

## **Review on heat transfer enhancement during solidification of PCM**

Aneesh.V<sup>1</sup>, Gnanadurai Ravikumar Solomon<sup>2</sup>

<sup>1</sup>(P.G Scholar, Department of Mechanical engineering, Hindustan University, Chennai, India.)

<sup>2</sup>(Professor, Department of Mechanical engineering, Hindustan University, Chennai, India.)

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**ABSTRACT :** *The continuous increase in the level of greenhouse gas emissions and the climb in fuel prices are the main driving forces behind the research toward energy conservation and energy storage. The thermal energy storage and in particular Phase Change Materials (PCMs), have been a main topic in research for last 20 years. The main difficulty in using PCM for energy storage application is the low thermal conductivity of the PCM in its solid state, which will make the evacuation of energy tougher once solidification starts. To nullify the problem, different heat transfer enhancement techniques have been proposed by different researchers. This paper extensively reviews the work carried out by different researchers in enhancing the heat transfer.*

**Keywords -** *PCM: Phase change material, solidification time, TES: Thermal energy storage system, LHTES: Latent-heat thermal energy storage, SHS: Sensible heat storage*

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### **I. INTRODUCTION**

The growing demand for sustainable energy from consumers and industry is constantly changing. The highest demand of energy consumption during a single day brings a continuous and unsolved problem: how to maintain a consistent desired temperature in a sustainable way. Periods of extreme cold or warm weather are the triggering factors for increasing the demand on heating or cooling. Working hours, industry processes, building construction, operating policies, and type and volume of energy production facilities are some of the main reasons for peak demand crises. Better power generation management and significant economic benefit can be achieved if some of the peak load could be shifted to the off peak load period. This can be achieved by thermal storage for space heating and cooling purposes.

Thermal energy can be stored as a change in the internal energy of certain materials as sensible heat, latent heat or both. The most commonly used method of thermal energy storage is the sensible heat method, although PCMs, which effectively store and release latent heat energy, have been studied for more than 20 years. Latent heat storage can be more efficient than sensible heat storage because it requires a smaller temperature difference between the storage and releasing functions. Phase change materials are an important and underused option for developing new energy storage devices, which are as important as developing new sources of renewable energy. The use of phase change material in developing and constructing sustainable energy systems is crucial to the efficiency of these systems because of PCM's ability to harness heat and cooling energies in an effective and sustainable way.

Thermal Energy Storage systems (TES) employed in several applications act as a thermal flywheel, to store surplus energy when the demand was less, and to deliver the same at other times. Latent Heat Thermal Energy Storage systems (LHTES) with phase change materials have dominated the sensible heat storage systems, due to their large storage capacity and near isothermal charging/discharging behaviour. In recent years, PCM based thermal energy storage systems have received great research attention to store the cool energy available in the ambient during the early morning hours, and to utilize the stored cool energy for the space cooling of buildings during the day time. In such LHTES, during the phase change, the solid liquid interface moves away from the heat transfer surface. In this process, the thermal conductivity of the solidified PCM being very low, the surface heat flux decreases with respect to time, due to the increasing thermal resistance of the growing layer of the molten/solidified medium. Hence, the study of various heat transfer enhance techniques play important role in effective utilization of stored thermal energy.

### **II. PHASE CHANGE MATERIAL**

A phase-change material (PCM) is a substance with a high heat of fusion which, melting and solidifying at a certain temperature, is capable of storing and releasing large amounts of energy. Heat is absorbed or released when the material changes from solid to liquid and vice versa; thus, PCMs are classified as latent heat storage (LHS) units.

## **2.1 Classification of PCMs**

A large number of phase change materials (organic, inorganic and eutectic) are available in any required temperature range. There are a large number of organic and inorganic chemical materials, which can be identified as PCM from the point of view melting temperature and latent heat of fusion. However, except for the melting point in the operating range, majority of phase change materials does not satisfy the criteria required for an adequate storage media as discussed earlier.

2.1.1 Organic PCMs: Organic materials are further described as paraffin and nonparaffins. Organic materials include congruent melting means melt and freeze repeatedly without phase segregation and consequent degradation of their latent heat of fusion, self nucleation means they crystallize with little or no super cooling and usually non-corrosiveness.

2.1.2 Inorganic: Inorganic materials are further classified as salt hydrate and metallics. These phase change materials do not super cool appreciably and their heats of fusion do not degrade with cycling.

2.1.3 Eutectics: A eutectic is a minimum-melting composition of two or more components, each of which melts and freeze congruently forming a mixture of the component crystals during crystallization. Eutectic nearly always melts and freezes without segregation since they freeze to an intimate mixture of crystals, leaving little opportunity for the components to separate. On melting both components liquefy simultaneously, again with separation unlikely. Some segregation PCM compositions have sometimes been incorrectly called eutectics, since they are minimum melting. Because of the components undergoes a peritectic reaction during phase transition, however, they should more properly be termed peritectics.

## **III. CHARACTERISTICS OF PCM**

PCMs latent heat storage can be achieved through solid–solid, solid–liquid, solid–gas and liquid–gas phase change. However, the only phase change used for PCMs is the solid–liquid change. Liquid–gas phase changes are not practical for use as thermal storage due to the large volumes or high pressures required to store the materials when in their gas phase. Liquid–gas transitions do have a higher heat of transformation than solid–liquid transitions. Solid–solid phase changes are typically very slow and have a rather low heat of transformation.

Initially, the solid–liquid PCMs behave like sensible heat storage (SHS) materials; their temperature rises as they absorb heat. Unlike conventional SHS, however, when PCMs reach the temperature at which they change phase (their melting temperature) they absorb large amounts of heat at an almost constant temperature. The PCM continues to absorb heat without a significant rise in temperature until all the material is transformed to the liquid phase. When the ambient temperature around a liquid material falls, the PCM solidifies, releasing its stored latent heat. A large number of PCMs are available in any required temperature range from –5 up to 190 °C. Within the human comfort range between 20–30°C, some PCMs are very effective. They store 5 to 14 times more heat per unit volume than conventional storage materials such as water, masonry or rock.

### **3.1. Selection criteria for PCM**

The phase change material should possess:

#### **3.1.1 Thermodynamic properties**

Melting temperature in the desired operating temperature range, High latent heat of fusion per unit volume, High specific heat, high density and high thermal conductivity, Small volume changes on phase transformation and small vapour pressure at operating temperatures to reduce the containment problem, Congruent melting

#### **3.1.2 Kinetic properties**

High nucleation rate to avoid super cooling of the liquid phase, High rate of crystal growth, so that the system can meet demands of heat recovery from the storage system,

#### **3.1.3 Chemical properties**

Chemical stability, complete reversible freeze/melt cycle, No degradation after a large number of freeze/melt cycle, Non-corrosiveness, non-toxic, non-flammable and non-explosive materials

3.1.4 Economic properties

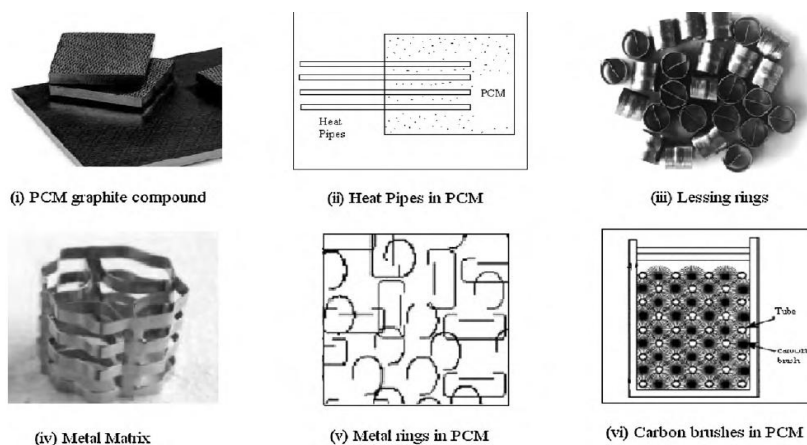
Low cost, Availability

**IV. PROBLEM ENCOUNTERED DURING SOLIDIFICATION**

**4.1. Low thermal conductivity on freezing**

The great technical limitation on the increased application of PCMs for thermal storage is their low conductivity, especially in the liquid phase. For example paraffin's have a typical thermal conductivity of 0.21-0.24 W/m K. This means that the charging or discharging of the PCM is slow which results in an unreactive system that absorbs only a small amount of the excess heat available. It is desired to find different enhancement techniques to improve the heat transfer.

Some of the methods for improving heat transfer are shown in Fig 1:



**Fig. 1. Heat transfer enhancement technique in PCM**

**4.2. Heat transfer enhancement techniques and research**

4.2.1 Heat transfer enhancement through fin:

Cast ell et al. (2008) conducted experimental [1] work about the performance enhancement of LHTES during solidification, by adding external longitudinal fins to the HTF while the PCM was stored in the inner tube. The study focused on the calculation of the heat transfer coefficient and it was found that the introduction of vertical fins did not increase the heat transfer coefficient; however the time needed to solidify the PCM decreased. When using small fins, a lower temperature difference was sufficient to achieve the same heat transfer coefficient as with no fins. When longer fins were used, there was a decrease in the heat transfer coefficient due to the dampening effect on natural convection. Nevertheless, the increase of the heat transfer area resulted in an increase of the heat transfer rate; hence, the solidification time in the finned system was considerably less compared to the unfinned system.

Arkar et al. (2005) carried out DSC analysis [2] at various cooling rates of 5, 1 and 0.1 k/min, in order to determine the temperature distribution of the Latent Heat of Paraffin RT 20 (recently renamed as RT 21 by the manufacturer) in the form of apparent heat capacity. They reported that the shape of the DSC curve depended significantly on the heating /cooling rate, and the size (mass) of the sample used in the DSC. In particular, during solidification, it could be seen that the peak temperature,  $T_p$ , shifted towards higher temperatures at lower cooling rates, and the peak became narrow and higher as well, which showed that the greatest part of the latent heat evolved in a narrow temperature range. A comparison of the numerical and experimental results carried out with a cylindrical LHTES system based on spheres with encapsulated paraffin, the apparent heat capacity,  $C_{app}$ , a parameter that described how the latent heat of the PCM evolved over the temperature range, should also include an additional influential parameter- the heating or cooling rate.

Lamberg et al. (2004) discussed [3] about the finned PCM storage system. In this he used an approximate analytical model to analyze the two phase solidification problem in a finned PCM storage system,

and concluded that the solidification was dominated by conduction while natural convection existed only during the beginning of the solidification process. The natural convection effect diminished with respect to time, and its effect became almost negligible compared to conduction.

Velraj et al. (1997) conducted [4] both numerical and experimental study about enhancement of heat transfer in a thermal storage system consisting of a cylindrical vertical tube with internal longitudinal fin arrangement is discussed in this paper. This configuration that forms a V-shaped enclosure for the phase change material (PCM) gives maximum benefit to the fin arrangement. A theoretical model that also accounts for the circumferential heat flow through the tube wall is developed using enthalpy formulation and is employed in conjunction with the fully implicit finite difference method to solve the solidification in the convectively cooled vertical tube. A generalized enthalpy-temperature ( $H-T$ ) relationship, developed by Date, is suitable for constant phase change temperature and this is modified in the present work to accommodate materials having either constant or a range of phase change temperatures. The numerical model is validated with experimental data. The instantaneous surface heat flux and the solidified fraction for different number of fins and tube radii, that are of interest for the design of latent heat thermal storage system consisting of an array of vertical cylindrical tubes containing PCM inside it, are also discussed.

#### 4.2.2 Enhancement through Metal Matrix material:

Bauer et al. (2000) experimentally [5] studied that thermal Energy Storage (TES) system uses a Phase Change Material (PCM) to store heat during peak power operation of variable power dissipating devices via the latent heat effect. The TES composite developed is a plate-like structure that consists of a central core of foamed aluminium that is packed with a PCM. By considering the elements of the composite to be thermal resistors and constructing a flat-plate thermal conductivity apparatus, the plate-to-plate effective thermal conductivity is determined. The composite effective thermal conductivity is primarily composed of the thermal conductivity of the aluminium foam which is reduced by the effect of the aluminium foam-to-plate bond resistance. Heat flow through the PCM slightly augments the effective thermal conductivity. An increase in aluminium foam metal fraction results in an increase in the effective thermal conductivity of the composite because only about 2% of the heat flow is through the PCM, and the interfacial bond resistance decreases due to increased contact area. The trade-off is that as there is an increase in aluminium foam metal fraction, the volumetric latent heat decreases; thus, the storage time is reduced.

Tong et al. (1996) demonstrated [6] increase in the heat transfer rate during melting and freezing of a phase change material (PCM) with a low thermal conductivity by inserting a high-porosity metal matrix into the PCM. A vertical annulus space homogeneously fitted with water and an aluminum matrix is selected for this study. The Navier-Stokes equations are modified to account for Darcy's effect. For both the melting and freezing cases, the density inversion phenomenon of water is considered. The irregularity and time-varying nature of the solid and the liquid regions are accounted for by a geometric coordinate transformation. The numerical results are presented in the form of solid-liquid interface movements, isotherms, streamlines, and heat transfer rates for some representative cases. The heat transfer rates for enhanced cases show an order-of-magnitude increase over the base case, where no metal matrix is inserted.

Cabeza et al. (2002) Experiments [7] were performed in a small thermal improvement in the PCM (water/ice) with three different heat transfer enhancement methods. These were the addition of stainless steel pieces, copper pieces, and a graphite matrix impregnated with the PCM. The use of graphite composite allows an even larger increase in the heat transfer than with copper. The heat flux is about four times larger on heating and three times larger on cooling as compared to using pure ice.

#### 4.2.3 Enhancement through Graphite compound material:

Mehling et al. (2000) conducted experiment [8] using graphite compound material, where the PCM is embedded inside a graphite matrix. The main advantages of such a material is the increased heat conductivity in the PCM without much of reduction in the energy storage, also the other advantages include a decrease in the sub cooling of the salt hydrates and a decrease in the volume change of the paraffin's. This technique is being employed in building material applications.

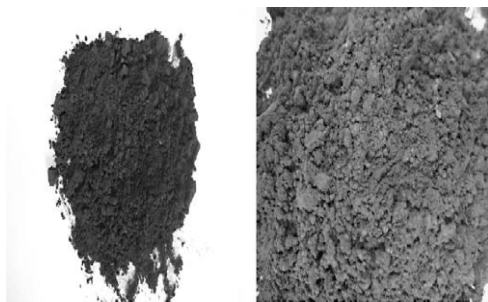
Marin et al. (2005) further explained [9] about the improvement made to the experiment by including graphite compounded material with the paraffin PCM for heat transfer enhancement in PCM. Due to graphite addition thermal conductivity is increased in the PCM without much reduction in energy storage. Other advantages of adding graphite are the decrease in sub cooling of salt hydrates and the decrease of volume change in paraffin. These plates contain alternatively the PCM and the composite with the PCM embedded in a graphite matrix. It was found that the great reduction of time, about one half in the case of using the graphite

matrix as compared with the PCM only. But the reduction of the energy stored between 12% and 20%, based on the storage volume occupied by the graphite.

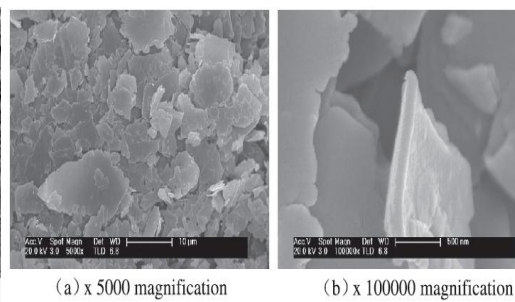
Py et al. (2001) conducted experiments [10] with new phase change material (PCM) made of paraffin impregnated by capillary forces in compressed expanded natural graphite (CENG) matrix is presented. High loads of paraffin were obtained: from 65% to 95% weight depending upon the bulk graphite matrix density. Composite PCM/CENG thermal conductivities were found to be equivalent to those of the sole graphite matrix from 4 to instead of the pure paraffin. Thermal power and capacity of the composite are theoretically compared to those of conventional systems in the case of two usual external geometries: tubes and spherical hollow nodules. The CENG induced a decrease in overall solidification time and a stabilization of the thermal storage power. An optimization procedure of the composite composition was proposed according to the antagonistic behaviours of the thermal power and the thermal capacity with respect to the CENG content. Within the usual external heat transfer coefficient range, the estimated CENG matrix optimized densities fell within the practicable range.

#### 4.2.4 Heat Transfer through high thermal conductivity particles:

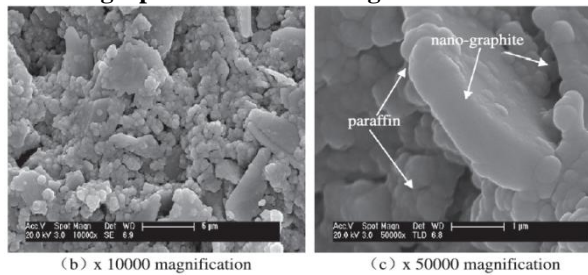
Min Li (2013) experimentally [11] studied the improvement in thermal conductivity of PCMs with Nano-graphite (NG) shown In Fig 2- 4. The environmental scanning electron microscopy and differential scanning calorimeter were used to check the thermal properties of NG. It was found that the NG content increased the thermal conductivity of the NG/paraffin composite, but the latent heat gradually decreased.



**Fig .2. Appearance of Nano-graphite**



**Fig.3.Microstructure of the nano-graphite**



**Fig.4. Microstructure of the paraffin/nano-graphite composite.**

Kumaresan et al. (2012) conducted an experiment [12] to study the heat transfer properties by enhancement of Nanofluid phase change material (NFPCM) during freezing. The dispersed Multi-walled carbon nanotubes (MWCNT) in paraffin (RT 21) at 4 different volume fractions. They observed that the K increases with the increased volume fraction of MWCNT and K is not depending on temperature. Also they found that the MWCNT not only decreases; the solidification time but also suppress the sub cooling effect. They concluded that the heat transfer enhancement offered by NFPCM will alleviate the major problems that have been encountered in the conventional phase change material.

Raj et al. (2010) detailed review [13] of works carried out by various researchers, on free cooling or ventilation cooling is studied. It also deals with the various PCMs design used for free cooling like geometry of encapsulation is explained in detail. They concluded that the performance of free cooling system will be good if the phase change temperature of PCM selected the midrange of diurnal temperature variation. Also the air flow should be optimized during operation to control the volume flow and pressure drop which decides the capacity of the fan and power consumption.

Parameshwaran and Kalaiselvam (2014) experimentally [14] studied the chilled water based variable air volume air conditioning system integrated with the silver nano particles embedded latent thermal energy storage system were investigated with the demand controlled ventilation (DCV) and combined DCV-economizer cycle ventilation techniques for year- round operation in buildings and also the thermal performance and energy efficiency of the unit are also noted. The PCM along with silver nanoparticles show an improved heat transfer mechanism in charging and discharging cycles. They concluded that the proposed air conditioning system achieved an on-peak and per day average energy savings potential of 36-58% and 24-51%, when compared to the conventional air conditioning system.

Teng et al. (2013) conducted an experiment [15] to study the influences of the concentrations of the MWCNTs and graphite on their temperature and phase change heat variations at the thermal energy charging and discharging process by charging/ discharging temperature difference and DSC experiments were done to check the feasibility for thermal storage. In this they use modified phase change materials (MPCMs) along with the direct synthesis method to mix paraffin with MWCNTs and graphite as experimental sample was used. They concluded that the adding MWCNTs were more effective than graphite for better thermal storage performance of paraffin has great potential in future.

Kalaiselvam et al. (2012) studied the analytical [16] and experimental investigations of the phase change heat transfer characteristics and thermodynamic behaviour of spherically enclosed PCM with dispersion of nanoparticles for latent thermal energy storage system in buildings. Also the heat transfer characteristics in terms of transient temperature variations, solidification and melting were analyzed for the six different PCMs. They found that for the same thermal load conditions the rate of solidification for the PCMs decreased with the increased mass fractions of nanoparticles while compared to the pure PCMs. The deviations observed between the analytical solutions and the experimental results were in the range of 10%-13%.

#### 4.2.5 Enhancement through Nano material:

Kumaresan et al. (2012) reported an experimental [17] study on the convective heat transfer characteristics of a secondary refrigerant based CNT nano fluids in a tubular heat exchanger. The nano fluid is prepared by dispersing the multiwalled carbon nanotubes (MWCNT) in the water- ethylene glycol mixture (70:30 by volume). The results show that the convective heat transfer coefficient is enhanced to a maximum of ~160% for the nanofluid containing 0.45 vol. % MWCNT, which could not be attributed solely by enhanced thermal conductivity of the nanofluids. Particle rearrangement, the very high aspect ratio and delaying the boundary layer development due the random movement of the carbon nanotubes are the possible mechanisms. Further, there is an appreciable decrease in Reynolds number for a given velocity for all the nanofluids. The enhancement in the friction factor is negligible at higher velocity and higher temperature for the nanofluids with 0.15 vol. % MWCNT.

Kumaresan et al. (2012) experimentally [18] tested about the nano fluid phase change material (NFPCM) dispersed with 0.6 % ( by volume) multi-walled carbon nano tube enhances the heat transfer, with 33.64% reduction in solidification time. An enhancement in the thermal conductivity of 30%~ 45% was achieved both in the liquid and solid states of the NFPCM compared to that of pure PCM. Increasing the concentration of the MWCNT had steadily increased the thermal conductivity of the NFPCM, up to a volume fraction of 0.6%.

Zhang et al. (2012) reported about multiwall carbon nano-tube (MWCNT) particles [19] that were dispersed in an organic liquid (n-hexadecane), and reported that with the addition of 0.1% (by mass) MWCNT, the super cooling of hexadecane can decrease by 43%, which produced the most significant effect among the test samples. It is also interesting to note that there was an effective concentration range of nanoparticle for super cooling reduction, and better results cannot be obtained by continuously increasing the nanoparticle concentration.

Chandrasekhar et al. (2012) experimentally [20] shown that there is an enhancement in the heat transfer by reduction in the solidification time of 45% , when iron – water nano fluid is used as the PCM, compared to the water PCM. Further, it is inferred that the addition of nanoparticle, has much influence in enhancing the heat transfer in the passive way than increasing the temperature difference between the HTF and the freezing temperature of the PCM.

## V. CONCLUSIONS

The review of this paper carried out different methods of heat transfer enhancement techniques in thermal energy storage system and solidification of PCM. The paper mainly focused on PCM based thermal energy storage system, which is more attractive and useful to the energy conservative system and covered current research papers in particular field.

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