Amassing of Cold Thermal Energy by Utilizing Phase Shift Material: A Review

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Abstract. Storing of cold energy is a predominant area in the cold thermal energy storage system in which the PCM plays a major role in hosting this energy storage process. This study fetches an encyclopedic review based on the current and erstwhile research in the field of cold energy storage using PCM. This dissertation provides an expansive view of the PCM solidification with the methodology of reducing the sub-cooling with the ramping up of heat flow rate besides of variegated nano-particulate and with protrusions. The effect of the fill volume of PCM in solidification is also delineated and how the size and material of PCM containment plays a role in solidification is also scrutinized and eventually, the application area of PCM cold storage is also explored.

1. Introduction
The cold storage involves the storage of cold energy in PCM, which changes its phase from liquid to solid and vice-versa. The process of cooling consumes more electric power to provide the degree of coldness. The PCM solidification or freezing is a process of charging the PCM and make it to solidify so, that the cold thermal energy will be saved which can be used for cooling purposes during the peak load period. This act of solidification provides a way for cooling applications. The storage of cold thermal energy is by releasing the concealed heat present in the PCM so, that the transformation of phase is established. The hidden heat storage is very attractive methodology of storing energy when compared with other methods of storage due to its high energy storing capability and the energy can be stored at a constant temperature which lies on the phase transition temperature of PCM [1] and when used in solidification process the PCM faces difficulties related to freezing time because of the encounter of sub-cooling stage this can be prevented by nano inclusions embedded into PCM, nano particles increases thermal conductivity due to ramification in convective heat transfer which takes place between the fluid and the surface [2] similarly, the size of nano particles also influences the heat transfer enhancement [3] and in addition the PCM in cold storage fetches an energy saving potential which can be coupled with renewable energy sources and use their surplus energy for powering low cold thermal storage [4] the energy is stored during off-peak period which can be utilized when demand is high [5].
This article represents that how the PCM can be employed in various applications thereby, saving the energy and about different PCM combinations in addition to this, it deals with decreasing the time of freezing with the help of various techniques like heat transfer enhancement has been reviewed.

2. Categorization of PCM utilized in cold thermal storage
The PCM plays a vital role in energy storage applications, by depending upon the nature of the compound the PCM compounds can be categorized into three types namely organic, inorganic and finally eutectic comes into the picture, which is shown, figure 1, [6].

![PCMs classification](image)

**Figure 1.** PCMs classification [6].

2.1. Organic PCM
The organic PCM has a capability to release as well as absorb a large quantity of latent heat over a wide temperature values and with greater stability in nature and they also possess no undercooling and have the capability to restrict corrosion when reacted with other materials [6].

2.2. Inorganic PCM
These PCMs are made up of materials which are hydrates of salts and metallic compounds when comparing with organic PCMs here the thermal conductivity is high but the corrosion rate is high when reacting with other materials this type of PCMs possess high capacity of heat and the cost is less when compared with other PCMs [6].

2.3. PCM of Eutectic nature
The eutectic PCM has a high storage density and they are specially made by combining two or more PCMs to form into a eutectic PCM, the eutectic PCM has a sharp melting point [6]. The thermal properties of various PCMs are shown in table 1.

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Table 1. Thermal properties of various PCMs.

| Category   | PCM                      | Liquidus temperature (°C) | Heat of fusion (KJ/Kg) | Reference |
|------------|--------------------------|---------------------------|------------------------|-----------|
| Organic    | Paraffin C<sub>18</sub>  | 28                        | 244                    | [7], 2009 |
|            | Paraffin C<sub>15-16</sub> | 8                         | 153                    | [8], 2011 |
|            | Paraffin C<sub>14</sub>  | 5.5                       | 228                    | [8], 2011 |
|            | Dodecane                 | -9.6                      | 216                    | [9], 2007 |
|            | Isopropyl palmitate      | 11                        | 95-100                 | [14], 2008|
|            | Isopropyl stearate       | 14-18                     | 140-142                | [14], 2008|
|            | Capric acid+Stearic acid | 26.8                      | 160                    | [15], 1991|
| Inorganic  | FeBr<sub>3</sub>-6H<sub>2</sub>O | 21                      | 105                    | [8], 2011 |
|            | H<sub>2</sub>O           | 0                         | 333                    | [10], 2012|
|            | LiClO<sub>3</sub>·3H<sub>2</sub>O | 8.1                      | 253                    | [10], 2012|
|            | KF·4H<sub>2</sub>O       | 18.5                      | 231                    | [10], 2012|
|            | H<sub>2</sub>O+Polyacrylamide | 0                     | 295                    | [10], 2012|
| Eutectic   | Diethylene glycol        | -10                       | 247                    | [11], 2002|
|            | Tetrahydrofuran          | 5                         | 280                    | [11], 2002|
|            | Carpic acid+Lauric acid  | 18                        | 120                    | [12], 1989|
|            | Tetradecane+Geneicosane  | 3.54-5.56                 | 200.28                 | [13], 2010|
|            | Tetradecane + Docosane   | 1.5-5.6                   | 234.33                 | [13], 2010|

3. To augment the heat flow rate

3.1. Addition of nanoparticulate, dispersants and various PCM and HTF combinations
Different types of nano inclusions along with various PCM and dispersants combinations are investigated by many researchers for myriad decades, out of which some selected research are explored in this section.

Chandrasekaran et al. [16] examined the output of NFPCM. This NFPCM was produced by disentangling MWCNT by ball milling and ultra-sonication process and mixing with deionized water in addition to nanoparticles, pseudomonas and sodium dodecylbenzene sulphonate (SDBS) was also mixed homogeneously in the solution of MWCNT which acts as a nucleating agent and surfactant and the PCM is filled in an LDPE spherical capsule and immersed in an HTF bath of 30% of ethylene glycol and 70% of water and performed experiments at different bath temperatures (-2-6,-9,-12°C) and construed that the presence of nucleating agent reduced the subcooling time. Whereas the presence of MWCNT gave an appreciable reduction in freezing time by 25% due to the increase in the thermal conductivity when compared with water as a PCM. Vikram et al. [17] studied experimentally on the freezing effect of deionized water and its decrease in subcooling time when dispersants were introduced into the base PCM. They framed a method of introducing the dispersants like sodium chloride and D-sorbitol in the de-ionized water of 200 ml in which the mass fraction of dispersants was in the order of 0.5, 1 and 1.5%. The PCM is filled in a spherical glass and immersed in an HTF bath of water +ethylene glycol mixture in the ratio of 55:45 by volume whose temperature is -7°C the fill volume of PCM is said to be 90%. Finally, the investigation based on DSC analysis and ramification of heat is studied for a sample of 32 to 35 mg in a crucible made of aluminium under nitrogen environment and construed that 0.5 wt % of NaCl (sodium chloride) helps in reducing under
cooling from -5.4 to -2.8°C and crystal growth starts at -15.6°C with 0.5wt% D-sorbitol and DI (deionized water) combination. Cabeza et al. [18] studied the augmentation of heat transfer in the water when it is used as a phase change material. They composed a methodology of using a composite material made of graphite with PCM, adding steel of stainless pieces and with copper pieces was also performed in a bath where water and anti-freezing agents were mixed together and the temperature in the thermostatic bath for freezing and heating ranges from -15°C and 15°C. At first, the thermal enhancer was absent in the experiment and at the next case the enhancers are added to the one-half side of the exchanger and finally, various enhancers are used in combination whose properties are depicted in table 2 and both freezing and melting were experimented and construed that the use of a composite of graphite paves the way for increased heat transfer compared to other combinations used.

### Table 2. Material properties of the materials used for heat transfer.

| Base material          | ρ(Kg/l) | ΔH (KJ/l) | Cₚ (KJ/K) | λ (W/mK) |
|------------------------|--------|-----------|-----------|----------|
| Stainless steel        | 7.8    | -         | 3.9       | 45       |
| Copper                 | 8.9    | -         | 3.4       | 393      |
| Graphite matrix        | 2.3    | 330       | 4.1       | 25-470   |
| Water                  | 1.0    | 330       |           | 0.6-2.4  |

| Storage material       | Vol% water | Latent heat (KJ/l) | Cooling ΔT = 20K | Heat ΔT = 15K | Effective λ |
|------------------------|-------------|--------------------|------------------|---------------|-------------|
| Water                  | 100         | 330                | 84               | 63            | 0.6-2.4     |
| Water + stainless steel| 97          | 319                | 81               | 57            | ?           |
| Water + copper         | 97          | 319                | 66               | 50            | ?           |
| Water + graphite       | 90          | 297                | 78               | 59            | 20-30       |

Sathishkumar et al. [19] performed an experimental study based on NEPCM’s solidifying behaviour under different conditions. They used de-ionized water as the base PCM with inclusions of nano-platelets of graphene along with SDS, triton and gum Arabic as surfactants and prepared the nano PCM solution with different percentage of graphene (0.2,0.4,0.6 wt%) which is encapsulated and immersed in HTF bath of water + ethylene glycol followed by immersion in bath temperature of -9 and -12°C and resulted in an outcome in augmenting the thermal conductivity (9.5% for 0.6 wt.% of graphene) with in addition reduces the sub-cooling with eventually reduces the time for solidification for 0.6wt.% at -9°C the reduction is 18% and for -12°C it is of 24%. Sheikholeslami et al. [20] numerically investigated how the shape of nanoparticles helps in augmenting the heat transfer rate in the process of solidification. In this analysis, they developed a simulation model which is powered by the fluid PCM combination of water with shapes of CuO (copper oxide) nanoparticles. They followed Galerkin finite element method along with the approach of Newton-Raphson method, along with finite configurations and nano PCM mixture and ended up with the decrease in the time of solidification when employing CuO particles with water in the form of platelets. Prabakaran et al. [21] investigated the solidification when nanoparticle is added to phase shift material. They followed the methodology of covalent functionalization so as to develop a stable PCM using OM08 as the base in addition to it nano platelets of graphene is mixed with a quantity of 0.1, 0.3, 0.5 % of volume and experimentation was performed in an HTF bath where the sphere containing the PCM is immersed at first test were
conducted at -10°C, at first the sphere is heated initially to 31°C and finally immersion was also tested with HTF temperature of 2 and 5 °C. They encountered an outcome in reduction of freezing time of 40% for -10°C, HTF temperature with 0.5% volume of platelets of graphene. Gajendiran et al. [22] investigated experimentally about how the HTF solution helps in the latent heat storage system. They followed a methodology of using paraffin as PCM with the various combinations of HTF fluids (ethylene glycol-water and copper-based nanofluid) with the addition of SDBS as a surfactant. The heat required to increase the degree of hotness of HTF is obtained from solar collector and the heat transfer occurs to the PCM when TES (Thermal energy storage) tank is filled with HTF and the heat is stored in the capsule of PCM of diameter 45mm. They observed an outcome of reduction of 33.3% for copper nanofluid and 22.2% for ethylene glycol and water mixture. Liu et al. [23] experimentally investigated about augmenting the heat transfer rate which in turn results in the reduction of freezing time by using nanoparticles as PCM fillers. They adopted a methodology of using nanoparticles into the PCM where it is 1-tetradecanol whose liquidus temperature is 37°C. GNP (Graphite nanoplatelets) after processing is added to the PCM and the experiment was conducted by filling the compositions of both PCM and nanoparticles with three modes like filling and testing using pure 1-tetradecanol, then by PCM with 0.5wt% of nanoparticle and finally with wt of 1% was mixed with PCM and the capsule which is made of stainless steel whose diameter is said to be 59.6 mm with the thickness of 1 mm to evaluate the mass fraction of PCM a vertical tube is attached to the spherical capsule. At first, the capsule is maintained at a temperature of 38°C for five hours then it is immersed in a bath of water which is at a temperature of 5, 10 and 15°C respectively. They yielded a valuable result of a decrease in the time of freezing due to the presence of nanomaterial which augmented the thermal conductivity and they found a difference in temperature of 32, 27 and 22°C between the surrounding bath and melting temperature. Parameshwaran et al. [24] studied about augmentation of energy saving potential and parameters of thermal of an conditioning system of air whose volume of air varies and which is retrofitted with PCM and inclusions of silver nano particles for latent thermal energy storage, the PCM with silver nanoparticles is shown in figure 2(a-d). They identified experimental progress of using PCM in spherical capsules which are charged and discharged which helped in catering the load demand because of charge which is stored during off-peak hours with the help of HTF which flows inside the energy storage area. Due to the act of nano inclusions, the thermal conductivity is increased which directly related to increased heat transfer. The experimental outcome reported the potential of energy saved per day is 24 to 51% and for an on-peak period it is about 36 to 58% respectively for the proposed ac system which is shown in figure 3(a). For VAV A/C system the energy-saving potential was about 7.5-18.6% (on-peak) and 7.9-17.8% (energy saved per day) which is shown in figure 3(b).

Figure 2. Views of silver nano particulate into PCM (a) Initiation of charging process (b) intermediate stage of charging (c) halfway of discharging process(d) Ending of discharge process [24].
Figure 3(a). Energy savings of proposed air conditioning module vs conventional module [24].

Figure 3(b). Energy savings of proposed air conditioning module compared with basically similar VAV air conditioning system [24].

Zhang et al. [25] experimentally studied about how the inclusion of nanoparticles helps to decrease the time taken in undercooling process in latent heat storage systems when an organic fluid of n-hexadecane is used as a base PCM. They formed a methodology of adding various surfactant (SDS, CTAB, PVA, PEG, TEMED, TEA, AcCOOH, 1-decanol, Tween-80, SA and Triton X-100) so as to eliminate clustering and sedimentation of nanoparticles in the base. The nanoparticles were mixed with base in the quantity range of 30-50 mg/L and additive was about 1% to the ratio of weight by volume. The Surface is modified using sulphuric and nitric acid thermal analysis was carried out using DSC for different modes of cooling and heating process (-5 to 30 °C and 30 to -5°C) and they obtained a curve. They construed that the DSC curves ranging from concentration of 0.1 to 10% were tested and finalized that undercooling decreases with concentrations of 0.1 and 0.5% but 1.0% contributes to
a very slight change. Ismail et al. [26] conducted a numerical study for analysing the crystal formation inside a capsule of spherical geometry. They proposed a methodology of solidification of PCM (water) and about the transfer of heat and they compared with the experimental findings which have done previously. A spherical model was created to analyse it numerically with the PCM filled in it and it is subjected to boundary conditions of convection at the outer shell. Initially, the PCM temperature is placed above the phase change temperature after some time the capsule is subjected to the HTF which is lower than phase change temperature crystallization begins after entering the phase change temperature. The numerical findings were compared with the experimental results and yielded a better understanding of solidification but the cooling curve is not reproduced in case of numerical findings but the findings of a larger amount of cooling rate are observed after complete freezing in case of numerical and construed that when the sphere size increases solidification time increases and vice-versa.

Even non-metallic composites also help in decreasing the solidification time is construed. Kumaresan and Velraj [27] investigated experimentally about the enhancement of thermophysical properties of de-ionized water (70% of volume) with ethylene glycol (30% of volume) mixture when mixing nanoparticles of carbon to the solution. They performed the experiments under various test conditions with SDBS as a surfactant and three test samples were developed with the MWCNT volume fraction of 0.15, 0.30 and 0.45% whose images are shown in figure 4. In addition to it, SDBS is added with a volume of 0.1% and the nano solution is prepared. The sample was tested for measurements of parameters like viscosity, density etc. which are shown in figure 5. From the above experimentation they construed that the density of the solution increases when MWCNT is mixed with it which is shown in table 3, MWCNT with the volume fraction of 0.15% volume has augmented a high specific heat, with MWCNT of 0.45% the thermal conductivity is enhanced by 19.73%, fluid’s viscosity increases at 0.30 and 0.45% volume respectively.

![Figure 4](image-url)  
**Figure 4.** Digital photograph of the nanofluids with various concentrations of MWCNT [27].

Malarmannan et al. [28] experimentally studied the solidification characteristics of deionized water and studied how nanoparticle enhances the rate of heat transfer and the study was focused in reducing the solidification time based on the reduction of undercooling. They adopted an experimental preparation of NFPCM with the inclusion of graphene nanoparticles with a concentration of 0.25 and 0.4 wt% with the addition of sodium lauryl sulphate as a surfactant (0.2 wt %) in de-ionized water of 180 ml. The prepared solution is filled in a spherical capsule whose diameter is 71mm and immersed in HTF bath of 70% of water and 30% of ethylene glycol. From the above experimentation, they construed that the inclusion of nanoparticles and surfactant has made an appreciable reduction in the time of solidification by adding 0.25% of GnP and the time of solidification at the centre of the shell 3690 seconds and when 10 mm is promoted from the centre, the time for solidification is reduced by 24.93% and for 20mm from the centre the reduction was about 65.32% , for DI + 0.25% surfactant the
solidification time at the centre is 3800 seconds and for normal DI water, it is 4120 seconds respectively.

![Figure 5](image_url)

**Figure 5.** Experimental set-up for thermal conductivity measurement [27].

| MWCNT concentration | $m_f$ (Kg) | $m_t$ (Kg) | $\rho$ (Kgm$^{-3}$) | Uncertainty (%) |
|---------------------|------------|------------|----------------------|-----------------|
| Flask Volume = 25 ml|            |            |                      |                 |
| 0 vol% (water+EG)   | 0.057615   | 0.031811   | 1032.144             | 0.798           |
| 0 vol% (water+EG+SDBS) | 0.057716 | 0.031792   | 1036.96              | 0.802           |
| 0.15 vol%           | 0.057741   | 0.031777   | 1038.57              | 0.801           |
| 0.30 vol%           | 0.057845   | 0.031816   | 1041.16              | 0.805           |
| 0.45 vol%           | 0.057987   | 0.031818   | 1046.744             | 0.796           |
| Flask Volume = 50 ml|            |            |                      |                 |
| 0 vol% (water+EG)   | 0.096955   | 0.045855   | 1022                 | 0.400           |
| 0 vol% (water+EG+SDBS) | 0.097013 | 0.045805   | 1024.17              | 0.401           |
| 0.15 vol%           | 0.09769    | 0.04599    | 1034                 | 0.400           |
| 0.30 vol%           | 0.097787   | 0.045905   | 1037.63              | 0.401           |
| 0.45 vol%           | 0.097991   | 0.045913   | 1041.55              | 0.399           |

Shafee et al. [29] observed experimentally about how the addition of nanoparticles plays an effective role in increasing the heat transfer ability of paraffin (RT21) and how it makes an effect on decreasing the solidification time. They induced the experimental technique of performing the test using base PCM (RT21) with the inclusion of MWCNT along with surface modifier (polysorbate-80). The annular pipe contains one inner pipe made of copper and an outer pipe made of acrylic. The prepared PCM whose preparation steps are shown in figure 6 is filled in the annular space and at the bottom, a diffuser is attached whose major and minor diameter is 300 and 75 mm a flow straightener with 400 holes each of 3mm diameter is made. The experimental setup is shown in figure 7 during the initial stage, ambient air is allowed to ensure that the thermocouples in PCM area acquire an equal temperature and followed by the climatic simulator and the temperature is decreased. The HTF is allowed to flow with the temperature of 12 and 14°C with a velocity of 4 and 5 m/s which offered low
and high heat flux. They construed that the HTF (without nanoparticles) whose velocity is 4 m/s made a time duration of 68 min to make a drop in temperature from 30.0 to 22°C where nano inclusions placed a time duration of 54 min, similarly HTF whose velocity is 5 m/s without MWCNT yielded 71 to get cooled and it reduced to 56 min when nanoparticles are included. The enhancement of heat transfer is said to be 18.41 and 11.61% for the velocities of 4 and 5 m/s.

Figure 6. Preparation of nano fluid [29].

Figure 7. Experimental setup [29].

Sriharan and Harikrishnan [30] investigated the enhanced thermal energy storage experimentally of a novice PCM composite. They used myristic acid as base PCM with the inclusions of silver nano particles with the mass fraction of 0.1, 0.2 and 0.3 wt %. AgNO₃ and NaBH₄ with the quantity of 0.0034 g and 0.001135 g were mixed with 20 and 30 ml of water and after certain procedures, a homogeneous mixture was formed and Bi-distilled water is used to purify the mixture and SDBS were used to maintain homogeneity of nanoparticles with base. They finally construed the thermal properties with the help of DSC analysis between the base material and PCM (composite) and it is evident that when a number of nanoparticles increase the phase change temperature, but latent heat tends to decrease (-1.13 and 1.09%). The augmentation of thermal conductivity was addressed at 0.3 wt% of silver nano particles with 108% respectively. Sidney et al. [31] observed experimentally about the solidification and the melting phenomenon of graphene nanoparticles dispersed in PCM. They
followed a methodology of using graphene nanoparticles which are chemically treated using concentrated nitric acid (250 ml) so as the addition of surfactant are avoided. The experimentation part consisted of 0.1, 0.2, 0.3, 0.4 and 0.5% of nanoparticle mixed with de-ionized water, the mixture of PCM is filled in stainless steel capsule (80% fill volume) of cylindrical geometry (ID is 46mm and height is 120mm). The HTF is water + ethylene glycol mixture for freezing and melting the bath temperature is said to be -6 and -10°C, 31 and 36°C respectively. They finally construed that the 0.5% volume of nanoparticles has made an appreciable outcome of enhancement of freezing rate by 43% for HTF temperature of -6°C and 32% for bath temperature of -10°C similarly, the thermal conductivity was enhanced by 24% and 53% for 0.5% volume of nanoparticles for the states of liquid and solid. Liu et al. [32] studied experimentally studied the effect of nucleation and supercooling behaviour of nanosheets of graphene oxide in de-ionized water (100ml). They used different quantity of same nanoparticles (10, 20, 30, 40,50mg) and dispersion was done by an ultrasonic oscillator here the addition of dispersants is completely avoided. The solution of nanomaterial is filled in a beaker made of glass (48mm) and the measurements were carried out in an HTF bath temperature of -15°C. They compared the results between the de-ionized water and nanofluid and they finally construed that the 50mg of graphene oxide in 100 ml of DI water has produced an outcome of 69.1% of reduction in the degree of supercooling when compared with DI water and nucleation time is also reduced by 90.7% when the results of both are compared. Althohamy et al. [33] studied experimentally about how the NFPCM makes an effect of reducing the time of solidification during the charging cycle and how it can be used for cold storage. They experimented with the help of pure water as the base PCM in addition to it the nanomaterial which is known as gamma-alumina (γ-Al₂O₃,50 nm) which is dispersed with the volume fractions of 0, 0.5, 1,1.5 and 2%. The solution (initial temperature of 22°C ) is filled to a volume of 80% in an LDPE capsule of spherical geometry (OD 84 mm) and it is immersed in an HTF bath of ethylene glycol and water (solidus temperature -15°C)so that the experiment was carried out by varying the bath temperature (6, -8, -10, -12 °C) and flow rate (6,8,10,12 lpm). They encountered a result of the reduction in the charging duration when the bath temperature of -12°C was maintained with addition to it the lpm level (12,10,8, and 6) has made the percentage of reduction rate to 32,28,18,12% respectively. Dannemand et al. [34] observed experimentally about the solidification behaviour of composites of sodium acetate trihydrate with the addition of various mixtures in laboratory test conditions. They implemented a test rig in which it contains a stainless-steel cylinder whose height is around 150 cm with a diameter of 30 cm and insulation of 4 cm is provided and aluminium material act as protrusions. The HTF here used is water and the PCM used here tested with water as PCM for six cycles and others combinations of sodium acetate trihydrate (93.6%) + water (6.4%) (SATH₂O) for 17 cycles and other combination was with sodium acetate trihydrate (95.1%) + 0.5% xanthan rubber (thickening agent) + 4.4% of graphite powder (SATXC) for 40 cycles of experimental test. Along with this, another inclusion of a 0.5l (after 10 cycles) of paraffin was added to sodium acetate trihydrate and xanthan mixture and additionally paraffin (oil) was also added the main aim is to augment the heat transfer. The range of temperature for inlet during charging and discharging and said to be 90-95°C and 20-25°C respectively. Finally, they construed that addition of 11 paraffin oil has increased the rate of heat dissipation and the transfer capacity is decreased because of the thickening agent added to the PCM when compared with the mixture of sodium acetate trihydrate and water.

Ji et al. [35] experimentally investigated how different quantities of dispersants affect the supercooling behaviour of aqueous solution (mannitol) of PCM. They elected two dispersants namely TNWDIS (Carbon nanotubes water dispersant) and PAAS (Polymer polyacrylic acid sodium) and a two-step approach were performed for the proper generation of composite PCM, firstly the TNWDIS was mixed with mannitol and addition to it MWCNT was also mixed they both were mixed on the basis of varying concentration and diameter and another composite was developed by PAAS with MWCNT in mannitol solution. During solidification the composite PCM solution was filled in a beaker(100ml) in which the PAAS was mixed in the concentrations of 0 wt%, 0.2 wt%, 0.4 wt%, 0.6 wt%, 0.8 wt%, and
1 wt% maintained at -25°C and similarly, the same method was tested with TNWDIS and finally the solidified part is left at room temperature. They finally construed that when MWCNT:TNWDIS ratio becomes (0.5:1) the supercooling is at a reduced level when the ratio increases it leads to agglomeration increasing the supercooling degree and when the size of the particle increases with reduction in contact angle the supercooling decreases. Wu et al. [36] studied on developing the low-temperature range nano PCM to maintain the temperature of low-temperature products. They adopted the preparation of nanofluid by choosing magnesium chloride hexahydrate (23wt% of MgCl2) mixed in de-ionized water along with the inclusion of modified MWCNT (M-MWCNT) in addition to it there comes the addition of anhydrous calcium chloride (1%) with calcium hydroxide (0.25%) were employed and after certain steps xanthan gum (0.5 wt%) was mixed and the testing range was from -70 to -10°C. The different mass fractions (0.5,1,1.5,2,2.5,3 wt%) of modified MWCNT were tested. They finally construed that at 1wt% of modified MWCNT possess low supercooling at the order of 2.157°C Whereas the modified MWCNT is tested with other agents the supercooling is said to be 86.9% lesser than MgCl2 and the solution obtained confirms the presence that the thermal conductivity of PCM increases with increasing concentration of MWCNT which enhances the heat transfer rate. Munyalo et al. [37] experimentally tested the thermal properties of a composite PCM. They proposed a methodology of producing nano-fluid based composite PCM such, that the barium chloride dehydrate (BaCl2.2H2O) was mixed with the deionized water so as to make it as an aqueous solution(24wt.%) and MgO(1wt.%) was mixed along with SDS(1wt.%) with sample quantity of 0.2,0.4,0.6,0.8,1wt% in the similar fashion another composite PCM was prepared by dissolving MWCNT in aqueous barium chloride dehydrate to form an aqueous solution with the quantity of samples (0.2,0.4,0.6,0.8,1wt%) along with N,N dimethyl form amide (surfactant). The PCM is filled in a beaker and immersed in a bath where the temperature range is said to be -20 and 20°C for freezing and melting aspects. They finally construed that MgO nanoparticles have augmented the thermal conductivity of PCM by 17% and MWCNT has also enhanced the thermal conductivity by 6% respectively. Kumaresan et al. [38] experimentally studied the heat transfer enhancement of the base PCM with the assistance of inclusion of nanoparticles and the PCM can be converted in NFPCM. They tested this case using water as the base PCM and along with the addition of MWCNT to form a nano solution of PCM. They encapsulated the NFPCM (35°C) with the help of LDPE capsule (r=75mm) and immersed the capsule in a bath of water + ethylene glycol (70:30) which is maintained at two different temperature of -9 and -12°C. They construed that when the concentration of nanoparticles (above 0.15% vol) increases the ramifications of heat transfer is not increased because of the increase in the viscous nature of the liquid which tends to block convection phenomenon and finally the conclusion was made with DSC analysis that the 0.6% vol of nano inclusions in base PCM has reduced the sub-cooling from -8 to -4°C and the energy-saving potential of 5% can be attained. Chandrasekaran et al. [39] studied the characteristics of solidification of water- based NFPCM. The experimental study was performed with different HTF bath temperature with de-ionized water as PCM with the inclusions of copper oxide nanoparticles, CTAB and pseudomonas as a nanomaterial, surfactant and nucleating agent with the quantity of 0.1 wt % in an LDPE capsule of 68 mm diameter with a fill volume of 90% the experimental setup is shown in figure 8. They yielded an outcome of a reduction in the time of solidification of 35% when the HTF is at -6°C and 33.3% for -2°C which is shown in figure 9 and figure 10 respectively.

Kumaresan et al. [40] conducted an experimental study based on the solidification behaviour of water-based NFPCM with different volume fractions of nano-particles, different volume fractions of 0.15%, 0.3%, 0.45%, and 0.6% of nanoparticles is mixed with DI water with SDSBS as surfactant with 0.15% volume filled in LDPE material of 72mm immersed at different bath temperatures and yielded an outcome of that the NFPCM whose mixture is said to be composed of 0.15% MWCNT has gained an appreciable advancement of 33.3% in the process of starting of freezing when it is compared to regular base PCM and a reduction in undercooling (-3.8°C) was observed again with 0.15% of MWCNT whereas the pure PCM attained a subcooling of -7°C in solidification time of 14% at a bath
temperature of -9°C and 20.1% for -12°C and besides the potential of saving energy is increased as 6-9% respectively.

Figure 8. Schematic diagram of the experimental setup [39].

Figure 9. Transient temperature variation of the PCM and NFPCM at the centre of the capsule (T_{surr}=-6°C) [39].

Figure 10. Transient temperature variation of the PCM and NFPCM at the centre of the capsule (T_{surr}=-2°C) [39].

3.2. Attachment of protrusions to enhance heat transfer rate
Premnath et al. [41] experimentally studied the solidification of PCM using protrusions and studied the effect of subcooling in solidification. A spherical capsule of stainless steel with two to four protrusions are used with water as PCM at different HTF bath temperature (-6, -9, -12°C). They yielded a reduction in solidification time with a range of 3% to 33.3% with two fin modes, but with four fin configurations, the time for solidification is increased ranging from 8% to 14.53% when comparing the above cases with the solidification time of spherical capsule without fin. Nallusamy et
al. [42] experimentally augmented the heat dissipation rate in hidden heat thermal storage with different protrusions. They adopted a methodology of using protrusion of hollow and solid, and the PCM here is paraffin which is selected based on the need. The heat transfer fluid is water used for transferring heat to PCM area from the source enters at 65 and 70°C with a flow rate of 4 and 6 litres per minute. They reported that during the charging cycle of PCM, time for charging showed 160 min with the HTF parameters of 65°C and 6 litres per minute and when the inlet temperature is 70°C the ramification of heat occurs which reduces the time of charging by 25% under the absence of protrusions. When protrusions have introduced the reduction in charging time is said to be 28 and 23% for internal hollow and internal solid cylindrical protrusions. Premnath et al. [43] experimentally investigated the process of solidification of de-ionized water and how the heat transfer enhancement has accomplished based on the addition of rectangular protrusions. They formed a methodology of testing the de-ionized water in a stainless-steel sphere (ID=73mm, OD=75mm) with the rectangular protrusions made of copper whose length, width and thickness are 20.6mm,10.6mm and 1mm which is placed radially in the inner side of the capsule. The capsule is immersed in an HTF (70%water+30%ethylene glycol by wt%) bath of the varying temperature of -6, -9, -12°C. They plotted a comparison between with fin capsule and without fin capsule and construed an output of reduction in time of solidification of PCM with finned capsule due to more surface area and obtained a 13% of time reduction in solidification and the heat flux seemed to be more in a finned capsule. Premnath et al. [44] studied experimentally about how the implementation of protrusions influences the solidification of PCM. They performed experiments based on the implementation of adding the different size of protrusions basically whose diameter is 3mm with varying length of 7.5, 13.5 and 19.5 mm they used de-ionized water as the base PCM with the fin material as copper attached radially towards the inner side of the capsule four stainless steel of 73mm inner diameter with a 1mm thickness in which one with no fin and the other three fins with 7.5, 13.5 and 19.5mm length .The capsule is filled with PCM and immersed in a bath of -6, -9,-12°C where the HTF bath is provided with 70% wt of water + 30% wt of ethylene glycol. Finally, the experimental values are statistically analysed using cubic models and the normal probability plot is performed and based on the model analysis the time for solidification is less when fin length is about 10.5 and 16.5 mm. Finally, they construed that the time of freezing is reduced when bath temperature is decreased, and the plots convey that the fin length of 13.5mm has yielded the progress of 50% of freeze front when it is maintained at different temperature of HTF and the capsule when placed in -12°C with the fin of 16.5mm length has adopted a reduction freezing time of 21%.

3.3. Effect of fill volume and various concentrations of CNT in heat transfer enhancement
Chandrasekaran et al. [45] studied experimentally how the fill volume of PCM (water) has a momentous effect on freezing. The experimentation was performed by filling the capsule with water of varying fill volumes of 80, 85, 90, 92, and 95% of its full volume and immersed at various HTF temperatures and yielded an outcome of the complete elimination of subcooling at 95% of fill volume when the surrounding temperature was -6°C, -9°C and -12°C whereas other fill volumes like 90,92 % showed elimination of subcooling at a bath temperature of -9°C and finally they construed all fill volumes eliminated the stage of subcooling when the bath temperature was -12°C. whose graphical representations are shown in figure 11 (a-c).
Figure 11(a). $T_{\text{surr}} = -6^\circ\text{C}$ [45].

Figure 11(b). $T_{\text{surr}} = -9^\circ\text{C}$ [45].

Figure 11(c). $T_{\text{surr}} = -12^\circ\text{C}$ [45].
Kumaresan et al. [46] studied how the addition of a small quantity of MWCNT increases the heat transfer rate. They tested using paraffin as the PCM in addition to it the MWCNT was also added with the quantity of 0, 0.15, 0.3, 0.45 and 0.6% respectively at 30°C. They followed the methodology of filling the NFPCM (25°C initially) in a cylinder whose diameter is 6.6 cm surrounded with HTF of ethylene glycol and water (13°C). They construed that at higher concentration of MWCNT (0.60%), the enhancement of heat transfer is more which directly contributes to the reduction of freezing time of 33.64% which is clear. Chandrasekaran et al. (2015) [47] investigated how the spherical capsule’s size influences the solidification of PCM. The experimented was conducted with different size of stainless-steel capsules (74, 86, 100 mm) with the PCM fill volume of 90% and immersed in a temperature bath of (-6, -9, -12°C). The result yielded that due to the increase in the capsule size the time of subcooling is lowered at a bath temperature of -6°C which is shown in figure 12 (a) and elimination of subcooling occurred at -9 and -12°C for all sizes of capsules which is shown in figure 12 (b-c).
Castell et al. (2011) [48] experimentally examined about augmenting the transfer of heat in the cold storage system. They tested based on the criteria of the flow rate of HTF. The experimental setup which is shown in figure 13 and 14 was accommodated with a single and a two-coil loop (one has high packing factor PF and another has high heat transfer surface) for the HTF to pass through the PCM (melting point -27°C) was filled inside the tank. The PCM was a salt mixture of hydrated non-gel, the test was performed with a different flow rate for each type with a constant temperature at the inlet. The results proved that the effectiveness of heat exchange does not change with time, but when increasing flow rate, the effectiveness decreases and when the heat transfer area is increased effectiveness increases.

Ismail and Moraes [49] investigated the solidification characteristics of PCM by the way of experimentally and numerically with the combinations of cylindrical and spherical capsule geometry of varying material and dimensions and how it affects freezing. The experiment was performed with water and water + ethylene glycol (3.75%, 7.5%, 15%, 25%, 30%, 40% and 50% of glycol in water) as PCM and ethanol is used as HTF with varying temperatures (-5, -10, -12, -15, -18, -20, -25 °C). The capsule (0.035, 0.076, 0.106 and 0.131m in diameter) is immersed in an insulated tank and observations are made. They addressed an outcome of an increase in glycol content made the solidification time to increase, using small diameter capsule will reduce solidification time when HTF fluid temperature is reduced freezing time is minimized. Ismail and Henriquez (2002) [50] discussed the experimental and numerical work on parameters of geometry and operation in the solidification of PCM in LHTS system. They investigated about the solidification with the spherical capsule (copper, aluminum, PVC, acrylic and polyethylene) filled with water (PCM) and immersed in a tank and the HTF (ethylene glycol with a concentration of 30%) temperature ranges from -3 to -15°C with a rate of the volumetric flow of 0.5 to 1.5 m³/h with a diameter of 0.128 and 0.066m with a constant wall thickness of 0.002m. From the above research they compared the experimental data with simulation it is construed that the curve of numerical follows nearer to the ease of experimental but subcooling is not present which is shown in figure 15 and 16 and they observed for charging of PCM in a copper capsule it took 7 hours followed by 8 hours and 9 hours and 20 minutes for polyethylene and polyvinyl chloride (PVC).
Solomon et al. [51] experimentally studied the phenomenon of undercooling of PCM here termed as RT 21 with a vertical tube of annular section. They experimented the solidification of paraffin which is located in the space between the copper and the acrylic tube whose outer diameter is said to be 75 and 150 mm, the copper pipe having the thickness and height of 1mm and 300 mm whereas the acrylic thickness is 5mm with a height of 280mm which is shown in figure 17. They circulated the ambient air throughout the test section to ensure that the thermocouples temperature was the same in the PCM area, and then the space temperature was decreased using a climatic simulator. The test was conducted with the HTF temperatures of 12 and 14°C with a varying velocity of 3,4,5,6 m/s. Since the HTF enters via bottom the PCM in that area experiences a greater under cooling when compared to the top portion. They construed that the temperature of solidification of paraffin is 20.75 to 21.2°C with the air as HTF and identified that if the air was replaced by water as HTF the temperature of solidification may drop to 20°C which possess a higher order of subcooling.
4. Applications of phase shift materials
The major fact of this article is to make a pavement for the better option of employing a stable PCM in the cold thermal energy storage areas which in turn return us the best possibility of energy-saving potential. The major area where PCM can be utilized is judged by the temperature range at which the PCM is well efficient to charge and discharge, the main areas concentrated is food storage, refrigeration and air conditioning.

4.1. PCM in refrigeration
Azzouz et al. [52] proposed a methodology of improving the design of a conventional refrigerator using a slab of PCM (0.48 m²) in which it is placed at the in-between the evaporator coil and insulation was further simulated with varying PCM thickness of 0.25, 0.35, 0.5 cm and varying temperature ranges of -9, -7, -5, -3 and -1°C. The aqueous eutectic solution (-9 to 0°C) is filled and placed at the back of evaporator, and the thermal loads corresponding to the exchange of heat with ambient is of the order of 15, 20, 25 and 30°C. The simulated outcome has subjected to the positive yield of 5-15% increase in COP and they found the difference in on and off slots of the compressing unit and also construed by using PCM thickness of 0.5 cm the food is preserved for about 4-8 h without power supply to the refrigeration unit and the relative running saving time is 32.6%(when PCM is embedded) for the thickness of 0.5cm. Azzouz et al. [53] studied the performance improvement of a conventional refrigerating unit when it is employed with a slab of PCM here termed to be a water + eutectic mixture and placed on the backside of the evaporator coil. The experimentation compiled the cases of the varying quantity of thickness of PCM (0.005 and 0.01 m)
and one case with no PCM, PCM as water and another with a eutectic aqueous solution (solidification point of -3°C). They finally ended up concluding that the main driving factor here is the thermal load and using PCM has made the conventional unit to operate for 5-9 h without an external power source and obtained a 10-30% of the increase in COP when using PCM.

4.2. PCM in food packaging
Gin et al. [54] experimentally investigated how the implementation of PCM plays a vital role in improving the storage condition of food. They developed an experimental phenomenon which is shown in figure 18 of placing PCM slabs of 10 mm thickness, inside the freezers (153 L of storage volume) internal wall, the selected PCM is a eutectic composition of water with ammonium chloride (melting and freezing point of -15.4°C) the food samples analysed were ice-cream and meat. They construed the results by getting an output based on the temperature response, the crystal size of ice-cream and finally, the meat was checked for drip loss. During power cut conditions the PCM helps in the reduction of temperature of the freezer. For the test conditions for the power loss of 180 min, the product temperature becomes -3°C (without PCM) and for with PCM case, the temperature of the product is -11°C which is shown in figure 19 when comparing with drip loss the loss was 17% without PCM and for with PCM it is observed as only 10% respectively and the crystal size of 40-50 and 70-80µm have resembled for the case of with and without PCM.

![Figure 18. Mounted PCM panels inside refrigerator [54].](image)

![Figure 19. Difference in food temperature during a 3h power cut [54].](image)
Hoang et al. [55] experimentally studied the aspects of thermal behaviour of two different mass fraction of phase change material in food packaging. They progressed with the PCM RT5 (phase change temperature of 5°C) which is enclosed inside a polymer known as polycaprolactone (biopolymer). The testing was between two plates were tested under varying mass fractions of PCM in the order of 30% and 38% for plate 1 and 2. The plates are tested with heating and cooling cases for heating the plate initially was maintained at a temperature of -10°C and the simulator’s temperature was 20°C, for cooling case the plates initial temperature is said to be 17°C with the simulator’s temperature be -10°C, numerical simulation is performed on adopting another plate named as plate 3 and the obtained results were compared with regular cardboard packaging. They construed that the novel packaging provides a better thermal buffering to maintain and augment the thermal protection.

Leducq et al. [56] experimentally addressed the packaging methodology of storing a temperature-sensitive food product (ice cream). They provided a comparison between the packaging of the sensitive food item in normal polystyrene packing versus PCM (water + sodium chloride) packing. They adopted three cases for testing one with carton board box in which 8l of ice is present and in the second case the box and items are same as the first case but the major change is the insulation of wall with polystyrene (thickness 25 mm). Then finally box 3 contains 8l of ice cream and they are covered with PCM bricks of thickness 25 mm. The packages were kept at -22°C for 140 samples were collected and analysed every 30 days by diluting the sample in silicone oil of 30ml at -15°C. They finally construed that the usage of PCM packing has provided a good quality food product because of stable temperature and founded that PCM slab of thickness 4 mm is enough to maintain the stable temperature during a temperature abuse of 40 minutes.

4.3. PCM in Ventilation and air conditioning

Hu et al. [57] investigated experimentally about the concept of PCM integrated with windows to provide advancement in cooling and heating of the room to maintain comfort. The methodology adopted is cooling and as well as heating the incoming ventilated air to improve the potential of energy saving. The PCM setup is arranged such that the PCM window is compared with existing conventional window. The PCM here used is paraffin whose specific heat capacity is 2.3 KJ/Kg°C. In ventilation cooling mode the hot ambient air is cooled by PCM which absorbs heat and pre-cools it, whereas in heating mode the PCM absorbs heat from solar radiation and transfers the heat to the incoming air and pre-heating it reducing the HVAC loads. Overheating is prevented by vents which perform natural convection. They construed that in the heating application the air via ventilated window whose temperature is augmented by 2°C followed by cooling the findings where the inlet air temperature is lowered by 1.4°C which directly relates to 0.7 MJ/day of energy saving. Solgi et al. [58] assessed the effect of PCM in night purge ventilation in hot-arid climatic conditions. They followed a numerical methodology in simulating the condition using Energy plus tool. The simulation study was performed, and the dimensions of the room were 4.876*3.675*2.436 m with a roof slope of 4.12 degrees (pitched). They yielded an outcome by comparing both their experimental and simulated model that the PCM with night purge ventilation technique has offered an appreciable reduction in room temperature which in turn reduces the cooling load of the HVAC system which directly relates with energy-saving potential. Waqas et al. [59] studied the thermal energy storage capacity of PCM to maintain the thermal comfort in dry atmospheric conditions. The developed study depends upon the passive way of maintaining the thermal comfort inside the building by adopting a hidden heat storage concept on behalf of its high energy storage capacity by the addition of phase shift material. In the summer season at night time, the PCM is set to be recharged using the cold air and during day time the hot air is made to pass through the PCM where the heat is absorbed by PCM and the air is cooled. The PCM utilized here is SP27 whose latent heat capacity is 190 KJ/Kg. They finally construed a valid point that hot air is cooled by incorporating PCM by which comfort is maintained and this can be linked with air heating system during winter these both techniques fetches directly to energy-saving potential of the HVAC system. Chaiyat and Kiatsiriroat [60] studied how the PCM possess its domination on energy saving potential of a conventional air conditioning unit. The authors performed
this experimentation about climatic conditions of Thailand (day time temperature more than 25°C), they selected RT 20 (whose melting and freezing temperature is 22 and 20 °C) as the base PCM filled inside a capsule (70% by volume) made of celluloid which is shown in figure 20. The schematic view regarding the modified system is shown in figure 21 (a), In the mode of charging which is shown in figure 21 (b), during off-peak hours, the air from the evaporator is used to solidify PCM, the air needs to be maintained at a range of 15 – 20°C, so the ambient air (> 25°C) is cooled by the evaporator passes to the area to be cooled and the air temperature is increased by 22-25°C. The air then passed to the PCM bed so as to reduce its temperature and then fed to evaporator such that a pre-cooling is performed by PCM now, the incoming air is (< 25°C) which is shown in figure 21 (c), so, a load of cooling is reduced which directs to energy saving. They construed the experimental results with numerical values and ended up with electricity saving cost was around 9.10% for the proposed system which, when compared with the conventional system and economic analysis was carried out and estimated period of payback was 4.15 years respectively.

Figure 20. The capsule of PCM [60].

Figure 21 (a-c). (a) The remodelled setup (b) Charging sequence (c) Discharging sequence [60].
5. Conclusion
The cold storage is a promising technology in recent trends which has undergone various research perspectives, and still upgrading itself so as to provide betterment to mankind although there are certain drawbacks regarding this technology like the increase in freezing duration due to the subcooling behaviour which can be minimized by the methods discussed in this review and few valuable outcomes are stated.

- The inclusion of MWCNT has contributed a reduction in freezing time by 25% due to the ramification of thermal conductivity.
- The NaCl (0.5 wt %) made an appreciable reduction in subcooling from -5.4 to -2.8°C and nucleation starts faster with the combination of D-sorbitol.
- Results reflected that 0.5% volume of nanoparticles has made an outcome of enhancing the freezing rate by 43% for bath temperatures of -6°C and 32% for bath temperature of -10°C.
- Elimination of undercooling was achieved when the fill volume was at 95% and ended in the reduction of freezing time.
- The inclusion of nanoparticles has resulted in an appreciable increase in heat transfer due to the augmentation of thermal conductivity.
- Effectiveness of heat exchange does not vary with time, but when increasing the flow rate, the reduction in effectiveness is observed and increases with an increase in the heat transfer area.
- When MWCNT concentration is 0.6%, the ramification of heat transfer is more which directly fetches reflects in decreasing the freezing duration by 33.64%.
- The employment of phase change material in food preservation has recorded a good result of maintaining the food quality due to its stable temperature maintenance.
- When the sphere size is said to increase the solidification time also tends to increase. When protrusions have introduced the heat, transfer increases up-to certain fin length.
- The energy-saving potential is experienced when employing PCM in air conditioning application and the cold thermal energy can be stored during off-peak hours which can be utilized when there is a need in peak hours.

6. Nomenclature

\[
\begin{align*}
T_m & \quad \text{Melting temperature} \quad (°C) \\
T_{m, \text{peak}} & \quad \text{Melting peak temperature} \quad (°C) \\
T_f & \quad \text{Freezing temperature} \quad (°C) \\
T_{f, \text{peak}} & \quad \text{Freezing peak temperature} \quad (°C) \\
\rho & \quad \text{Density of material} \quad (\text{Kg/l}) \\
\Delta H & \quad \text{Latent heat of fusion} \quad (\text{KJ/l}) \\
C_p & \quad \text{Specific heat at constant pressure} \quad (\text{KJ/lK}) \\
\lambda & \quad \text{Thermal conductivity} \quad (\text{W/mK}) \\
\Delta T & \quad \text{Temperature range} \quad (\text{K}) \\
m_t & \quad \text{Total mass} \quad (\text{Kg}) \\
m_f & \quad \text{Mass of flask} \quad (\text{Kg}) \\
m_{fb} & \quad \text{Mass of base fluid} \quad (\text{Kg}) \\
T_m & \quad \text{Phase transition temperature} \quad (°C) \\
T_{\text{sur}} & \quad \text{Surrounding temperature} \quad (°C) \\
T_{\text{co}} & \quad \text{Surrounding coolant temperature} \quad (°C) \\
T_{\text{ext}} & \quad \text{External temperature} \quad (\text{K}) \\
T_{\text{pcm}} & \quad \text{PCM temperature} \quad (\text{K}) \\
r & \quad \text{Radius} \quad (\text{mm}) 
\end{align*}
\]
7. Abbreviations

AcCOOH  Glacial acetic acid
COP  Coefficient of performance
CTAB  City Trimethylammonium Bromide
DSC  Differential Scanning Calorimetry
EG  Ethylene glycol
HTF  Heat Transfer Fluid
HVAC  Heating, ventilation, and air conditioning
LDPE  Low density polyethylene
LHTS  Latent heat thermal storage
MWCNT  Multiwall Carbon Nanotubes
NEPCM  Nanoparticle Enhanced Phase Change Material
PCM  Phase Change Material
PEG  Polyethylene Glycol
PVA  Poly vinyl alcohol
RTDs  Resistance Temperature Detector
SA  Salicylic acid
SDS  Sodium Dodecyl Sulphate
SDBS  Sodium Dodecyl Benzene Sulphonate
SEM  Scanning Electron Microscope
TEA  Tri ethyl amine
TEM  Transmission Electron Microscopy
TEMED  Tetra methyl ethylene diamine
VAV A/C  Variable air volume air conditioning system

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9. Conflict of interest
The authors do not have any sort of conflict of interests.

10. References
[1] Sharma, S., & Sagara, K. (2005). Latent heat storage materials and systems: A review. *International Journal of Green Energy*, 2(1), 1-56. doi:10.1081/ge-200051299
[2] Özerinç, S., Kakaç, S., & Yazıcıoğlu, A. G. (2009). Enhanced thermal conductivity of nanofluids: A state-of-the-art review. *Microfluidics and Nanofluidics*, 8(2), 145-170. doi:10.1007/s10404-009-0524-4
[3] Sudarsana Reddy, P., & Chamkha, A. J. (2016). Influence of size, shape, type of nanoparticles, type and temperature of the base fluid on natural convection MHD of nanofluids. *Alexandria Engineering Journal*, 55(1), 331-341. doi:10.1016/j.aej.2016.01.027
[4] Beck, M., Müller, K., & Arlt, W. (2016). Storing surplus solar energy in low temperature thermal storage for refrigeration applications. *Energy and Buildings*, 122, 192-198. doi:10.1016/j.enbuild.2016.04.041
[5] Wang, C., He, Z., Li, H., Wennerstern, R., & Sun, Q. (2017). Evaluation on performance of a phase change material based cold storage house. *Energy Procedia*, 105, 3947-3952. doi:10.1016/j.egypro.2017.03.820
[6] Zhou, D., Zhao, C., & Tian, Y. (2012). Review on thermal energy storage with phase change materials (PCMs) in building applications. *Applied Energy*, 92, 593-605. doi:10.1016/j.apenergy.2011.08.025
[7] Sharma, A., Tyagi, V., Chen, C., & Buddhi, D. (2009). Review on thermal energy storage with phase change materials and applications. *Renewable and Sustainable Energy Reviews, 13*(2), 318-345. doi:10.1016/j.rser.2007.10.005

[8] Cabeza, L., Castell, A., Barreneche, C., De Gracia, A., & Fernández, A. (2011). Materials used as PCM in thermal energy storage in buildings: A review. *Renewable and Sustainable Energy Reviews, 15*(3), 1675-1695. doi:10.1016/j.rser.2010.11.018

[9] Kenisarin, M., & Mahkamov, K. (2007). Solar energy storage using phase change materials. *Renewable and Sustainable Energy Reviews, 11*(9), 1913-1965. doi:10.1016/j.rser.2006.05.005

[10] Oró, E., De Gracia, A., Castell, A., Farid, M., & Cabeza, L. (2012). Review on phase change materials (PCMs) for cold thermal energy storage applications. *Applied Energy, 99*, 513-533. doi:10.1016/j.apenergy.2012.03.058

[11] Cabeza, L., Mehling, H., Hiebler, S., & Ziegler, F. (2002). Heat transfer enhancement in water when used as PCM in thermal energy storage. *Applied Thermal Engineering, 22*(10), 1141-1151. doi:10.1016/s1359-4311(02)00035-2

[12] Feldman, D., Shapiro, M., Banu, D., & Fuks, C. (1989). Fatty acids and their mixtures as phase-change materials for thermal energy storage. *Solar Energy Materials, 18*(3-4), 201-216. doi:10.1016/0165-1633(89)90054-3

[13] Kenisarin, M. M. (2010). High-temperature phase change materials for thermal energy storage. *Renewable and Sustainable Energy Reviews, 14*(3), 955-970. doi:10.1016/j.rser.2009.11.011

[14] Regin, A. F., Solanki, S., & Saini, J. (2008). Heat transfer characteristics of thermal energy storage system using PCM capsules: A review. *Renewable and Sustainable Energy Reviews, 12*(9), 2438-2458. doi:10.1016/j.rser.2007.06.009

[15] Peippo, K., Kauranen, P., & Lund, P. (1991). A multicomponent PCM wall optimized for passive solar heating. *Energy and Buildings, 17*(4), 259-270. doi:10.1016/0378-7788(91)90009-r

[16] Chandrasekaran, P., Cheralathan, M., Kumaresan, V., & Velraj, R. (2014). Solidification behavior of water based nanofluid phase change material with a nucleating agent for cool thermal storage system. *International Journal of Refrigeration, 41*, 157-163. doi:10.1016/j.ijrefrig.2013.12.017

[17] Vikram, M. P., Kumaresan, V., Christopher, S., & Velraj, R. (2019). Experimental studies on solidification and subcooling characteristics of water-based phase change material (PCM) in a spherical encapsulation for cool thermal energy storage applications. *International Journal of Refrigeration, 100*, 454-462. doi:10.1016/j.ijrefrig.2018.11.025

[18] Cabeza, L., Mehling, H., Hiebler, S., & Ziegler, F. (2002). Heat transfer enhancement in water when used as PCM in thermal energy storage. *Applied Thermal Engineering, 22*(10), 1141-1151. doi:10.1016/s1359-4311(02)00035-2

[19] Sathishkumar, A., Kathirkaman, M. D., Ponsankar, S., & Balasuthagar, C. (2016). Experimental investigation on solidification behaviour of water base Nanofluid PCM for building cooling applications. *Indian Journal of Science and Technology, 9*(39). doi:10.17485/ijst/2016/v9i39/94966

[20] Sheikholeslami, M., Ghasemi, A., Li, Z., Shafiee, A., & Saleem, S. (2018). Influence of CuO nanoparticles on heat transfer behavior of PCM in solidification process considering radiative source term. *International Journal of Heat and Mass Transfer, 126*, 1252-1264. doi:10.1016/j.ijheatmasstransfer.2018.05.116

[21] Prabakaran, R., Sidney, S., Lal, D. M., Selvam, C., & Harish, S. (2019). Solidification of graphene-assisted phase change Nanocomposites inside a sphere for cold storage applications. *Energies, 12*(18), 3473. doi:10.3390/en12183473
[22] Gajendiran, M., Sivaram, P., & Nallusamy, N. (2015). Performance of latent heat solar thermal energy storage system using various heat transfer fluids. *Applied Mechanics and Materials*, 878, 27-31. doi:10.4028/www.scientific.net/amm.878.27

[23] Liu, M. J., Zhu, Z. Q., Fan, L. W., & Yu, Z. T. (2016, July). An Experimental Study of Inward Solidification of Nano-Enhanced Phase Change Materials (NePCM) Inside a Spherical Capsule. In ASME 2016 Heat Transfer Summer Conference collocated with the ASME 2016 Fluids Engineering Division Summer Meeting and the ASME 2016 14th International Conference on Nanochannels, Microchannels, and Minichannels (pp. V002T08A016-V002T08A016). *American Society of Mechanical Engineers*.

[24] Parameshwaran, R., & Kalaiselvam, S. (2014). Energy conservative air conditioning system using silver nano-based PCM thermal storage for modern buildings. *Energy and Buildings*, 69, 202-212. doi:10.1016/j.enbuild.2013.09.052

[25] Zhang, S., Wu, J., Tse, C., & Niu, J. (2012). Effective dispersion of multi-wall carbon nanotubes in hexadecane through physiochemical modification and decrease of supercooling. *Solar Energy Materials and Solar Cells*, 96, 124-130. doi:10.1016/j.solmat.2011.09.032

[26] Ismail, K., Henríquez, J., & Da Silva, T. (2003). A parametric study on ice formation inside a spherical capsule. *International Journal of Thermal Sciences*, 42(9), 881-887. doi:10.1016/s1290-0729(03)00060-7

[27] Kumaresan, V., & Velraj, R. (2012). Experimental investigation of the thermo-physical properties of water–ethylene glycol mixture based CNT nanofluids. *Thermochimica Acta*, 545, 180-186. doi:10.1016/j.tca.2012.07.017

[28] Malarmannan, S., Chandrasekaran, P., & Khan, M. Q. (2020). Experimental investigation on reducing the solidification time of NFPCM by reducing sub cooling for different heat transfer fluid temperature for cooling applications. *IOP Conference Series: Materials Science and Engineering*, 912, 042055. doi:10.1088/1757-899x/912/4/042055

[29] Shafee, S., Gnanasekaran, K., Ravikumar Solomon, G., & Arshi Banu, P. (2020). Analysis of heat transfer mechanisms during energy storage in a vertical cylindrical unit filled with nano enhanced phase change material for free cooling applications. *Materials Today: Proceedings*, 22, 743-750. doi:10.1016/j.matpr.2019.10.080

[30] Sriharan, G., & Harikrishnan, S. (2018). Improved performance of composite phase change material for thermal energy storage. *Materials Today: Proceedings*, 5(6), 14215-14224. doi:10.1016/j.matpr.2018.03.001

[31] Sidney, S., Dhasan, M., C., S., & Harish, S. (2019). Experimental investigation of freezing and melting characteristics of graphene-based phase change Nanocomposite for cold thermal energy storage applications. *Applied Sciences*, 9(6), 1099. doi:10.3390/app9061099

[32] Liu, Y., Li, X., Hu, P., & Hu, G. (2015). Study on the supercooling degree and nucleation behavior of water-based graphene oxide nanofluids PCM. *International Journal of Refrigeration*, 50, 80-86. doi:10.1016/j.ijrefrig.2014.10.019

[33] Althohamy, A. A., Abd Rabbo, M., Sakr, R., & Attia, A. A. (2015). Effect of water based Al2O3 nanoparticle PCM on cool storage performance. *Applied Thermal Engineering*, 84, 331-338. doi:10.1016/j.applthermaleng.2015.03.066

[34] Dannemand, M., Johansen, J. B., Kong, W., & Furbo, S. (2016). Experimental investigations on cylindrical latent heat storage units with sodium acetate trihydrate composites utilizing supercooling. *Applied Energy*, 177, 591-601. doi:10.1016/j.apenergy.2016.05.144

[35] Ji, J., Wang, Y., Zhang, X., Chen, Y., Munyalo, J. M., & Liu, S. (2019). Supercooling characteristics of mannitol phase transition system under heterogeneous nucleation. *Journal of Materials Science*, 55(7), 2994-3004. doi:10.1007/s10853-019-04195-z

[36] Wu, T., Xie, N., Niu, J., Luo, J., Gao, X., Fang, Y., & Zhang, Z. (2020). Preparation of a low-temperature nanofluid phase change material: MgCl2–H2O eutectic salt solution system with
multi-walled carbon nanotubes (MWCNTs). *International Journal of Refrigeration*, **113**, 136-144. doi:10.1016/j.ijrefrig.2020.02.008

[37] Munyalo, J. M., Zhang, X., & Xu, X. (2018). Experimental investigation on supercooling, thermal conductivity and stability of nanofluid based composite phase change material. *Journal of Energy Storage*, **17**, 47-55. doi:10.1016/j.est.2018.02.006

[38] Kumaresan, V., Velraj, R., Chandrasekaran, P., Nanda, M., & Maini, A. (2012). Role of PCM based Nanofluids for energy efficient thermal storage in electronic cooling system. *10th International Energy Conversion Engineering Conference*. doi:10.2514/6.2012-4237

[39] Chandrasekaran, P., Cheralathan, M., Kumaresan, V., & Velraj, R. (2014). Enhanced heat transfer characteristics of water based copper oxide nanofluid PCM (phase change material) in a spherical capsule during solidification for energy efficient cool thermal storage system. *Energy*, **72**, 636-642. doi:10.1016/j.energy.2014.05.089

[40] Kumaresan, V., Chandrasekaran, P., Nanda, M., Maini, A., & Velraj, R. (2013). Role of PCM based nanofluids for energy efficient cool thermal storage system. *International Journal of Refrigeration*, **36**(6), 1641-1647. doi:10.1016/j.ijrefrig.2013.04.010

[41] Premnath, K.Hemalatha, Dr.G.Balaji, Dr.L.R. Ganapathy Subramanian, Study of Solidification Characteristics in a Metallic Spherical Capsule Using Extended Surfaces, *International Journal of Mechanical Engineering and Technology*, **9**(5), 2018, pp. 548–555

[42] Nallusamy, N., Roy, R., & Surya, A. (2019). Experimental investigation on heat transfer enhancement of latent heat storage system containing spherical capsules with internal hollow and solid fins. *renewable energy sources and technologies*. doi:10.1063/1.5127592

[43] Premnath, D., Chandrasekaran, P., & Ganapathy Subramanian, L. R. (2020). Solidification characteristics of phase change material in a rectangular finned spherical capsule. *IOP Conference Series: Materials Science and Engineering*, **912**, 042012. doi:10.1088/1757-899x/912/4/042012

[44] Premnath Doss, Chandrasekaran Ponnusamy & Ganapathy Subramanian Lalgudi Ramachandran (2020) “Predictive modeling of solidification characteristics of a phase change material in a metallic spherical capsule fitted with fins of different lengths, *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, DOI: 10.1080/15567036.2020.1817192

[45] Chandrasekaran, P., Cheralathan, M., & Velraj, R. (2015). Effect of fill volume on solidification characteristics of DI (deionized) water in a spherical capsule – An experimental study. *Energy*, **90**, 508-515. doi:10.1016/j.energy.2015.07.086

[46] Kumaresan, V., Velraj, R., & Das, S. K. (2012). The effect of carbon nanotubes in enhancing the thermal transport properties of PCM during solidification. *Heat and Mass Transfer*, **48**(8), 1345-1355. doi:10.1007/s00231-012-0980-3

[47] Chandrasekaran, P., Cheralathan, M., & Velraj, R. (2015). Influence of the size of spherical capsule on solidification characteristics of DI (deionized water) for a cool thermal energy storage system- An experimental study. *Energy*, **90**, 807-813. doi:10.1016/j.energy.2015.07.113

[48] Castell, A., Belusko, M., Bruno, F., & Cabeza, L. (2011). Maximisation of heat transfer in a coilintankPCMcoldstoragesystem. *AppliedEnergy*, **88**(11),4120-4127. doi:10.1016/j.apenergy.2011.03.046

[49] Ismail, K., & Moraes, R. (2009). A numerical and experimental investigation of different containers and PCM options for cold storage modular units for domestic applications. *International Journal of Heat and Mass Transfer*, **52**(19-20), 4195-4202. doi:10.1016/j.ijheatmasstransfer.2009.04.031

[50] Ismail, K., & Henriquez, J. (2002). Numerical and experimental study of spherical capsules packed bed latent heat storage system. *Applied Thermal Engineering*, **22**(15), 1705-1716. doi:10.1016/s1359-4311(02)00080-7
[51] Solomon, G. R., Karthikeyan, S., & Velraj, R. (2013). Sub cooling of PCM due to various effects during solidification in a vertical concentric tube thermal storage unit. *Applied Thermal Engineering, 52*(2), 505-511. doi:10.1016/j.applthermaleng.2012.12.030

[52] Azzouz, K., Leducq, D., & Gobin, D. (2008). Performance enhancement of a household refrigerator by addition of latent heat storage. *International Journal of Refrigeration, 31*(5), 892-901. doi:10.1016/j.ijrefrig.2007.09.007

[53] Azzouz, K., Leducq, D., & Gobin, D. (2009). Enhancing the performance of household refrigerators with latent heat storage: An experimental investigation. *International Journal of Refrigeration, 32*(7), 1634-1644. doi:10.1016/j.ijrefrig.2009.03.012

[54] Gin, B., & Farid, M. M. (2010). The use of PCM panels to improve storage condition of frozen food. *Journal of Food Engineering, 100*(2), 372-376. doi:10.1016/j.jfoodeng.2010.04.016

[55] Hoang, H., Leducq, D., Pérez-Masia, R., Lagaron, J., Gogou, E., Taoukis, P., & Alvarez, G. (2015). Heat transfer study of submicro-encapsulated PCM plate for food packaging application. *International Journal of Refrigeration, 52*,151-160.

[56] Leducq, D., NDoye, F., & Alvarez, G. (2015). Phase change material for the thermal protection of ice cream during storage and transportation. *International Journal of Refrigeration, 52*, 133-139. doi:10.1016/j.ijrefrig.2014.08.012.

[57] Hu, Y., Heiselberg, P. K., & Guo, R. (2020). Ventilation cooling/heating performance of a PCM enhanced ventilated window - an experimental study. *Energy and Buildings, 214*, 109903. doi:10.1016/j.enbuild.2020.109903

[58] Solgi, E., Kari, B. M., Fayaz, R., & Taheri, H. (2017). The impact of phase change materials assisted night purge ventilation on the indoor thermal conditions of office buildings in hot-arid climates. *Energy and Buildings, 150*, 488-497. doi:10.1016/j.enbuild.2017.06.035.

[59] Waqas, A., & Kumar, S. (2011). Utilization of latent heat storage unit for comfort ventilation of buildings in hot and dry climates. *International Journal of Green Energy, 8*(1), 1-24. doi:10.1080/15435075.2010.529406

[60] Chaityat, N., & Kiatsiriroat, T. (2014). Energy reduction of building air-conditioner with phase change material in Thailand. *Case Studies in Thermal Engineering, 4*,175-186. doi:10.1016/j.csite.2014.09.006