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Materials Horizons: From Nature to Nanomaterials

Zafar Said

Adarsh Kumar Pandey *Editors*

# Nano Enhanced Phase Change Materials

Preparation, Properties and  
Applications



Springer

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Zafar Said · Adarsh Kumar Pandey  
Editors

# Nano Enhanced Phase Change Materials

Preparation, Properties and Applications

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# Chapter 5

## Nanostructure-based Colloidal Suspension for Thermal Enhancement for NEPCM



**Suman S. Kahandal, Sandeep K. Jare, Yelim Kwon,  
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### 1 Introduction

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

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

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

## **2 Nano Enhanced Phase Change Material (NEPCMs)**

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

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

Following are the characteristics of ideal NEPCMs.

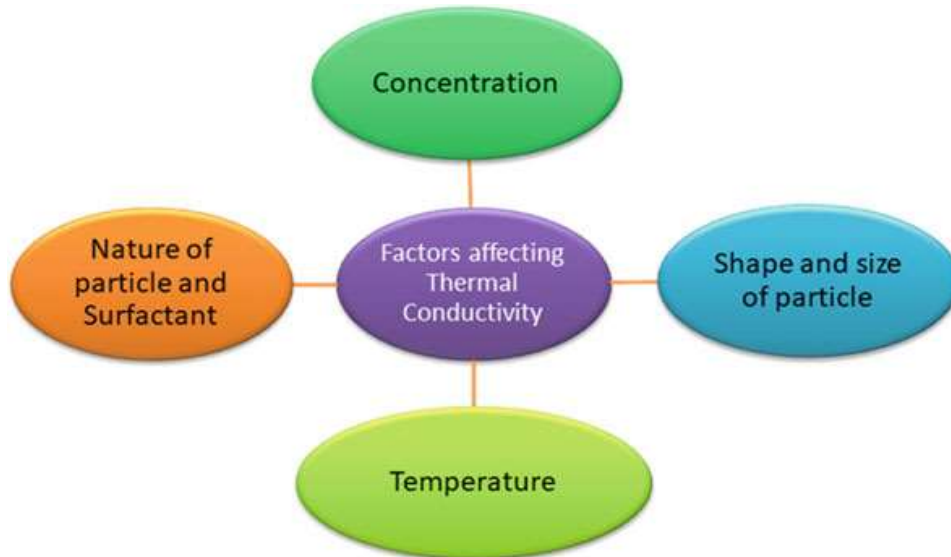
- (a) **High thermal conductivity**—transference of heat is a property of all materials. Any PCM material with high conductivity indicates that heat is released or stored within a short period of time. For effective thermal energy storage, a fast heat transfer rate is essential.
- (b) **Suitable phase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

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

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

### 2.2.1 Thermal Conductivity

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



**Fig. 1** Factors affecting thermal conductivity

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

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

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

### 2.2.2 Latent Heat Stability

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

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

### 2.2.3 Super Cooling

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

### 2.2.4 Density

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

### 2.2.5 Viscosity

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

## 2.3 Preparation Methods for NEPCM

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

### 2.3.1 One-Step Method

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

### 2.3.2 Two-Step Method

In a two-step process, dry powder nanomaterials are first fabricated using various mechanical and chemical methods such as sol-gel strategy, ball milling, and chemical reduction. At this point, this powder was mixed with PCM using various methods, such as magnetic stirring and homogeneous ultrasonic bath mixing. A two-step strategy is used for the industrial production of NEPCMs materials. Aggregation issues within the two-step strategy can be minimized by including various surfactants that make a difference in lowering the surface tension between the liquid and nanomaterials and stabilize the assembly. PCM nanocomposites were assembled by mixing capric and palmitic acids into graphite nanosheets through a sonication strategy [30]. Paraffin expanded perlite with graphene Nano platelets composite formed in acetone by ultrasonic probe sonicator method [31]. A two-step strategy to place NEPCMs of  $\text{TiO}_2$ ,  $\text{CuO}$ , and  $\text{ZnO}$  with lauric acid and stearic acid by sonication strategy was performed [32]. Made from palmitic acid and multi-walled carbon nanotubes, NEPCM is shaped to enhance its thermal properties. Carbon nanotubes were mixed with potassium hydroxide, and the resulting mixture was ball milled. Then the mixture was diluted with water and proceeded for the drying process. The composite was prepared by carbon nanotube with palmitic acid by sonication method [33].

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

The application part of NECPMs focused on two areas:

### (1) Thermal Management

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

processes while capturing and reducing CO<sub>2</sub> levels. It also helps to monitor the thermal condition of the photovoltaic system [34–37].

## (2) Thermal Storage

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

## 3 Classification of Nanostructure Based Enhanced PCM

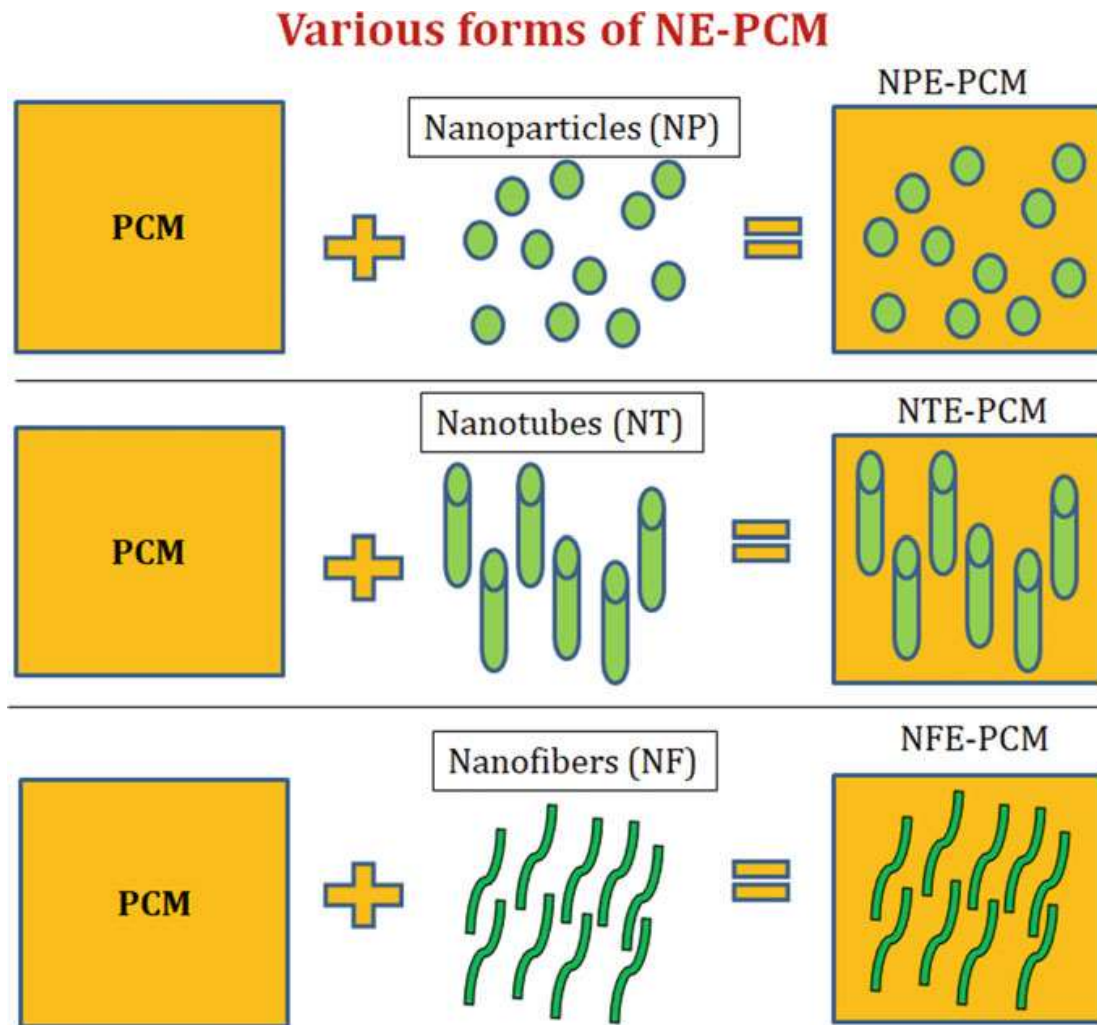
In heat exchange devices, the use of PCM increases the huge TES capacity over a wide temperature range. However, the low thermal conductivity of PCM limits its application in such devices, as it requires both high capacity and high heat removal rate. According to the Gibbs hypothesis, increasing temperature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

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

### 3.1 Nanoparticle-Based Colloidal Suspensions

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

These PCM emulsions are liquid–liquid mixtures of colloidal suspensions and nanoparticles, such as KNO<sub>3</sub> liquid salt containing nanometer-sized oxide nanoparticles of Al<sub>2</sub>O<sub>3</sub> and SiO<sub>2</sub>. In colloidal suspension-based PCMs, latent heat changes remarkably, while the melting point remains unchanged after the accumulation of nanoparticles. Latent heat change of PCMs shows an increasing trend due to single species of nanoparticles while decreasing trend is observed due to hydrophilic fumed



**Fig. 2** Various forms of nanoenhanced PCMs

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

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

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



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

### 3.1.2 Properties of Colloidal Suspension of Nanoparticles

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

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

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

### 3.2 *Nanotube-Based Colloidal Suspensions*

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

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

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

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

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

- (5) Platinum Green Chemicals Sdn manufactured petroleum-based multi-wall CNTs and hydro-drilling fluids. Bhd., Malaysia, used as received. Hydrogenated oils contain a mixture of straight and branched chain paraffins with carbon chain lengths from C15 to C18, which are naturally formed as non-polar groups. At  $80,000 \times$  magnification, it can be seen that the CNT bundles with normal outer spacing of 10–12 nm are trapped by only 10–12 nm. Traps can cause CNTs to accumulate in the nanofluid if they are not consistently dispersed. The multi-walled CNTs consist of a fixed inner width with numerous outer CNT layers with a typical thickness of 4.7 nm. Within the range of 6–7 nm, the internal spacing of multi-walled CNTs had been consistently observed. In order to make mixtures of 1-Cyclohexyl-2-pyrrolidone (CHP) and water, the required amount of CHP was first weighed out and then added to the water. Previously, the formula for calculating the gravimetric concentration of water in C.H.P. was as follows:  $X = [\text{water}]/([\text{C.H.P.}] + [\text{water}])$ . The CHP and water mixture had the required quantity of MWCNTs added to it so that it could be transformed into a suspension consisting of CHP, water, and MWCNTs. After that, the suspension was sonicated with an ultrasonic disperser at a frequency of 44 kHz and a power of 400 W so that it could be more evenly distributed. The suspension had been sonicated in a bath of cold water to prevent it from becoming overheated and ensure that the temperature did not go over 313 K. The heavily entangled or aggregated MWCNT samples were easier to disperse thanks to sonication, but the MWCNTs themselves were damaged as a result of the process. In the experiments, each suspension had been sonicated for ten minutes prior to being used, and the preparation was done right before the experiment. An investigation was conducted on a number of samples, each of which had an MWCNT concentration (C) ranging from 0.0 to 1.0 wt% and a water concentration (X) ranging from 0 to 1 [45].
- (6) It had been determined that a mixture of double-walled alumogermanate nanotubes, also known as Ge-DWINTs and imogolite-like nanotubes (INTs), should be produced. Ge-DWINT had been obtained through the use of a sol-gel technique, much as Levard et al. had stated. The majority of the synthesis had been carried out in a container made of PTFE by vigorously swirling the mixture while adding Ge(OEt)<sub>4</sub> to an aluminum perchlorate assembly with a ratio of 2 of Al to Ge. A concentration of 0.25 mol L<sup>-1</sup> of aluminum had to be incorporated into the material to create a nanotube structure resembling a quasi-double-walled tube. The NaOH solution at a concentration of 0.25 mol L<sup>-1</sup> was added in increments up until the [OH]/[Al] 2 ratio caused the solution to hydrolyze. At this stage, the mixture had been baked in an oven at a temperature of 95 degrees Celsius for a period of five days. Following the completion of the maturation process, the suspension was dialyzed after being allowed to reach room temperature naturally [49].

### 3.3 Nanofiber-Based Colloidal Suspensions

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

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

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

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

## 4 Conclusions

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

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

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# Chapter 6

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



Mathew George and Reji Kumar Rajamony

### 1 Introduction

#### 1.1 Why Prediction and Theoretical Models?

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

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

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

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NEP अभ्यासक्रमावर आधारित

# परकीय विनिमय बाजार

अर्थशास्त्र : ऐच्छिक पेपर-३

डॉ. अमोल गायकवाड  
डॉ. अंबादास कापडी

डॉ. मनिषा आहरे  
प्रा. युवराज्ञी मथुरे



# परकीय विनिमय बाजार

## Foreign Exchange Market

एम.ए. : प्रथम वर्ष

सेमिस्टर 1 : अर्थशास्त्र - ऐच्छिक पेपर-3

(Course Code Eco 512 : Credits – 04) Major Electives

◆ लेखक ◆

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- अर्थशास्त्र विभाग प्रमुख व संशोधन समन्वयक, मराठा विद्या प्रसारक समाज नाशिक, संस्थेचे के.टी.एच.एम. महाविद्यालय, नाशिक येथे कार्यरत.
- २३ वर्षे पदवी व १९ वर्षे पदव्युत्तर वर्गांना अध्यापनाचा अनुभव.
- म. वि. प्र. संस्थेचे कला व वाणिज्य महाविद्यालय सातपूर, नाशिक येथे प्रगती प्राचार्य म्हणून कामकाज (२०१५ ते २०१७)
- एम. फिल. व पीएच.डी. मार्गदर्शक, सावित्रीबाई फुले पुणे विद्यापीठ, पुणे. • अर्थशास्त्र अभ्यास मंडळ सदस्य- सावित्रीबाई फुले पुणे विद्यापीठ, पुणे.
- व्यावसायिक अर्थशास्त्र अभ्यास मंडळ सदस्य, रांगमनेर नगरपालिका कला, डी.जे. मालपाणी वाणिज्य व बी. एन सारडा विज्ञान (स्वायत्त महाविद्यालय) ता. रांगमनेर, जि. अहमदनगर
- राज्यस्तरीय चर्चासत्राचे यशस्वी आयोजन (२०१५) कला व वाणिज्य महाविद्यालय सातपूर, नाशिक.
- राज्य, राष्ट्रीय आणि आंतरराष्ट्रीय स्तरावर ४९ शोधनिबंध प्रकाशित व अनेक रोमिनार व कार्यशाळांमध्ये तज्ज्ञ मार्गदर्शक म्हणून सहभाग.
- अर्थशास्त्र विषयावरील ०५ क्रमिक पुस्तकांचे लेखन व प्रकाशित. • सावित्रीबाई फुले पुणे विद्यापीठ बी.सी.यू.डी अंतर्गत एक लघुशोध प्रकल्प पूर्ण.
- सावित्रीबाई फुले पुणे विद्यापीठ पुणे अंतर्गत विविध महाविद्यालयांच्या साहाय्यक प्राध्यापकांच्या निवड समितीवर विषयतज्ज्ञ म्हणून कामकाज.
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- सावित्रीबाई फुले पुणे विद्यापीठद्वारा मान्यताप्राप्त एक लघुशोध प्रकल्प पूर्ण
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### डॉ. अंबादास कापडी

M.A., B.Ed., M.Phil, SET, Ph.D

एम.ए., बी. एड., एम.फिल., सेट, पी. एच.डी.

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६. तृतीय वर्ष कला शाखेसाठी 'आंतरराष्ट्रीय अर्थशास्त्र' या पुस्तकाचे सहलेखन

## डॉ. मिनाक्षी निगरो

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## डॉ. मनिषा आहरे

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१. साहाय्यक प्राध्यापक अर्थशास्त्र विभाग, एस.व्ही.के.टी. महाविद्यालय, देवळाली कॅम्प, नाशिक.
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६. आतापर्यंत राज्य, राष्ट्रीय आणि आंतरराष्ट्रीय स्तरावर ३८ शोधनिबंध प्रकाशित

## डॉ. गोरक्षनाथ पिंगळे

एम. ए. (अर्थशास्त्र), एम.फिल., पीएच. डी., सेट

१. साहाय्यक प्राध्यापक, अर्थशास्त्र विभाग मराठा विद्या प्रसारक समाजाचे के.टी.एच.एम.महाविद्यालय, नाशिक
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## डॉ. अमोल गायकवाड

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- व्यावसायिक अर्थशास्त्र अभ्यास मंडळ सदस्य, संगमनेर नगरपालिका कला, डी.जे. मालपाणी वाणिज्य व बी. एन सारडा विज्ञान (स्वायत्त महाविद्यालय) ता. संगमनेर, जि. अहमदनगर
- राज्यस्तरीय चर्चासत्राचे यशस्वी आयोजन (२०१५) कला व वाणिज्य महाविद्यालय सातपूर, नाशिक.
- राज्य, राष्ट्रीय आणि आंतरराष्ट्रीय स्तरावर ४९ शोधनिबंध प्रकाशित व अनेक सेमिनार व कार्यशाळांमध्ये तज्ज्ञ मार्गदर्शक म्हणून सहभाग.
- अर्थशास्त्र विषयावरील ०५ क्रमिक पुस्तकांचे लेखन व प्रकाशित. • सावित्रीबाई फुले पुणे विद्यापीठ बी.सी.यू.डी. अंतर्गत एक लघुशोध प्रकल्प पूर्ण.
- सावित्रीबाई फुले पुणे विद्यापीठ पुणे अंतर्गत विविध महाविद्यालयांच्या साहाय्यक प्राध्यापकांच्या निवड समितीवर विषयतज्ज्ञ म्हणून कामकाज.
- अर्थशास्त्र विषयातील प्रथम संयुक्त पेटंट प्राप्त (एप्रिल २०२२) • प्रथम वर्ष पदवी व पदव्युत्तर अर्थशास्त्र अभ्यासक्रम समितीवर अनुक्रमे समन्वयक व सदस्य म्हणून कामकाज
- नाशिक जिल्हा परिषद नाशिक, जिल्हा पंचायत विकास कार्यक्रम/ समितीवर (DPDP) सदस्य म्हणून निवड (२०२१).

## डॉ. दिपक कारे

एम.ए., एम.फिल., पीएच.डी., सेट, नेट

मराठा विद्या प्रसारक समाजाचे कला, वाणिज्य व विज्ञान महाविद्यालय, खेडगाव येथे अर्थशास्त्राचे साहाय्यक प्राध्यापक म्हणून कार्यरत.

- १३ वर्षे पदवी आणि ९ वर्षे पदव्युत्तर वर्गांना शिकविण्याचा अनुभव.
- एम.फिल., पीएच. डी. मार्गदर्शक सावित्रीबाई फुले पुणे विद्यापीठ, पुणे.
- विविध राष्ट्रीय, आंतरराष्ट्रीय परिषदा, चर्चासत्रे आणि कार्यशाळांमध्ये सहभाग.
- सावित्रीबाई फुले पुणे विद्यापीठ बी.सी.यू.डी. अंतर्गत एक लघुशोध प्रकल्प पूर्ण
- आतापर्यंत राज्य, राष्ट्रीय आणि आंतरराष्ट्रीय स्तरावर ४२ शोधनिबंध प्रकाशित.



## डॉ. मनिषा आहरे

एम.ए. (अर्थशास्त्र), एम.फिल., पीएच.डी., सेट, नेट

साहाय्यक प्राध्यापक अर्थशास्त्र विभाग, एस.व्ही.के.टी. महाविद्यालय, देवळाली कॅम्प, नाशिक.

- १६ वर्षांचा पदवी आणि पदव्युत्तर वर्गांना शिकविण्याचा अनुभव
- एम.फिल., पीएच.डी., मार्गदर्शक, सावित्रीबाई फुले पुणे विद्यापीठ, पुणे.
- विविध राष्ट्रीय, आंतरराष्ट्रीय परिषदा, चर्चासत्रे आणि कार्यशाळांमध्ये सहभाग
- सावित्रीबाई फुले पुणे विद्यापीठद्वारा मान्यताप्राप्त एक लघुशोध प्रकल्प पूर्ण
- आतापर्यंत राज्य, राष्ट्रीय आणि आंतरराष्ट्रीय स्तरावर ३८ शोधनिबंध प्रकाशित



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