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Review Article

# A Review on Influence of Geometry and Other Initial Conditions on the Performance of a PCM Based Energy Storage System

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***Abstract***

*Latent heat storage (LHS) is one of the most effective ways of storing thermal energy. Unlike the sensible heat storage method, this method provides much higher storage density, with a smaller temperature difference. Phase Change Materials (PCM) are suitable for this application due to their high storage density and isothermal operation. Important aspect in LHS system is the design of storage, which has considerable effect on heat transfer. The study of melting and solidification phenomena of Phase Change Material (PCM) needs to be understood for the design of thermal storage systems. One of the serious problems associated with the operation of PCM storage system is the heat transfer in and out of the element containing the PCM. Three aspects have been the focus of this review: influence of geometry, the influence of finning on capsule surfaces on the heat transfer enhancement and influence of some other aspects on the thermal performance. Problems in long term stability of the materials, such as corrosion, phase segregation, stability under extended cycling or subcooling are discussed*

***Keywords:*** *Fins, Heat transfer, Latent heat storage, Phase Change Material (PCM), PCM storage geometry.*

## 1. Introduction

Several studies are carried out on phase change materials over the last three decades. Phase change materials are very interesting due to their absorbing of large amount of energy as latent heat at a constant phase transition temperature. These materials can be used for passive heat storage.

Major disadvantage of the PCM is related to their low thermal conductivity which impedes high rate of charge and discharge of heat flux.

These types of materials have many useful properties including heat source at constant temperature, heat recovery with small temperature drop, high storage density, melting point which matches the applications, low vapor pressure at the operational temperature, and chemical stability and non-corrosiveness. These properties allow the PCM to be used in many industrial applications such as thermal storage of solar energy, thermal management of electronic devices, thermal storage in buildings, cooling of engines etc.

An ever-increasing world population combined with a strong rise in energy demand has led to a significant environmental crisis that already shows its clear beginning (Konstantinidou, 2010).

Energy demands in the commercial, industrial and utility sectors vary on daily, weekly and seasonal bases e.g. Solar heating, waste heat recovery, building space-heating and cooling, thermal comfort, electronic cooling, and also to reduce the HVAC equipment size by leveling or shifting the peak load demand. These demands can be satisfied by smoothing the temporal variations with the help of thermal energy storage (TES) systems, (A.H. Mosaffa, *et al*, 2012), (F. Talati, *et al*, 2011), (Karthikeyan, *et al*, 2011).

Energy storage is an effective approach to increase energy efficiency and energy savings, since many energy sources are intermittent in nature. It is the most appropriate way and method to correct the gap between the demand and supply of energy. Energy storage is not only plays an important role in conservation of the energy but also improves the performance and reliability of wide range of energy systems, and become more important where the energy source intermittent such as solar (Mahmud M, *et al*,2011 ).

Thermal energy storage (TES) is recognized as one of the key technologies for energy storage in the future (Yuefeng Li, *et al*, 2012).

Three major methods are currently considered for thermal storage: sensible heat, latent heat and thermo chemical heat. Sensible heat storage has been used for centuries by builders to store/release passively thermal energy, but a much larger volume of material is required to store the same amount of energy in comparison to latent heat storage., latent heat energy storage, using phase change materials (PCM), is the most effective technique because of its advantages of high energy storage density and isothermal characteristics (Shuangmao, *et al*, 2012).

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High energy storage density and high power capacity for charging and discharging are desirable properties of any storage system (E. Oró, *et al*, 2012).

Latent thermal energy storage (TES) systems rely on the use of phase change materials (PCMs) to store a significant amount of thermal energy (Ehsan Mohseni Languri, *et al*, 2013).

Phase change materials are very interesting due to their absorbing of large amount of energy as latent heat at a constant phase transition temperature. These materials can be used for passive heat storage. In the recent years, many researchers have shown great interest in using PCM because of greenhouse gas emission and increasing cost of fossil fuels (S.F. Hosseinizadeh, *et al*, 2012).

The principle of the phase change material (PCM) use is simple. As the temperature increases, the material changes from solid to liquid phase. The reaction being endothermic, the PCM absorbs heat. Similarly, when the temperature decreases, the material changes from liquid to solid phase. The reaction being exothermic, the PCM desorbs heat (Damien David, *et al*, 2011).

## 2. Applications of PCM based ESS

Defence Laboratory Jodhpur (DLJ) has initiated a R&D programme (P.K. Sharma, *et al*, 2011) to apply PCM in solving many heat related problems being faced by Indian forces during desert operations specially failure of mission-critical components. Under the programme, special organic PCM with low melting metal alloys have been developed which are well tuned to desert diurnal cycle. The PCM panels, when applied as an internal lining in buildings, structures and vehicles can moderate the extreme temperature within human tolerable range (below 40 °C) without the use of any external power for cooling. The panels can also act as power saver in air conditioned buildings. A cool vest has also been developed with chargeable PCM packs to provide comfortable microenvironment to a soldier on field duty (below 30 °C) for 2-3 hrs.

Heating, ventilation and air conditioning (HVAC) in buildings consume a large quantum of energy, which in turn increases the fossil energy consumption and also pollutes the environment. Hence, research related to energy-efficient buildings is of great importance. Thermal energy storage (TES) system is an economical energy storage technique, where the energy stored during part load operations was reused during the peak load hours (Kalaiselvam Siva, *et al*, 2010).

PCMs could be integrated into building walls and they would absorb the solar energy, thereby reducing room temperature. This effect leads to reduced cooling loads or, in the absence of an air conditioner, to a significant increase in comfort (Kalaiselvam Siva , *et al*, 2010).

The TES system in free cooling mode stores the energy in the form of coolness from the outdoor air during the night and provides cooling during the day having on-peak load conditions. Free heating is another principle wherein the solar radiation during the day is stored to provide heat during the night (Kalaiselvam Siva, *et al*, 2010).

Industrial thermal processes of intermittent nature or processes where energy availability and its utilization are not coincident require a means of matching the use of energy with its availability. This is usually done efficiently by energy storage system which stores energy when it is available and reutilize it when needed (K.A.R. Ismail, *et al*, 2003).

The thermal energy storage can be used in places where there is a variation in solar energy or in areas where there is a high difference of temperature between day and night (Mahmud M, *et al*, 2011).

In construction, the use of Phase Change Materials (PCM) allows the storage/release of energy from solar radiation and internal loads. The application of such materials for lightweight construction (e.g., a wood house) makes it possible to improve thermal comfort and reduce energy consumption (Damien David, *et al*, 2011).

## 3. Phase change materials

All materials are phase change materials. The most important difference between these materials is the phase change temperature. Each material makes its phase change at different temperature. In addition, each material has different value of latent heat and thermal conductivity. The most important feature for the selected phase change material is to have its phase change temperature fitted with the application temperature range. Indeed, there is no specific material that is called as an ideal material to be used as a phase change material; each material has its advantages and disadvantages. Phase change materials are classified as shown in fig.1

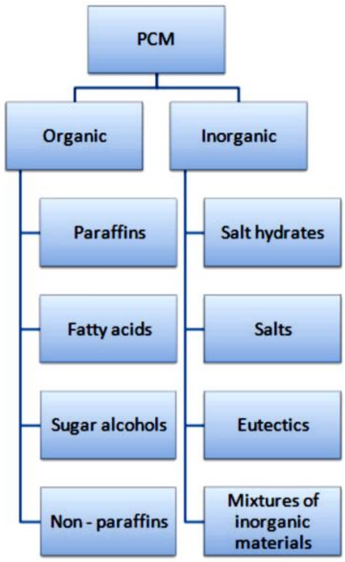


**Fig.1** Classification of Phase Change Material

Compared to inorganic PCM, organic PCM melts and freezes repeatedly without phase segregation and consequent degradation of their latent heat of fusion. Among the PCM investigated, paraffins have been widely used due to their high latent heat storage capacity and appropriate thermal properties, such as little or no supercooling, low vapor pressure, good thermal and chemical stability, and self-nucleating behavior (Shuangmao, *et al*, 2012).

Many materials were chosen as PCM for cool thermal energy storage. Water is widely used as the PCM because of its high latent heat of freezing, low cost and no environmental pollution. However, the sub-cooling phenomenon occurs in solidification stage of water during the charging process and affects the performance of the cool storage systems (Shuangmao, *et al*, 2012).

## 4. Encapsulation of PCM

In most cases, except for some applications of water-ice, the PCM needs to be encapsulated. The two main reasons are to hold the liquid phase of the PCM, and to avoid contact of the PCM with the environment, which might harm the environment or change the composition of the PCM. Further on, the surface of the encapsulation acts as heat transfer surface. In some cases, the encapsulation also serves as a construction element, which means it adds mechanical stability. Encapsulations are usually classified by their size into macro- and microencapsulation (Mahmud M, *et al*, 2011).

Macroencapsulation means filling the PCM in a macroscopic containment that fit amounts from several milliliters up to several liters. These are often containers and bags made of metal or plastic. Macroencapsulation is very common because such containers or bags are available in a large variety already from other applications. In that case, macroencapsulation is mainly done to hold the liquid PCM and to prevent changes in its composition due to contact with the environment. If the container is rigid enough, the encapsulation can also add mechanical stability to a system.

Microencapsulation is the encapsulation of solid or liquid particles of 1 μm to 1000 μm diameter with a solid shell. Physical processes used in microencapsulation are spray drying, centrifugal and fluidized bed processes, or coating processes e.g. in rolling cylinders. Chemical processes used are in-situ encapsulations which have ability to yield microcapsules with the best quality in terms of diffusion – tightness of the wall. Such microcapsules are now days widely used in carbonless copy paper (Springer, 2008).

Besides the containment of the liquid phase, other advantages of microencapsulation regarding PCM are the improvement of heat transfer to the surrounding because of the large surface to volume ratio of the capsules, and the improvement in cycling stability since phase separation is restricted to microscopic distances. Further on, it is also possible to integrate microencapsulated PCM into other materials (Springer, 2008).

Many researchers have tried to solve leakage problem and improve thermal conductivity properties of paraffin. In order to solve the leakage of paraffin during the phase change, the conventional methods including encapsulation (Hawlader MNA, *et al*, 2002, Hawlader MNA, *et al*, 2003) and physical mixing technologies (Fang XM, *et al*, 2006, Liu X, *et al*, 2006, Inaba H, *et al*, 1997, Zhang ZG, *et al*, 2006) have been investigated. The prepared thermal storage materials by physical-mixing are actually a kind of composite phase change material. Paraffin has been encapsulated in three-dimensional net structure formed by polymer materials, such as high density polyethylene (HDPE) (Inaba H, *et al*, 1997).

The PCM can be encapsulated in a variety of ways using cylindrical geometries with or without fins, cans, plates or spherical capsules. This last seems to offer a number of advantages which ranks it up among the most attractive methods of encapsulation (K. Lafdi, et al, 2008). A large improvement in the heat transfer rate was obtained by encapsulating the PCM in small plastic spheres (Wood RJ, et al, 1981, Saitoh T et al, 1981) to form a packed bed storage unit. However, the expected high pressure drop through the initial cost may be major drawbacks of such units.

## 5. Effect of various parameters on ESS

### *5.1 Effect of geometry*

Geometry of containers used for PCM storage plays important role in design of LHTE storage. Number of researchers worked on the geometry and effect of geometry. Some interesting numerical investigations were realized by Formin *et al.* (1999) who investigated the close contact melting within a spherical capsule. Their complete mathematical model was solved by the method of boundary fixing.

Numerical model for predicting the thermal performance of cylindrical storage tank containing spherical PCM capsules as packed bed latent heat storage system are presented by Ismail *et al.* (2002). Their model is used to investigate the effect of the working fluid inlet temperature, flow rate of the working fluid and materials of the spherical capsule of 77mm diameter during the solidification process.

Keumnam *et al.* (2000) experimentally investigated the thermal characteristics of paraffin in a spherical capsule packed inside a storage tank at different values of the Reynolds number and inlet temperatures. They concluded that the phase change period for the capsule at the edge of the storage tank was shorter than that at the center of the storage tank, because the porosity at the center was smaller than at the edge of the storage tank. Also, the influence on the average heat transfer coefficients due to the fluid inlet temperature and Reynolds number is more during the melting process, than the freezing process due to the presence of the natural convection effect of the melting process. (Karthikeyan, *et al*, 2011).

Kalaiselvam Siva *et al.* (2010) analyzed geometries filled with the same volume of PCM, and concluded cylinder provides a better encapsulation than a sphere. Cylinder has 38% more surface area than sphere thereby giving 47% reduction in complete solidification time. The dimensions of the selected cylinder were such that the radius is not large as it would lead to increase in solidification time. Hence selection of configuration plays a vital role in TES systems.

Barba *et al.* (29) analyzed the behavior of encapsulated PCM in three different geometries, plane, cylindrical and spherical for possible application in domestic storage tanks. Their results show the influence of geometry and Jacob number on the time for complete solidification, and they concluded that the shortest time for complete solidification is obtained for small spherical shells with high Jacob number and high thermal conductivity.

Sergei A. Fomin *et al.* (2002) investigated that the melting rate of the solid depends on the shape of the capsule. Generally, elliptical capsules show higher rate of melting than circular ones. Elongated capsules provide more effective melting than oblate ones, even though they have the same aspect ratios and vertical cross-sectional areas. This phenomenon is caused by the fact, that the pressure necessary to support the solid is larger for the elongated capsules than that for oblate ones, which leads to thinning of the molten layer along with the increase of the heat flux across it. The time required for complete melting can be achieved by the right choice of the shape of the capsule, which is specified by the value of the aspect ratio. The found influence of the capsule shape on the melting rate can be used for design and optimization of practical latent-heat–thermal-energy systems.

Hill *et al.* (1983) developed a new semi-analytical procedure to study the solidification inside a spherical container including the effects of radiation at the container surface. The numerical values obtained for the position of the moving front are in agreement with available results from a completely numerical solution and an alternative semi-analytical solution of the problem.

Caldwell *et al.* (2000) applied a numerical scheme based on the enthalpy method to the problem of solidification in spherical geometry and compared their results with the heat balance integral method. They concluded that the two methods agree well enough except when the Stefan number is very small.

K. Lafdi *et al.* (2008) developed a model and its numerical solution based upon the finite difference approximations for the solidification of PCM in a spherical container under convective boundary conditions at the external surface of the spherical shell. Important parameters such as size of the spherical capsule, wall material, external temperature and the initial PCM temperature are investigated and their effects on the solidified mass fraction and the time for complete solidification were presented and discussed.

Ismail *et al.* (2000) realized a numerical study on the solidification of PCM inside a spherical capsule. Their mathematical model is based upon pure conduction and the boundary conditions of constant wall temperature and convection boundary condition on the external surface of the spherical shell were considered. Their numerical predictions were validated against available results and satisfactory agreement was reported.

Moreover, comparison between the melting time for the rectangular and cylindrical container was performed and the results show that the rectangular container requires half of the melting airtime as for the cylindrical container of the same volume (i.e. equal mass of the PCM filling the container) and the same heat transfer area between HTF and the container’s wall. It is, therefore, preferable to use rectangular containers for encapsulating the PCM.

Silva *et al.* (2005) investigated experimentally and mathematically melting and solidification of paraffin wax in a vertical rectangular enclosure, when the HTF was the air, they concluded that the correlations developed can be used for the rapid estimation of the charge and discharge times and so can be useful in the design of this kind of latent-heat thermal-energy store. A good amount of work has been devoted to investigate the performance enhancement by employing multiple PCMs in different configurations of LHTS units.

Wei *et al.* (2005) conducted experimental and theoretical study on rapid heat release. In their numerical studies they analyzed four different encapsulating geometries (sphere, cylinder, plate and tube) and compared their results with experiments and found agreement within 10%.

As mentioned by K. Lafdi, *et al.* (2008) the thermal conductivity of the capsule material has a strong effect on the time for complete solidification and the solidified mass fraction. Although metallic material has higher thermal conductivity than other nonmetallic material such as Polyethylene, the reduction in the time for complete solidification is around 30 minutes and consequently justifies the use of nonmetallic capsules.

Khodadadi *et al.* (2001) realized a numerical study to investigate the effects of buoyancy driven convection on constrained melting of PCM within spherical capsules. Their computational code is based upon iterative, finite volume numerical scheme in terms of primitive dependent variable. They found that buoyancy driven convection accelerates the melting process and that the Prandtl number in the range investigated from, 0.05 to 50, plays an important role during the melting process

K.A.R. Ismail *et al.* (2009) investigated that the working fluid temperature affects the solidification rate and hence the time for complete solidification. The reduction of the working temperature leads to reducing the time for complete solidification. Tests realized with different shell materials indicated that encapsulating materials of high thermal conductivity reduce the time for complete solidification.

Ettouney *et al.* (2006) realized an experimental study on spherical shells filled with PCM and some metallic beads to determine the effect of the metallic beads on the enhancement of heat transfer within the spherical shell. Their results showed a reduction of about 15% in the time for melting and solidification and similar increase in the heat stored in the spherical shells.

K.A.R. Ismail *et al.* (2009) presents the results of a numerical and experimental study to evaluate the suitability of different options for encapsulating PCM for cold storage modular unit intended for domestic applications. Spherical glass and plastic capsules, metal and plastic cans were also investigated because of their abundance, low cost and their ambient impact. The effect of increasing the diameter of the spherical shell is found to increase the time for complete solidification. Up to 0.076 m diameter, the increase is relatively small and in this case the dominant mode of heat transfer is conduction. As the diameter increases, convection in the liquid region moves the melt away from the solidifying front and hence increases the time for complete solidification.

The thermal characteristics of paraffin in a spherical capsule during freezing and melting processes were investigated by Cho and Choi (2000) Numerical analysis of latent heat thermal energy storage system was investigated by Vyshak *et al.* (2007) Review on thermal energy storage with phase change: materials, heat transfer analysis and applications are presented by Zalba *et al.* (2003)

Shih and Chou (1971) proposed an iterative method of successive approximation to study the solidification process in spherical geometry. Their results showed good agreement when compared with numerical data available except for high values of Stefan number and low Biot number.

Moore *et al.* (1982) studied the melting process of PCM within a spherical enclosure. The phase change material is initially considered at its saturation temperature. Suddenly the enclosure temperature is increased and consequently the melting process starts. Assuming that the solid density is more than the liquid density, the solid continually drops towards the bottom of the shell as melting progresses. A mathematical model is developed and the interface positions and the temperature profiles for various Stefan and Fourier numbers are determined and the energy storage characteristics are studied.

Bedecarrats *et al.* (1996) and Dumas *et al.* (1994) investigated the process of energy storage in a tank full with spherical capsules. In these studies they presented a mathematical model for the melting and solidification of the PCM in the spherical capsules and a simplified model for the charging and discharging of the storage tank. The proposed model includes a probabilistic study of the super cooling phenomenon in the spherical capsules.

K.A.R. Ismail *et al.* (2009) investigated that the time for complete solidification increases dramatically with the increase of the diameter of the shell. In the case of small spherical capsules up to 0.076 m, the variation of the solidification time with the increase of diameter and also with the variation of the temperature of the working fluid is relatively small. The dominant heat transfer mode in these cases is conduction. With the increase of the shell diameter convection currents grow stronger and the heat transfer is dominated by convection.

### *5.2 Effect of fins*

A common problem in latent heat thermal storages is the poor conductivity of the phase change materials. The crystallizing and thickening agents which prevent supercooling and phase separation in the PCM lower the thermal conductivity of the PCM and the inhibiting convection motion in the liquid PCM. Research work on increase of thermal conductivity of PCM is exhaustive. To show the effect of fins no of experimental work were carried out. During the phase change, the solid–liquid interface moves away from the heat transfer surface. Thus, the surface heat flux decreases due to the increasing thermal resistance of the growing layer of molten or solidified PCM. The problem arises especially in solidification processes where the sole heat transfer mode is conduction (Piia Lamberg, *et al*, 2003).

Fins have a greater influence on the solidification process than on the melting processes. If fins are near each other, the effect of natural convection decreases when conduction is the prime heat transfer mode in the melting process. Melting slows while solidification speeds up when fins enhance conduction in the storage (F. Talati, *et al*, 2011).

Reduction in charging time can be achieved by placing fins inside the encapsulations such that it protrudes to the centre, thereby aiding better heat transfer process. With the presence of fins, centre of the encapsulation reaches the external temperature at a faster rate than the radial portions of the encapsulation. Cylindrical encapsulation with slotted fins has proved to be the most ideal configuration in TES applications. Slotted fins placed in cylindrical configuration shows 72.27% reduction in total solidification time and for melting it is 51% of the same volume of PCM (Kalaiselvam Siva, *et al*, 2010).

To reduce the time for complete phase change two methods were investigated to enhance the heat transfer to and from the PCM elements that is, attaching fins on the tubes surfaces while the other is by inserting turbulence promoter inside the tubes (K.A.R. Ismail, *et al*, 2011).

Ehsan Mohseni Languri (2013) proved that the height of the external fins has a significant effect on the melting fronts surrounding each fin but has minimal effect on the region of PCM located between fins. The results of the study showed that the moving volume fraction (MVF) significantly increased by increasing the heights of the fins.

Velraj *et al.* (1999) investigated four different heat transfer enhancement techniques including tube with fins in a latent heat storage system using paraffin.

Ermis *et al.* (2007) studied heat transfer analysis of phase change process in a finned tube thermal energy storage system using a feed-forward, back-propagation artificial neural network algorithm. The authors compared the model results with numerical results from an experimental data and claimed better agreement for both laminar and turbulent flows in heat storage system with the experimental data, compared to the numerical model results.

Kalaiselvam Siva *et al.* (2010) investigate the phase change characteristics of finned encapsulations in heating, ventilation and air conditioning (HVAC) system for buildings. The effect of various fin configurations on moving interface position and complete solidification time was investigated for spherical and cylindrical geometries. Total solidification time was reduced by 65–72% on incorporating fins for different configurations. The slotted fin arrangement proves to be more effective with 72% reduction in charging time.

Agyenim *et al.* (2007) also investigated the most common and practical heat transfer enhancement techniques; circular fins, longitudinal fins and multitudes for both charging and discharging of Erythritol. The longitudinal finned system was recommended as the best overall performing system of the three enhanced systems.

Ismail *et al.* (1989) analyzed experimentally and numerically the case of vertical axially finned tube submersed in PCM by using the enthalpy approach, compared the numerical findings with experiments and found satisfactory agreement.

Solidification within two concentric cylinders having axial fins was studied by Padmanbhar *et al.* (1989). They obtained a correlation relating the solidified mass fraction to the fin thickness and length, the number of fins, the Stefan number and the Froude number. Agyenim *et al.* (2009) realized a comparative study on latent heat storage using bare and finned tubes and found that finned tubes exhibited the best performance.

Lamberg *et al.* (2003) simplified the two dimensional heat transfer problem to one dimensional one and derived an analytical solution for the melting process in a semi-infinite PCM storage unit with internal fins. Comparison with the experimental results showed good agreement.

Francis Agyenim *et al.* (2009) compared two practical heat transfer enhancement methods; circular finned and longitudinal finned systems with a control system with no heat transfer enhancement. Complete melting was achieved in the longitudinal finned system but not in the control and circular finned systems for an imposed 8-h charge time. The longitudinal finned system is recommended for the charging and discharge of Erythritol in a concentric tube PCM system because it achieved the best charge performance with insignificant subcooling during discharge. The circular finned system did not improve the heat transfer to the PCM over that in the control system sufficient enough to warrant further development. Based on temperature gradients in the axial, radial and angular directions in the three systems investigated, the experimental data has been shown to indicate most models that ignore the thermal conductivity in the axial direction.

Saha *et al.* (2008) experimentally studied the effect of pin–fin and plate-fin heat sinks saturated with n-eicosane at the operating powers of 4 and 8W. It was found that pin–fins are a more effective TCE than plate-fins due to the presence of natural convection cells that are in communication with each other. Results showed that an optimal volume fraction of pin–fins to PCM is 8% and that more pin–fins provide greater contact area between PCM and TCE and thus result in lower operating temperatures.

Velraj *et al.* (1999) experimentally studied the effect that a finned cylindrical enclosure had on solidification time and found that total PCM solidification time was reduced by 1/nfins, where nfins is the number of fins within the cylindrical enclosure.

Numerical computation was performed by H. Inaba *et al.* (2003) for the heat transfer characteristics of a rectangular latent heat storage vessel packed with nitric type molten salt. The obtained results revealed that the amount of transported heat through the fins increased with an increase in fin-thickness, and the heat release completion time period is shortened.. It was found that the effect of increasing the cooling area per unit latent heat storage material on the heat flux at the cooling wall with a decrease in fin pitch excelled that of the convection heat transfer. As a result, the completion time of heat release process decreased with a decrease in the fin-pitch.

Bugaje (1997) made experiments on the use of methods for enhancing the thermal response of paraffin wax heat storage tubes with the incorporation of aluminium fins and star structures. The conclusion was that internal fins performed much better than the star matrices by reducing time for loading and cooling.

Padmanabhan *et al.* (1986) presented a theoretical analysis for phase change in a cylindrical annulus with axial rectangular fins between inner and outer tubes. The finite-difference method was used. Based on the analysis, a working formula for the volume of the melt/frozen fraction for PCM was introduced for engineering purposes. The analysis also indicated that the addition of fins in the cylindrical annulus is advantageous for energy storage applications. The melting or solidification time decreases with an increase in the number of fins. The fins should be long and thin and they should be made of good thermal conductors.

Stritih *et al.* (2000) handled numerically and experimentally heat transfer enhancement in the solidification process in a finned PCM storage with a heat exchanger. The conclusion arrived at was that the biggest influence on heat transfer in the solidification process was the distance between the fins. The thickness of the fin is not as influential.

### *5.3 Effect of other parameters on PCM based ESS*

Other than geometry and fins the no of parameters remained are huge ones. The results show that higher inlet heat fluid temperature and higher mass flow rate of heat transfer fluid indicates shorter time for complete charging processes. The complete solidification time is too longer compared to the melting time. This is due to the very low heat transfer coefficient during solidification. The charging and discharging rate are significantly higher for the PCM capsule of smaller radius compared those of lager radius. The phase transition temperature range reduces the complete melting time; a difference of 31.7% is observed for the case when the PCM has melting in the temperature range as compared to that for a PCM with at fixed temperature (Zeinab S., *et al*, 2011).

Lafdi *et al.* (2008) investigated the merits of employing aluminum foam as a TCE for thermal management of electronics with a pulsed power profile. Results from numerical simulations indicate that performance of the foam/PCM composite is dependent on pore size, foam porosity, foam thermal conductivity, melting point of the PCM, latent heat of the PCM and viscosity of the liquid phase of PCM. It was shown that an increase in pore size extended the time of usable latent heat, while a decrease in pore size (and thus an increase in bulk volume of foam) decreased the maximum junction temperature and reduced the time of usable latent heat.

Ehsan Mohseni Languri (2013) investigated that Heat transfer enhancement in thermal energy storage systems was achieved by increasing surface area and aspect ratio. In heat transfer fluid direction plays a decisive role in charging and discharging processes of the thermal energy storage system. Small surface-to-volume ratio containers or enclosures that exhibit poor transient thermal performance. Significant enhancement in charging and discharging rates by as much as 9 times when compared to concentric systems due to the high surface-to-volume ratio of the PCM panels used in the study.

The effects of changing the HTF flow direction on the temperature profile and heat transfer enhancement of the TES system were studied. For HTF flow in the upward direction, it is anticipated that internal buoyancy effects can enhance heat transfer compared to the downward fluid flow case. Since the PCM at the bottom of the TES experiences phase change first when the HTF flows upwardly (Ehsan Mohseni Languri, *et al.* 2013).

Shuangmao Wu *et al.* (2012) shows in their results that the higher inlet temperature of the HTF results in the higher out temperature of the HTF, the higher cool release rate and the less time for complete discharging process .The larger diameter of coil pipes results in the higher outlet temperature of the HTF, the smaller cool release rate and the longer time for complete discharging process. Compared to inlet temperature and flow rate of the HTF, the diameter of coil pipes has little influence on the discharging performances of the cool storage system.

In place of foams or other solid matrices Fukai *et al.* (2000, 2002) studied the use of carbon fibers as a PCM enhancement. The carbon fibers used were 10 lm diameter and 5–200 mm long. The fibers were found to increase the effective thermal conductivity of the PCM.

Jun Fukai *et al.* (2002) shows that brushes made of carbon fibers are used to improve the thermal conductivities of phase change materials packed around heat transfer tubes. The transient thermal responses measured in brush/n-octadecane composites essentially improve as the volume fraction of the fibers and the brush diameter increase. However, there is a critical diameter above which further improvement is not expected due to thermal resistance between the fibers and the tube surface.

The heat transfer enhancement in the latent heat thermal energy storage system through dispersion of nanoparticle is reported Ali Akbar Ranjbar *et al.* (2011). The resulting nanoparticle-enhanced phase change materials (NEPCM) exhibit enhanced thermal conductivity in comparison to the base material. The effects of nanoparticle volume fraction and some other parameters such as natural convection are studied in terms of solid fraction and the shape of the solid-liquid phase front. It has been found that higher nanoparticle volume fraction result in a larger solid fraction. The results illustrate that the suspended nanoparticles substantially increase the heat transfer rate and also the nanofluid heat transfer rate increases with an increase in the nanoparticles volume fraction. The increase of the heat release rate of the nanoparticle-enhanced phase change materials shows its great potential for diverse thermal energy storage application.

Damien David *et al.* (2011) have developed a numerical model to evaluate several convective heat transfer correlations from the literature for natural, mixed and forced convection flows. The results show that the convective heat transfer highly influences the storage/ release process in case of PCM walls. For the natural convection, the numerical results are highly dependent on the correlation used and the results may vary up to 200%. In the case of mixed and forced convection flows, the higher is the velocity, the more important is the storage capacity. They had tested different correlations of the convective heat transfer coefficients for numerical modeling purpose.

The total melt fraction of the PCM in the bed for various values of Stefan number (heat transfer fluid temperatures) is shown in Fig.2. The time to reach the complete melting of bed (melt fraction of 100%) decreases as the inlet temperature of heat transfer fluid is increased. For the Stefan number of 0.2501 (Tin= 82 $^0$C), the time was shorter by about 42% to reach the melt fraction of 100% than that for the Stefan number of 0.1143 (Tin =70 $^0$C). This shows the melt fraction and the complete charging time are strongly affected by the inlet temperature of heat transfer fluid (Stefan number). Higher the Stefan number (i.e. higher inlet heat transfer fluid temperature) means the shorter of the time interval for complete charging (Zeinab S. Abdel-Rehim, *et al*, 2011).

The variation of total melt fraction of PCM as a function of time for different heat transfer fluid mass flow rates is illustrated in Fig.3. The curves rise to the complete melting position early with the increase in the mass flow rate. Higher the mass flow rate, the shorter the time interval needed for complete charging (Zeinab S. Abdel-Rehim, *et al*, 2011).

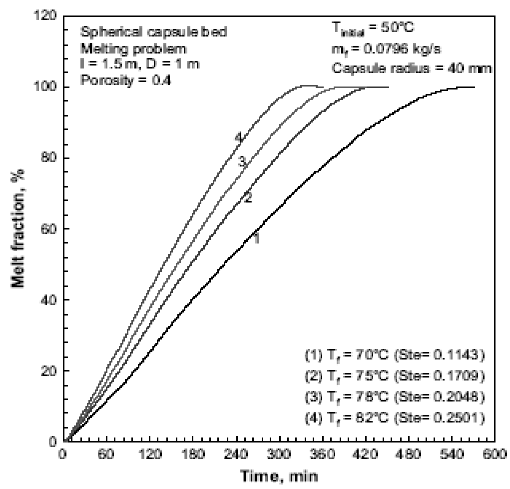


**Fig.2** Effect of heat transfer fluid temperatures (Stefan number) on melt fraction of the bed.

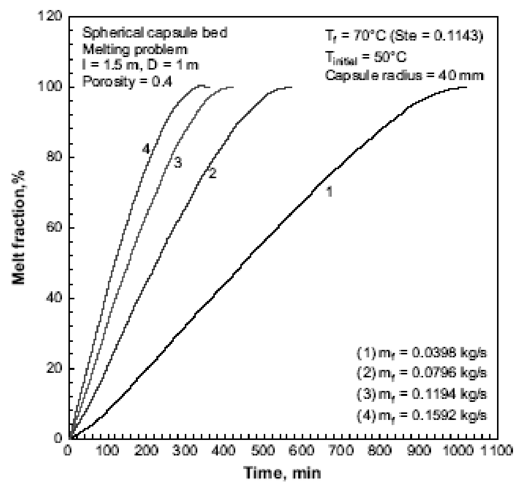


**Fig.3** Melt fraction with the time for various mass flow rate

## Conclusions

This review paper is focused on Melting and solidification phenomena of Phase Change Materials (PCM) encapsulated in different capsules. Melting rate of the solid depends on the shape of the capsule. Generally, elliptical capsules show higher rate of melting than circular ones. Elongated capsules provide more effective melting than oblate ones. The phase change period for the capsule at the edge of the storage tank was shorter than that at the center of the storage tank, because the porosity at the center was smaller than at the edge of the storage tank. Almost all results show that containers with fins enhance the thermal conductivity of Phase change Material. Fins have a greater influence on the solidification process than on the melting processes. Heat storage and release by system also depends upon initial temperature, mass flow rate and direction of flow of charging fluid. The influence on the average heat transfer coefficients due to the fluid inlet temperature and Reynolds number is more during the melting process, than the freezing process due to the presence of the natural convection effect of the melting process

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