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Nano-enhanced Phase Change Materials (NePCM) for Thermal Energy Storage in Buildings

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Abstract. With the increasing demand for energy due to the rise in temperature, passive cooling strategies are implemented to help achieve thermal comfort with an optimal energy reduction. One of the effective approaches can be the implementation of Nano-enhanced Phase Change Materials (NePCM) into a building envelope and active HVAC systems to help in temperature control by thermal energy storage. With pure PCM, low conductivity has been a major drawback that caused it to have a slow discharge rate. The inclusion of nanomaterials has dramatically improved its thermal conductivity which led to a shorter discharge time and better performance. Carbon-based nano-additives has shown the greatest enhancement in thermal conductivity while being one of the most expensive option. This review article delves into the characteristics that makes the integration of NePCM into buildings a promising thermal energy storage strategy that can lead to energy savings and reduce temperature fluctuations, especially for arid and hot weather climates without the use of an energy source.

Introduction

Buildings thermal regulation has become a necessity due to the increasing rate of global warming and temperature rise which makes it consumes most of the generated energy; around 40% of the energy used worldwide is consumed by buildings [1]. The need to cutdown on energy consumption and achieve thermal regulation has led to the focus on passive cooling strategies. One of the promising strategies to be incorporated into buildings is Phase Change Materials (PCMs). PCMs can absorb heat at either constant temperature while transitioning from one phase to another (*i.e.,* latent heat) or as sensible heat [2]. Such a mechanism of absorbing and releasing thermal energy without significant temperature changes can help in controlling temperature fluctuations in buildings [3]. By absorbing latent heat during the day and releasing it at night, PCMs can minimize thermal fluctuations which corresponds to less cooling load due to the less demand of HVAC system regulation [4].

There are three main categories of PCMs that are used in thermal applications: organic, inorganic and eutectic compounds [4]. Organic PCMs include paraffin and non-paraffin and are the most versatile in building envelope applications [5]. Inorganic PCMs such as salt hydrates and

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metallic PCMs have higher energy storage capacity and a higher thermal conductivity that in organic PCMs [6]. Eutectic PCMs can handle the drawbacks of a single-phase change material such as phase separation, unadjustable temperature, and supercooling

One of the drawbacks of pure PCM is its low thermal conductivity which can be as low as 0.2 W/(m-K) for PEG-1000 [7]. Therefore, pure PCM should be altered to minimize the response time which can be achieved by implementing nanotechnology to develop nano-enhanced phase change materials (NePCM) that can speed up its freezing and melting rates [7]. NePCMs has advanced thermal energy storage (TES) especially during its charging and discharging modes [7] which not only enhanced its thermal conductivity but also diminished supercooling. The combination of passive cooling and nanotechnology has a high potential in overcoming the increasing demand in energy due to the accelerating global warming. In this work, its integration into building envelopes is investigated as a viable solution to this issue. Future challenges, along with techno-economic and lifecycle analyses of current literature are studied herein as well to provide a comprehensive overview of the proposed strategy.

Nano-enhanced Phase Change Materials: Fundamentals

Phase change materials (PCM) have emerged in the buildings development research sector as one of the most promising strategies for thermal regulation [8]. Pure PCMs are constrained by their relatively low thermal conductivity which can limit their ability of an optimal rate of heat absorption and release [9]. Therefore, highly conductive nano-additives were introduced, and with the help of the characteristics of the PCMs, highly conductive NePCMs were developed [10].

NePCM can be integrated to a building for the goal of thermal regulation through macro-micro or nano-capsulation and then be used in walls, windows, roofs or the construction materials in between [11], [12], [13], [14]. By the release and absorption of heat, the building's temperature fluctuations can be decreased which could lower the load on the HVAC systems. Innovative integration and material selection such as bio-PCM and hybrid composites has led to better thermal properties and effective performance [10].

During operation, NePCM absorbs heat from the surroundings as the temperature rises during the day and reaches a temperature above its melting point. With the help of the nano-additives, the process of heat absorption can be accelerated in comparison with pure PCMs. On the other hand, when the temperature cools down at night to a temperature below its freezing point, the NePCM solidifies and releases the stored heat into the atmosphere [15]. The mechanism of a NePCM panel can be simply illustrated in Fig. 1. By undergoing such a cycle during the day, the integration of NePCM can help in substantially reducing the cooling load and peak energy demands as it acts as a thermal energy storage system that operates with the use of zero energy [16].

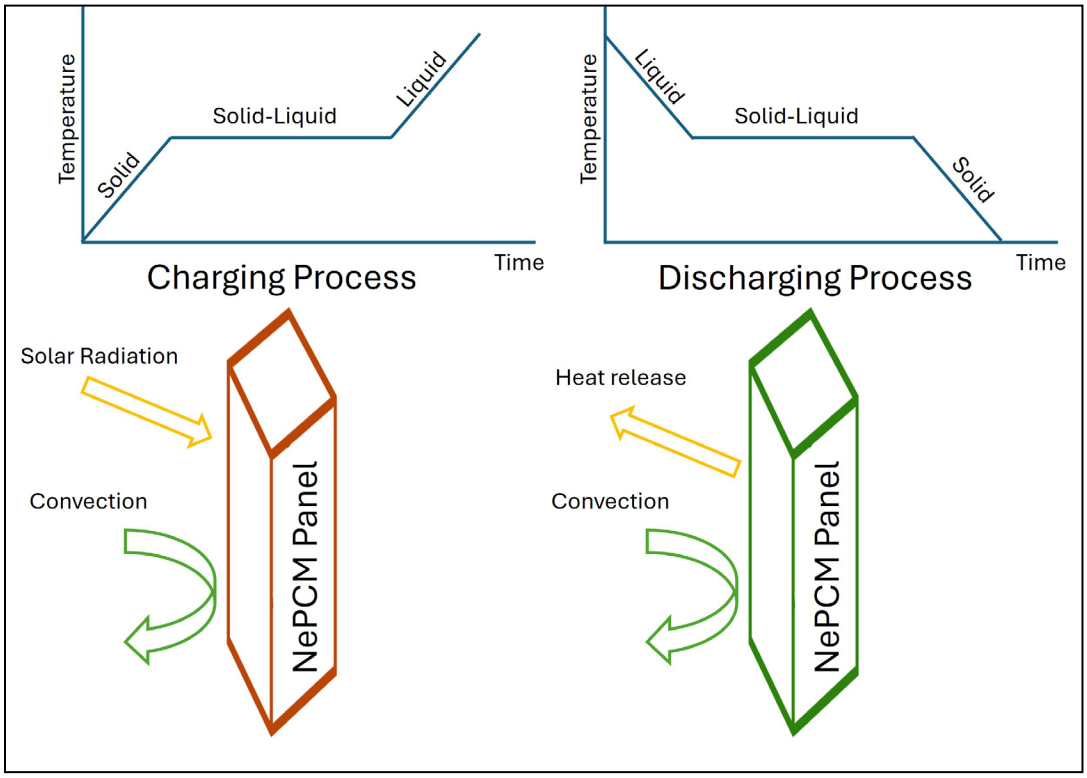


Fig. 1. Mechanism of NePCM thermal storage cycle.

Classification of Nano-enhanced Phase Change Materials

The incorporation of nanotechnology to traditional PCM applications in thermal regulation resulted in an advanced technology that can overcome the limitations of pure PCMs by improving their thermophysical properties [17]. Different materials and different incorporation techniques can lead to different performance results, especially in arid climate conditions.

Base PCMs and Nano-additives. The selection of the base PCM is the first step in the development of NePCMs. PCMs can range from organic, inorganic and eutectic PCM. Organic PCMs such as paraffin and fatty acids are known to be mostly non-toxic, non-corrosive and easily accessible. Their temperature range can go from 15-45°C which makes it applicable for most situations [2]. Although organic PCM has a high latent heat storage capacity [18], its thermal conductivity is very low (~0.2 W/(m-K)) [7], which results in high installation [17]. On the other hand, inorganic PCMs such as salt hydrates can offer a higher latent heat capacity but are prone to sub-cooling and phase separation [19]. Eutectic PCMs, on the other hand, are a mixture of two or more types of PCMs. The development objective of such PCMs is to alter the range of operation temperature to be tailored for a specific application [4]. When selecting a base PCM for a NePCM application for thermal regulation, one key criterion is the melting range of the PCM and the building's thermal fluctuations. Based on the location of the integrated PCM into the building envelope, the target range can vary.

The nano-additives in a NePCM depend on the desired enhancement to meet that a pure PCM lack in a certain application. In general, high-conductivity nanoparticles are incorporated to enhance the thermophysical properties [10]. The most commonly used nanoparticles (NPs) in NePCMs can be categorized into metallic, metal oxide and carbon-based NPs.

Metallic and metal oxide nanoparticles (Cu, CuO Ag, Al_2O_3, TiO_2, SiO_2, ZnO) can have very high thermal conductivity that can decrease super-cooling in PCM. Metallic NPs can increase the overall suspension's thermal conductivity by 46% with minor changes in phase transition temperatures [15]. Carbon-based nanomaterials such as graphene nanoplatelets, carbon nanotubes

(CNTs), graphite can be used as thermophysical properties enhancement to PCMs. Stonehouse and Abeykoon [20] concluded that even at values of less than 5 wt.%, 3D carbon-based NPs can have a thermal conductivity enhancement of around 300% when compared to that of lower dimensional carbon-based materials where the enhancement is around 50%[20].

Encapsulation strategies. In order to integrate the NePCMs into a building envelope, the suspension is encapsulated using an appropriate method that prevents leakage based on the desired application. Macroencapsulation, microencapsulation or shape-stabilization are all methods of encapsulation strategies that can be applied [21]. Macroencapsulation is when large quantities of NePCM is being contained in a shell such as panels, tubes or boxes. This strategy can be incorporated in concrete bricks in building cavities and building envelopes and act as a thermal regulation module [22], [23]. On the other hand, microencapsulation is the ability to contain the NePCM in a protective spherical micron size shell [24]. It was found that microencapsulation can have improved mechanical and chemical stability, extended thermal cycling and can prevent chemical reactions due to the core-shell characteristics [25]. Shape-stabilization of PCMs (SSPCMs) is another form of encapsulation where the PCM is absorbed or embedded into a matrix where it cannot flow when melted. The capillary forces within the porous material keep the liquid from leaking [26]. Shape-stabilization has shown excellent chemical and thermal cycling stability even under crucial thermal reliability tests [27], [28].

The placement of the NePCM panels can have an influence on its performance in thermal regulation. Achaku et al. [12] found that the optimal PCM placements were in an arrange of 341 mm and 356 mm away from the external surface of the wall through which an energy consumption reduction of 34–37% was achieved. Moreover, it was found that the closer the placement is to the inner wall, the more stabilization of indoor temperatures and achieved due to thermal storage of NePCM that causes a reduction in heat transfer. Fig. 2(a) illustrates the heat transfer rate versus the placement of the PCM. As a result, a significant energy consumption reduction corresponds to the ideal range of 341-356 mm as shown in Fig. 2(b). Although at 100 mm away from the external surface shows the most optimal results compared with the baseline (NO PCM), a temperature analysis showed that at the range of 341-356 mm the PCM reaches its phase change temperature which shows how the PCM can act as a thermal buffer by the storage and release of energy to the external wall [12].

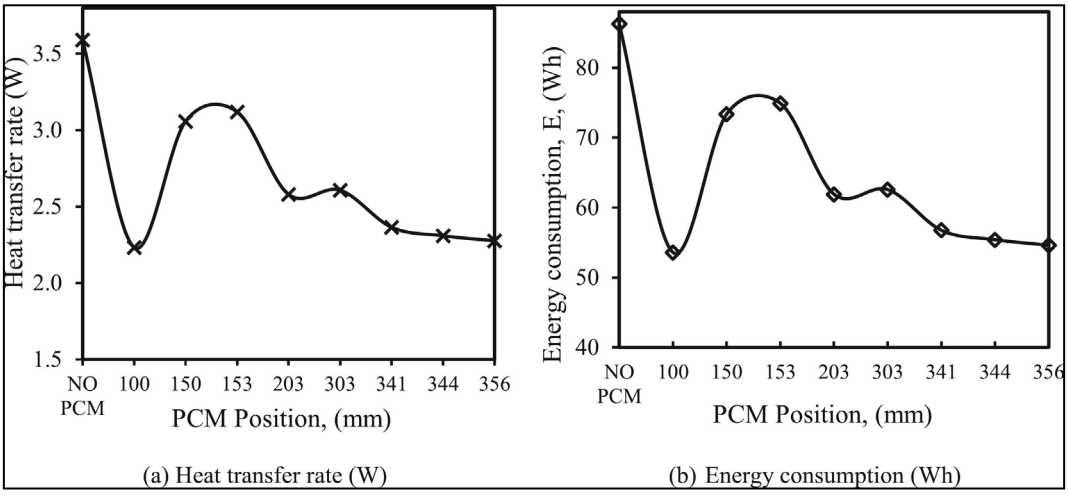


Fig. 2. Effects of PCM placement positions on: (a) Heat transfer rate (b) Energy consumption [12].

Performance Analysis

Thermal Properties. In literature, NePCMs have been characterized based on their thermophysical properties in comparison with pure PCM in a thermal regulation application. Studies have shown that thermal conductivity can be enhanced drastically through the incorporation of nanoparticles. Table 1 shows a comparison of a number of the studies where the level of enhancement of thermal conductivity varies based on the type of nanoparticle used in a NePCM. Carbon-based nanoparticles could achieve higher enhancement percentages due to their high thermal conductivity and low density, making them highly efficient additives [29]. One drawback of carbon-based nanomaterials is their cost. NPs' addition (CuO, CNT, Al_2O_3, TiO_2) to PCM has achieved significant enhancements in thermal conductivity and heat storage density which corresponds to the rapid charging and discharging rate, thereby facilitating a more responsive TES system that is applicable for dynamic thermal load regulation [30].

Table 1: Nanoparticle Influence on Thermal Conductivity for Different PCMs.

Nanoparticle	PCM	Thermal Conductivity Enhancement	Ref.
Copper and graphene oxide	Paraffin RT31	12.5%	[31]
Graphene and SiO_2	Paraffin 98	50%	[32]
GNT and MWCNT	Paraffin RT54HC	40%	[33]
CNT	Methyl stearate (MS)	2319%	[34]
Graphene nanoplatelets	Lauric acid	230%	[35]
Nano-sheet Graphene	Polyurethane–paraffin	97.4%	[36]

In addition to the change in thermal conductivity, the latent heat of NePCM was found to be lower than that of pure PCM. For instance, a reduction of 12% in latent heat capacity after the incorporation of titanium dioxide TiO_2 into paraffin PCM was exhibited due to a proportional relation between the amount of NPs added and the reduction percentage [37]. The overall efficacy of NePCM is also dependent on the phase transition temperature, spatial distribution within the building envelope, and local climatic conditions.

Mechanical properties. The addition of NPs to NePCM have shown that it can have an effect on the mechanical strength and properties when incorporated using a form stabilization encapsulation strategy [38]. The addition of NePCMs to building materials such as concrete or cement mortar can help improves their thermal and mechanical properties which can aid in the thermal regulation of the building [39]. For instance, the addition of Nano-Al_2O_3 to spherical bio-based encapsulated PCM into gypsum not only enhanced thermal properties and lowered subcooling degree, but it also enhanced compressive strength (1.28 kN) attributable to the structural reinforcement [40].

Application

The properties of NePCM can lead to a numerous range of applications in passive thermal energy system (TES). Researchers have investigated its integration into passive systems (building envelope elements) and active systems (HVAC components and energy systems) [23], [41] in order to thermally regulate the indoor temperature of a building. The integration of PCMs has been studied and analyzed in research where studies focusing on Paraffin wax micro-encapsulated into a building envelope have shown enormous results of energy reduction of cooling load up to 20% and excellent thermal insulation performance [42], [43].

An experimental study of a hybrid CPV/T system with a heat exchanger and a spectral splitting unit has incorporated glycerol/silver nanofluid (NF) and dotriacontane/gold (NePCM) which is an

example of NePCM integration in active systems. The Dotriacontane/gold NePCM's role was to act as an absorptive filter. By optimizing the system, an annual maximum energy and exergy efficiencies of 123.9 % and 17.08 % were achieved, indicating overall thermal improvements [41].

For passive systems, the NePCM can be integrated to the building walls, roof or windows. Yang et al. [13] evaluated the integration of a hybrid NePCM containing Paraffin with nano Al_2O_3-CuO particles with a ratio of 4:6 found a temperature deviation of 9.31 °C [13]. Moreover, integration of NePCM into roofing systems can aid in temperature and thermal regulation. Abbas and Muthulingam [23] integrated macroencapsulated nano-enhanced PCM (NePCM) in a two-way hollow concrete roof (HCR) where the NePCM samples tested consists of different NPS wt.% of 2 % and 4 % mass fractions of multi-walled carbon nanotubes (MWCNT) and graphene nanoplatelets (GNP). The resulted thermal conductivity as shown in Fig. 3 is improved compared with the baseline PCM of 0.22 W/m K. MWCNT–NePCM exhibited an increase of 27.3 % and 36.4 % for the 2 % and 4 %, respectively. Morever, the GNP–NePCM exhobited higher thermal conductivity values with an increase of 36.4 % and 45.5 %. This increase can be correlated to the two-dimensional planar geometry of GNPs [23].

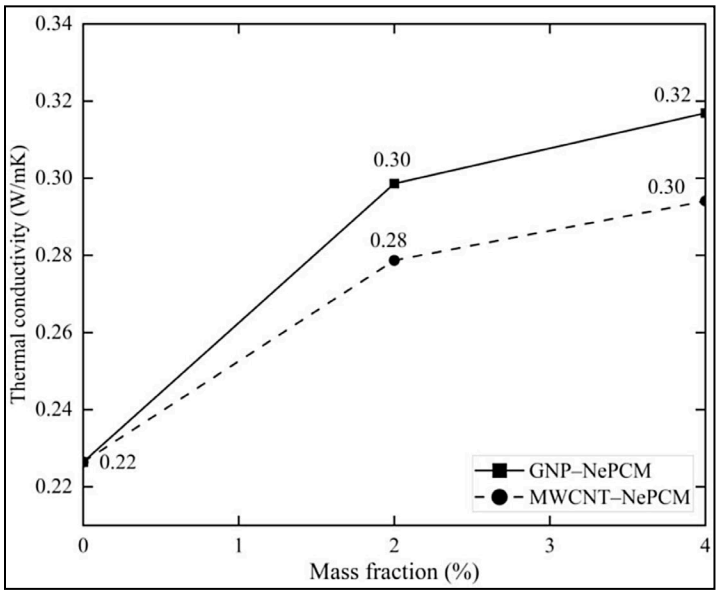


Fig. 3. Enhancement of thermal conductivity of MWCNT–NePCM and GNP–NePCM at different concentrations [23].

Limitations and Challenges

Dispersion and Stability. The incorporation of NePCM in a building makes it harder to maintain frequently, therefore, ensuring long-term stability of the NPs is one of the primary concerns in the development of NePCM. Agglomeration, sedimentation or even clustering can all lead to a non-uniform property throughout the fluid. This can degrade the enhanced thermal properties of the suspension and require researchers to do cycling stability tests in addition to properties characterization. AGuan and Chen [44] prepared a nano-encapsulated PCM with SiO_2 as the shell and conducted 2000 thermal cycles. The results highlighted that the melting enthalpy maintained its high value with only a 6.8 J/g reduction which corresponds to its remarkable cycling stability[44]. In NePCM fabrication, surfactants are used in order to assist stabilization and prevent agglomeration and/or phase separation [45].

Nanomaterials Concentrations. While the addition of nanomaterials into PCM has achieved an increase in thermal conductivity as discussed, higher concentrations can set some drawbacks that will affect its efficacy. A decrease in latent heat was observed with increasing graphene

nanoplatelets (GNP) and multiwall carbon nanotubes (MWCNT) hybrid nanoparticles weight fraction in RT-54HC organic PCM [9]. Moreover, Ho and Gao [46]evaluated the incorporation of 10 wt.% of Al_2O_3 NPs to paraffin and resulted in a 6% enhancement of thermal conductivity while a reduction of 13% in latent heat capacity was a major side-effect[46]. Higher nanomaterial content can lead to more agglomeration and sedimentation during the repetitive cooling periods which can negatively affect the thermal properties of the NePCM [47].

Other challenges can be related to the compatibility of the NePCM and the shell materials in all types of encapsulations [23], [43], [44]. Taken together, the limitations of NePCM are being investigated rapidly in the research field. The selection of PCM, nano-additives, method of encapsulation can all help in minimizing the drawbacks of NePCM given their effective performance in thermal regulations.

Conclusion

The growing global energy demand, combined with rising ambient temperatures, has made passive cooling a critical component in building design. The use of nano-enhanced phase change materials (NePCM) in buildings can offer a promising pathway towards thermal regulation and managing temperature fluctuations while reducing energy consumption. By taking advantage of the latent heat capacity of phase change materials (PCMs) and elevating the thermal conductivity through the integration of highly conductive nano-additives, an advanced suspension is developed with enhanced thermal properties and enhanced phase stability. This enhancement can help effectively accelerate the heat transfer rate from and to the NePCM enabling rapid charging and discharging cycles which are a crucial requirement for maintaining uniform interior thermal comfort in buildings. Although the addition of NPs to PCM has led to enhancement in thermal conductivity, high concentrations can have a negative effect on latent heat capacity which leads to the need to investigate the proper concentration that will have the optimal enhancement without compromising any other necessary properties. Moreover, lab-scale studies have investigated NePCM stability in short periods of time compared to the expected lifespan of the NePCM [44]. Future studies should focus more on the dispersion methods of NPs in PCM that can guarantee long-term stability through life-cycle assessments. The lab-scale data in literature show promising thermal energy storage results but more depth into the techno-economic analysis and life-cycle environmental impacts are underexplored for the future of integrating it into buildings. Due to that, scalability and commercialization remain a significant barrier to the future of NePCM within the building sector and thermal regulation. With the prioritization of the thermal conductivity enhancement and performance of NePCM using experimental and numerical approaches [48], [49], [50], [51] , the next step in research should aim to highlight it's compatibility in a real-life scenario through large-scale validation and long-term performance analysis under extreme circumstances that can navigate the development of such strategy in the future of thermal regulation. By addressing these limitations and challenges discussed herein, NePCM technology can be transitioned from being a lab-scale research objective to a reliable commercial building solution for thermal regulation.

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