The contribution of the natural convection has been taken under consideration. The effect of addition of metallic nanoparticles on average Nusselt number and melting rate represents the main focus of the numerical calculations.

The combined effect related to NePCM with various heat sink topologies for cooling electronic devices was experimentally studied by Fayyaz et al (2022) [58]. Aluminum is utilized as the pin fin heat sink material, RT-42 serves as the PCM, and MWCNTs (i.e., multi-walled carbon nanotubes) are utilized as NPs at concentration levels of 3wt% and 6wt%. Various heat sink forms, including triangle, square, and circular pin fins, are employed in opposition to the fins' set volume portion. Without and with PCM, the square form is determined to have the maximum heat transfer. A maximum 24.01% drop in base temperature was reported in square pin fins using RT42 as PCM. For a circular pin fin, the maximum base temperature decreased by 25.83% at 6wt% of NePCM. Findings indicate that all of the fin configurations with the NePCM together lower heat sink base temperature, and that a circular pin fin with the NePCM is useful for reducing the base temperature.

Adam-Cervera et al (2024) [59] have been encapsulating organic PCMs, which are octadecane and hexadecane, for thermal evaluation. This has been accomplished through formation of the nano-capsules of conducting polymer poly (3,4-ethylene-dioxythiophene) (PEDOT) that has been generated by the oxidative polymerization in the mini-emulsion. Polymer films are created on the support of the substrates for the purpose of studying NPs' energy storage capacity. The ability of the prepared systems in the effective storage and release of the thermal energy as latent heat has been observed from results, and it is vital for the improvement of thermoelectric devices' efficiency in the future.

Nano-PCM in miscellaneous applications:

The application of PCMs can be extended to include some thermal applications, especially fluids and solar energy. Nanoparticles can be integrated with the paraffin wax or the salt hydrates in order to increase the efficiency regarding concentrated solar power plants, thermal oils and to generate nano-fluids. Nano-PCMs play also an essential role in mitigating the high temperature of PV panel surface or in reducing heat radiation through the windows in residential building.

The characterisation and synthesis of fluids including PCMs, like NPs was the focus of Argilés (2020) [60]. The choice of adding nano-encapsulated thermal phase change materials (nePCMs) as solid component of the nanofluid is based on their capacity to store thermal energy as latent phase, in addition to typical heat storage technique via sensible phase change. Various nano-fluids, depending on molten salts (a mixture of $NaNO_3$ and KNO_3 in a 60:40 wt.% (majorly referred to as solar salt) and synthetic thermal oil (Therminol 66) were synthesized and characterized to investigate the effects of the addition of nePCMs (Sn, Sn/Pb, and Al/Cu encapsulated NPs) on their thermal properties, including specific heat capacity as well as thermal conductivity. Very nano-meters SiO_2 and Al_2O_3 encapsulating coatings were created using state-of-the-art techniques including atomic layer deposition (ALD). Thermal conductivity can be improved by up to 22% in nano-fluids that are made of Sn nePCMs and thermal oil TH66. Additionally, they show improvements in thermal capacity (up to 37% increase for a 25°C temperature step), which are particularly significant for applications with a tighter cycling temperature range since the impact of the NPs' latent heat becomes more significant. Yet, using nanofluids at high temperatures could sometimes lead to issues. For instance, the interactions of base fluid with the nano-particles could be harmful, or nano-fluid's increased capabilities could be affected negatively by colloidal stability lack.

The effects of adding nano-scale copper oxide to solar panel at a 0.05% concentration of total mass of PCM (beeswax) were experimentally studied by Mohammed et al (2023) [61] and compared with reference case which didn't include any nano-additions. Results showed that the average temperature of the plate decreased by 3°C and its electrical efficiency increased with the addition of nano-scale copper oxide. The performance of integrated solar energy systems with the phase change appears to be improved by the introduction of the NPs.

Albisher (2023) [62] gave a master's thesis on using nano-additives to enhance phase-change materials' thermal conductivity and their capacity to control photovoltaic cells' (PV) operating temperature within a typical operating temperature range, therefore increasing PV efficiency. This investigation is a follow-up to earlier studies. The impact of the shaped nanoparticles added to PCM was considered. The goal of the study was to determine whether adding various forms of silver nanomaterials—such as silver nanowires, silver nanoparticles, and nano-hybrids made of both silver nanowires and silver nanoparticles —could increase paraffin's thermal conductivity. At 0.5% and 1% volume fractions, nanomaterials were introduced. The study then looked at this material's potential for controlling and lowering solar cell temperature. They created a 3D system using the "Solidworks" application, and then conducted thermal analysis using the "Ansys Fluent" program. The results of various examples have been examined, and their abilities in lower photovoltaic temperature have been made clear. Including nano-wires at a 1% volume fraction had resulted in improvement of thermal conductivity of paraffin the most, however, the use of the PCM enhanced by nano-wire at a 0.50% volume fraction had resulted in producing the optimal results in the reduction of PV temperature. The average temperature of the PV had dropped by 14.9K. The photo-voltaic efficiency had increased as well by approximately 7.60%. The average PV temperature has been reduced by 12.9K. In addition to that, there has been a 6.60% increase in the photovoltaic efficiency.

The effectiveness of a parabolic concentrator solar cooker using PCMs that are nano-mixed binary salts was investigated by Kanase-Patil and Papade (2024) [63]. Alumina (Al2O3) NPs are combined with binary salts, such as KNO3 and NaNO3, in weight ratios of 0.5%, 1%, and 1.5%. Experimental calculations are used to determine properties including thermal diffusivity, melting point, specific heat, and thermal conductivity. Dal and rice are the two foods that are chosen to be cooked. The experimental outcomes of this study project indicate some encouraging results. The cooking time for both food items decreases as the amount of NPs added to PCM increases, and cooking time for plain PCM is reduced in comparison to the nano-mixed PCM. There was a noted variation in cooking time of 5min−6min between plain and nano-mixed PCMs. The fact that the addition of NPs alters the thermal properties regarding PCM material is another significant finding from this investigation. Both thermal diffusivity as well as thermal conductivity rise by 20% and nearly 10%, respectively. At 100°C and 250°C, respectively, PCM's melting point drops by 22°C and its specific heat reduces by 12% and 17%. Eventually, it is determined that thermal storage capacity of the PCM material is enhanced by incorporation of alumina nano-particles in the binary salts PCM.

Bahrami et al (2021) [64] have studied the effects of PCM and nano-enhanced PCM utilization as wallboard on thermal behavior of the room. Which is why, a 2-D room has been CFD (i.e., computationally fluid dynamics) modeled in the summer weather of Tehran. In the two cases, wall surface temperature, interior wall heat flow, and indoor temperature records have been made. There has been thermal improvement after the comparison of obtained results with those of pre-modified room. Based on findings, compared to a standard room, the use of solid nano-particles in the PCM results in lowering air conditioning system energy consumption by 7.40%. With a 21.60-minute increase in time delay to peak temperature, 4.37% more energy storage than pure PCM, and a 0.273 reduction in the temperature decrement factor, the room performs better thermally than the PCM wallboard boosted by nanotechnology. The temperature fluctuation in the room is reduced by 52% and 31%, respectively, when deploying nano-enhanced PCM, as opposed to conventional and pure PCM rooms. The findings of this research may aid researchers and designers in choosing PCMs for building ventilation system applications that are more suitable.

General scope on current studies:

Recent studies focus upon the utilization of NPs to enhance thermal behavior of PCMs for many applications. This study reviewed several references, and recognize some common features, as listed in **Table 3**. The bulk of research can be described as numerical works. This is explained by the expensive cost of nanoparticles, the challenge of homogeneous mixing with PCM, and the availability of software that makes problems easier to solve and produces accurate findings. For purposes of validation, some researches do experimental works. Nano-PCMs are used as a result of their high thermal conductivity and capacity, and their ability to disseminate effectively and sufficiently within the PCM. The research has applications in the areas of heat exchangers, energy storage, solar collectors, solar panels, and building air conditioning. A number of novel approaches have been seen in the investigations, including the use of magnetic fields in applications, the simulation regarding ANNs, the suspension of nano-PCM in the boundary layer of a surface, and the modification of enclosure's orientation in Ne-PCM. Regarding the content ratio of NPs, it can be observed that the ratio of nano-additive is as low as 1% (or less) for graphene. This ratio can be higher for certain purpose (studying the latent heat thermal storage with a compact finned tubes heat exchanger). By using CNTs, the content went higher for an extent. For SiO_2, TiO_2 and CuO, it goes higher up to 3%. For Al_2O_3, the content may be higher (up to 14%) for certain application, such as studying the magnetic field on PCM melting rate.

Table 3. Scope on available literature.

Ref.	Type of study	Contribution and application	PCM	Nano-content
[35]	Experimental	Enhance the heat transfer of PCMs.	Paraffin and salts	Graphene (1-5%)
[36]	Experimental	Improve energy efficiency in buildings.	Fatty acid	SiO2 (0.5-1.5%)
[37]	Experimental	Analyze the effects of NePCMs during Rayleigh-Benard convection.	Coconut oil	Al2O3 (<1%)
[38]	Numerical	Study the flow features within an annulus loaded with nano-PCM.	-	-
[39]	Numerical	Study impacts of the use of a magnetic field on PCM melting rate	Octadecane	Al2O3 (6-14%)
[40]	Numerical	Investigate natural convection of nano-PCM within boundary layer in heated flat surface.	-	-
[41]	Numerical	Improve the properties of n-PCM by changing the orientation of the enclosure.	RT-42	Al2O3, CuO, CNT (1-5%)
[42]	Numerical	Study latent heat thermal storage with a compact finned tubes heat exchanger	Paraffin	Graphene (0.5-6%)
[43]	Experimental	Study the ultra-sonication on particle agglomeration and effect on heat transfer.	Paraffin	CuO (0.5-3%)
[44]	Numerical	Investigate the magneto-hydrodynamic mixed convection of NEPCM contained within lid-driven trapezoidal enclosure.	-	-
[45]	Numerical	Study coupling between advanced 2-phase model for NePCM and enthalpy-porosity formulation for phase change.	RT-82	Al2O3 (>1%)
[46]	Numerical	Enhance capabilities of heat recovery of the nano-PCM composites through the grading of concentration along direction of the heat.	RT-55	-
[47]	Experimental and numerical	Enhance phase change material in cold thermal energy storage.	Paraffin	Al2O3, CuO and ZnO

[48]	Experimental	New method for nano-encapsulation of PCM for thermal energy storage.	n-Hexadecane	-
[49]	Experimental	Enhance finned cylindrical thermal energy storage with the nano-PCM.	Paraffin	Al2O3 and CuO
[50]	Numerical	Improve performance of shell-and-tube thermal energy storage with the use of a combined of nano-PCM and meal foam.	Capric acid	Graphene oxide and CuO
[51]	Numerical	Nano-PCM as thermal energy storage of solar-energy-based cooling and heating systems.	-	Al2O3, copper and graphene (3%)
[52]	Numerical	Improve latent heat thermal energy storage system.	-	Hybrid of TiO2–CuO (<1%)
[53]	Numerical	Develop artificial neural network for the purpose of predicting latent heat of the nano-PCM	Paraffin	Al2O3, SiO2, TiO2, graphene, CuO (<10%)
[54]	Experimental	Study effects of nano-loading on the thermo-physical characteristics of the PCM.	Paraffin	SiO2 and CuO (2-8%)
[55]	Numerical	Study the effect of nano-PCM in copper fins within both un-finned as well as the finned triplex-tube thermal energy storage systems.	-	Al2O3, Ag and CuO (1&3%)
[56]	Experimental	Study nano-PCM's thermal conductivity and thermal capacity.	Paraffin, Zn(NO3)6H2O and Na2S2O3·5H2O	SiO2 (0.02-0.1%)
[57]	Numerical	Improve the heat transfer within rectangular adiabatic enclosure filled with the Nano-PCM.	n-Eicosane	CuO
[58]	Experimental	Study combined effect of nano-PCM for cooling electronic devices.	RT-42	CNT (3-6%)
[59]	Experimental	Investigate PCM encapsulation through formation of the nano-capsules of conducting polymer poly(3,4-ethyl-enedioxythiophene).	Hexadecane and Octadecane	-
[60]	Experimental	Improve the efficiency of concentrated solar power plants using nano-encapsulated PCMs.	Thermal oil and molten salts	SiO2 and Al2O3
[61]	Experimental	Investigate the impact of nano-PCM in a solar panel.	Beeswax	CuO (0.05%)
[62]	Numerical	Improve PCM's thermal conductivity and the capability for regulation of PV cell temperature.	Paraffin	Ag (0.5&1%)
[63]	Experimental	Enhance parabolic concentrator solar cooker using mixed salts as the PCMs.	NaNO3 and KNO3	Al2O3 (0.5-1.5%)
[64]	Numerical	Nano-PCM as wallboard of a room.	-	-

Conclusion

By observing the collected sources and their corresponding ideas and data, the concluding statements of the works refer that nano-PCM can be used to improve thermal energy storage or heat transfer in general. However, sometimes they can be used in specific applications, as: electronics, air-conditioning and PV cells. However, common applications used nano-PCMs to improve thermal energy capacity of PCMs. Salt hydrates, paraffin waxes, and hybrid compounds are the PCMs that are employed. The following NPs are being considered: SiO_2, Ag, graphene, CuO, and Al_2O_3. Where, the content was between 0.5-15 %. When the PCM under use is a paraffin-based PCM, the content of NPs is usually less than 5%, while it can be higher for salts and other PCM types.

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