CHAPTER 2

LITERATURE OVERVIEW

The latent heat thermal energy storage systems have gained more popularity in free cooling application of buildings in the recent years, due to its advantages discussed in the previous chapter. In the present work, a detailed survey has been made on the various aspects in this field of research, which includes thermal storage materials, various techniques available to improve the thermal performance of the LHTES, heat transfer enhancement through fin configurations, and other physical phenomena like natural convection and sub cooling during the solidification process.

2.1 THERMAL ENERGY STORAGE MATERIALS

One major area of research in the field of thermal energy storage is material investigation. Though the present research is not focused on the material side, an overview of the studies made on the LHTES materials are reported in the present section.

A broad review of research in the field of phase change heat storage, especially on salt hydrates, has been done by Lane (1983). This book gives a detailed account of the development of phase change materials, criteria for their selection and the chemical aspects of the phase change phenomena. A detailed review of low-temperature phase change materials has
been done by Abhat (1983). Fouda et al. (1984) studied the characteristics of Glauber’s salt as a heat storage medium in a pilot heat storage system. The effect of several variables is studied over many complete cycles of the unit and quantitative results are presented in terms of thermal recovery efficiencies and the volumetric heat transfer coefficient in the direct contact storage unit. Vaccarino et al. (1985) studied a low-temperature heat storage system utilizing mixtures of Magnesium salt hydrates and Ammonium nitrate as PCM suitable for practical exploitation in connection with commercial flat plate solar collectors. For the use of PCM in buildings applications, an encapsulation of PCM (50-80 %) with unsaturated polyester matrix (45-10 %), and water (5-10 %) were studied by Morkima et al. (1985).

Ghoneim et al. (1991) studied the behaviour of three phase change materials including sodium sulphate decahydrate, medicinal paraffin and P116 wax for the use of thermal storage walls in solar passive systems. The melting and freezing characteristics of the various organic and inorganic heat storage materials, classified as paraffin, fatty acids, inorganic salt hydrates and eutectic compounds are investigated by him using the techniques of Thermal Analysis and Differential Scanning Calorimetry. A study has been made by Hoogendoorn and Bart (1992) on organic phase change materials for thermal storage in solar systems. The latent heat effects of these materials are obtained from Differential Thermal Analyser (DTA) measurements. It is concluded that paraffinic phase change materials are attractive for use in solar heat storage systems for the temperature range of 25-150 °C. Gustafsson and Seterwall (1998) have studied the thermal properties of some paraffin waxes and their binary mixtures and the suitability of these materials for cool storage system in district cooling system.
Sharma et al. (1999) conducted experiments to study the change in latent heat of fusion, melting temperature and specific heat of commercial grade stearic acid, acetamide and paraffin wax subjected to repeated melt/freeze cycles. The study shows that acetamide and paraffin wax are found to be more suitable phase change materials. Dimaano and Watanabe (2001) investigated LHS system with capric and lauric acid mixture. The thermal performance and phase change stability of stearic acid as a PCM has been studied experimentally by Sari and Kaygusuz (2001) and they compared the heat transfer characteristics of the stearic acid with other studies given in the literature. Py et al. (2001) presented a new supported PCM made of paraffin impregnated by capillary forces in a compressed natural graphite matrix. Saito et al. (2001) performed an analytical and experimental investigation on a heat removal process of the thermal energy storage capsule, using gelled Glauber’s salt.

Dincer and Rosen (2002) and Farid et al. (2004) presented a detailed review on thermal energy storage with phase change materials, heat transfer analysis and applications. Cabeza et al. (2003) studied the suitability and thermal performance of sodium acetate trihydrate thickened with benotine and starch as phase change energy storage material. The addition of gellants and thickeners avoids segregation of these materials. A review had been carried out by Zalba et al. (2003) that focused on the materials, heat transfer analysis and applications of PCM based TES systems. They listed over 150 materials used in research as PCMs and about 45 commercially available PCMs. Nagano et al. (2004) studied the feasibility of a mixture of magnesium nitrate hexahydrate as a base material and magnesium chloride hexahydrate as
an additive to store and utilize urban waste heat from emerged co-generation systems.

He et al. (2004) used the liquid-solid phase diagram of the binary system of tetrade cane and hexadecane to obtain information of the phase transition processes for cool storage applications. The analysis of the phase diagram indicates that, except for minimum melting point mixture, all mixtures melt and freeze in a temperature range and not at a constant temperature. Shiina and Inagaki (2005) studied the enhancement of effective thermal conductivity of phase change materials by saturating it with porous metals. The authors concluded that considerable reduction in melting time was obtained, especially for low conductivity PCMs and for high heat transfer coefficient. Hoshi et al. (2005) investigated the suitability of high melting point phase change materials for use in large scale solar thermal electricity plants. Zukowski (2007) experimentally studied the paraffin wax (RT 56) as PCM enclosed in a polyethylene film bag for short term thermal energy storage unit.

2.2 TECHNIQUES FOR HEAT TRANSFER ENHANCEMENT

There are various techniques available to improve the thermal performance of the LHTES, such as the use of fin configurations, introduction of a metal matrix, graphite compounded material, lessing rings, the addition of high conductivity particles and nano particles, etc. Siegel (1977) had studied improvements in the solidification rate for PCM containing a dispersion of high conductivity particles. Though theoretical studies on the dispersion of high thermal conductivity particles result in better enhancement, there is no practical feasibility to disperse these particles in the PCM as it
segregates in the repeated cycling. However the introduction of nano particles in the PCM removes the above obstacle. Velraj et al. (1999) investigated three different heat transfer enhancement techniques, such as fin configuration, lessing rings and bubble agitation in a latent heat storage system, using paraffin. They compared the total solidification time and the total quantity of heat stored for the above said three configurations. They further reported that, comparing the volume fraction occupied by the fins and the lessing rings in their respective storage system, the latter contribute more volume, without a proportionate reduction in time for complete solidification. Further they concluded that lessing rings configuration is very useful in packed bed latent heat storage system and bubble agitation may be suitable for applications where heat transfer enhancement for melting is required.

Mehling et al. (2000) and Py et al. (2001) proposed a 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, but other advantages include a decrease in the sub cooling of salt hydrates and a decrease in the volume change of the paraffins. This technique is being employed in building material applications. Experiments were performed by Cabeza et al. (2002) in a small thermal energy storage device to study the heat transfer 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. Other methods in
building cooling applications was to embed the PCM in a metal matrix structure suggested by Tong et al. (1996) and the use of thin aluminium plates filled with a PCM, as developed by Bauer and Wirtz (2000).

Eastman et al. (2001) conducted thermal conductivity study on ethylene glycol dispersed with 0.3 % of 10 nm size copper particles and found that 40% enhancement of thermal conductivity over base material. In the above studies it was observed that nano particles suspended in PCM not only enhances the heat transfer rate, but also acts as nucleating agents to reduce the sub cooling of the PCM. It was stated that the ending time for latent heat storage decreased considerably by faster nucleating and improved thermal properties of nano fluid PCM. Kumaresan et al. (2012) observed that 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, upto a volume fraction of 0.6 %.

Chandrasekaran et al. (2012) reported 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 nanoparticles, 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. In the study carried out by Zhang et al. (2012), multiwall carbon nano-tube (MWCNT) particles were dispersed in an organic liquid (n-hexadecane), and reported that
with the addition of 0.1 wt% 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 nanoparticles for super cooling reduction, and better results cannot be obtained by continuously increasing the nanoparticle concentration. Kalaiselvam et al. (2012) compared the reduction in the solidification time of various PCMs embedded with alumina and aluminium nanoparticles to the pure PCM and showed that the solidification time for the 60 % n-tetradecane: 40 % n-hexadecane PCM dispersed with the aluminium and alumina nanoparticles were expected to reduce by 12.97 % and 4.97 % than at its pure form respectively. Besides, increasing the mass fraction of the nanoparticles beyond the limiting value of 0.07, the rate of solidification was not significant further.

2.3 HEAT TRANSFER ENHANCEMENT THROUGH FIN CONFIGURATIONS

Padmanabhan and Krishna Murthy (1986) studied the phase change process occurring in a cylindrical annulus in which rectangular, uniformly spaced axial fins spanning the annulus are attached to the inner isothermal tube, while the outer tube is made adiabatic. They performed the parametric analysis and based on the results, they suggested a working formula to obtain the volume fraction solidified at any time for this fin configuration.

Radhakrishnan and Balakrishnan (1992) carried out an analytical heat transfer study with a surface heat flux of 500 W/m² and above, on the freezing of the PCM and reported that the rate of growth of the freeze thickness was rapid up to 20 % of the distance from the wall, and then it
slowed down due to the increased conductive resistance from the increasing solid layers. Also, the solidification time decreased with the increasing heat flux, and then remained constant beyond a heat flux of about 1000 W/m$^2$. Lacroix (1993) presented a theoretical model for predicting the transient behaviour of a shell and tube storage test unit having annular fins externally fixed on the inner tube with the PCM on the shell-side and the HTF flowing inside the tube. The numerical results have also been validated with experimental data for various parameters like shell radius, mass flow rate and inlet temperature of the HTF.

Velraj et al. (1997) performed an experimental and numerical analysis of the enhancement of heat transfer in a PCM storage system consisting of a cylindrical vertical tube with internal longitudinal fin arrangement. A theoretical model that also accounts for the circumferential heat flow through the tube wall was developed using enthalpy formulation and employed in conjunction with the fully implicit finite difference method to solve the solidification in the convectively cooled vertical tube. A generalized enthalpy-temperature relationship developed by Date, that was suitable for constant phase change temperature, was modified in that work to accommodate materials having either constant or a range of phase change temperatures. The numerical model was validated with experimental data. Lacroix and Benmadda (1998) noticed during melting of PCM, that the onset of natural convection was gradually prevented as the distance between the fins was decreased. It was concluded that natural convection would exists if less number of fins were used. They also found that too large distance between the fins led to the reduction in total heat transfer surface area, and hence they optimized the number of fins for a fixed size of module.
Ismail and Melo (1998) developed a two-dimensional axisymmetric model for the formulation of the problem of fusion of PCM around a vertical cylinder in the presence of natural convection. The basic equations of mass, momentum and energy were formulated in terms of the vorticity and the stream function. The numerical predictions were compared with available experimental results showing good agreement. Also, the effects of the geometrical and operational parameters on the solid-liquid interface, stream function, energy stored and melt mass fraction were analysed. The model was extended to produce charts and correlations for the mean heat transfer rate, total solidification (or fusion) time in terms of the geometrical parameter, the modified Rayleigh number and the Stefan number. Velraj and Seeniraj (1999) reported that the internal fin configuration gives maximum benefit of the fin to the PCM farther away from the convectively cooled surface. The necessity to include the effect of circumferential heat flow through the tube wall for higher value of Biot number in order to correctly predict the heat transfer behavior was also emphasized. Further for a given quantity of heat to be extracted uniformly, a combination of lower Biot number and higher Stefan number (within the practical range) was recommended.

A numerical model, for the solidification of Phase Change Material around a radially finned tube with a constant wall temperature, was developed by Ismail et al. (2000). The model was based upon a pure conduction formulation and the enthalpy method. The finite difference approach and the alternating direction implicit scheme were used to discretize the system of equations and the associated boundary, initial and final conditions. The tube material as well as the tube wall temperature seemed to exert a strong effect
on the time for complete solidification. The equations were developed, for the
time for complete solidification based on the aspect ratio, number of fins and
half the phase change temperature range. The equations presented enable the
prediction of the performance under different conditions than analysed in the
present model.

An experimental study of enhanced heat transfer in melting and
solidification with 32 longitudinal fins was carried out by Stritih (2004) on
paraffin whose melting temperature is 30°C for thermal storage applications
in buildings. Time-based variations of the temperature distribution and heat
flux were explained from the results of observations of the melting and
solidification layers. The dimensionless Nusselt number was calculated as a
function of the Rayleigh number for natural convection in the paraffin for
both the melting and the solidification processes. The effectiveness of the fins
was calculated from the quotient of the heat flux with fins and that without
fins. Lamberg (2004) used approximate analytical model to analyse the two
phase solidification problem in a finned PCM storage system.

Liu et al. (2005) analyzed the thermal performance of PCM under
different heat flux conditions, to determine the influence of heat flux on the
melting processes. Experimental results showed that the fin improved the heat
transfer of melting process greatly. The enhancement mechanism of the fin is
attributed to its ability to improve both heat conduction and natural
convection very effectively. The influence of fin size and pitch on the
enhancement was also studied. 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 numerical results with the results of the
experiments and claimed better agreement for both laminar and turbulent flows in heat storage system with the experimental data than to the model results.

The effect of melt convection on the thermal performance of PCM integrated heat sink was investigated by Saha and Dutta (2008). A single domain enthalpy technique coupled with genetic algorithm (GA) was used to determine the optimized geometric parameters. The parameters were optimized for maximization of "safe" operational time of heat sink with complete utilization of PCM. First the various parameters were identified and dependence on operational time was studied. It was found that the optimum half fin width can be different for given heat flux and critical temperature if melt convection was considered in PCM. Castell et al. (2008) had studied performance enhancement of LHTES during solidification by adding external longitudinal fins to HTF while the PCM was stored in the inner tube. The study focused on calculation of heat transfer coefficient through which it was found that the heat transfer coefficient was not increased by the introduction of vertical fins; 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 the longer fins were used, the increase of the heat transfer area resulted in an increase of heat transfer rate, hence solidification time in the finned system was considerably less as compared to the unfinned system.

Agyenim et al. (2009) have designed an energy storage system using a horizontal concentric tube heat exchanger incorporating erythritol as PCM with a melting point of 117.7 °C. Three experimental configurations, a control system with no heat transfer enhancement, system augmented with
circular and longitudinal fins were studied. They reported that the system with longitudinal fins gave the best performance with increased thermal response during charging and reduced sub cooling in the melt during discharging. Murat Parlak and Ugur Etiz (2010) had carried out a study on thermal control of an electronic device using paraffin and salt hydrate as PCMs. To overcome the PCM conductivity shortcoming, pin fins have been machined in the aluminium enclosure so that PCM was in direct contact with fins. They concluded that in the whole equipment paraffin had caused 7 - 8 °C drop in temperature compared to results obtained without PCM. On the other hand, salt hydrate had given better result compared to paraffin due to lower melt temperature.

Transient three-dimensional heat transfer numerical simulations were conducted by Wang and Yang (2011) to investigate a hybrid PCM based multi-fin heat sink. Numerical computation was conducted with different number of fins (0 fin, 3 fins and 6 fins), various heating power level (2 W, 3 W and 4 W), different orientation tests (vertical/horizontal/slanted), and charge and discharge modes. The theoretical model developed was validated by comparing numerical predictions with the available experimental data in the literature. The results showed that the transient surface temperatures are predicted with a maximum discrepancy within 10.2 %. They concluded that the operation temperature can be controlled well by the attendance of phase change material and the longer melting time can be achieved by using a multi-fin hybrid heat sink.

Rajesh Baby and Balaji (2012) studied the results of an experimental investigation of the performance of finned heat sinks filled with PCM for thermal management of portable electronic devices. The PCM,
n-eicosane was placed inside a heat sink made of aluminium. Aluminium acted as thermal conductivity enhancer and the heat sink as a heat storage-spreading module. Experiments were conducted for heat sinks on which a uniform heat load was applied for the unfinned and finned cases. The test section considered in all cases was an 80 mm× 62 mm base with TCE height of 25 mm. A 60 mm× 42 mm plate heater with 2 mm thickness was used to mimic the heat generation in electronic chips. Heat sinks with pin fin and plate fin geometries having the same volume fraction of the TCE were used. The effect of different types of fins for different power level (ranging from 2 to 7 W) in enhancing the operating time for different set point temperatures and on the duration of latent heating phase were explored in this study. The results indicated that the operational performance of portable electronic device can be significantly improved by the use of fins in heat sinks filled with PCM.

### 2.4 SUB COOLING AND NATURAL CONVECTION DURING SOLIDIFICATION

The study carried out by Shamsundar and Sparrow (1974) inferred that the sub cooling of the PCM during solidification fritters away the advantages of isothermal operation. For most of the available PCMs, the Biot number (\( Bi = hR/k \)) becomes larger as the thermal conductivity is very low, and the surface temperature of the PCM drops within a short period after solidification is started, and this results in a very low heat flux thereafter. Therefore, a major portion of the heat is extracted at a very low temperature difference. Lowering the Biot number value can be achieved, either by decreasing the radius of the PCM storage tube, or by increasing the effective thermal conductivity of the PCM. As reducing the storage tube radius makes
it uneconomical, the use of proper heat transfer enhancement techniques in LHTES systems becomes necessary.

Choi et al. (1996) studied heat transfer characteristics of a PCM with circular fins. They concluded that the sub cooling of the PCM is larger at the bottom of the vessel due to low HTF temperature at that section, and it is severest in the finned system than the unfinned system. They also concluded that the heat transfer rate depends only on the inlet temperature of HTF and not on its flow rate, as the flow is turbulent irrespective of velocity within the tested parameters. The presence of circular fins is detrimental to the crystal growth during freezing. For unfinned system once the nucleation starts, crystal grows rapidly along the heat transfer surface. With the finned system the attached circular fins prevent the crystal growth and delays the occurrence of the transition point compared with the no finned system.

Velraj (1998) has introduced a parameter called the sub cooled factor, which is defined as the fraction of the solid sensible heat to that of the maximum energy stored, in the heat transfer enhancement study carried out on a LHTES system. He observed that the sub cooled factor (SF) increases with an increase in the Biot number. For a given Biot number, as the Stefan number increases, the solid sensible heat increases, whereas the SF decreases. This is because, the increase in the Stefan number due to an increase in the temperature difference, is utilized more for solidification than for sub cooling. However, the increase in the Stefan number due to an increase in the heat capacity with a constant temperature difference, is utilized more to extract sensible heat, than for solidification.
Experimental work carried out by Chen et al. (2000) concluded that when the inlet HTF temperature was -3 °C the nucleation of PCM (water) did not occur until after being sub cooled for a long period of time, which therefore failed to finish complete solidification within 9 hours. On the other hand, in -5 °C, the sub cooling of water almost did not appear and the entire charging process was finished within 9 hours. It was obvious that the inlet coolant temperature seriously affected the onset of the phase change of water, the sub cooling time of water and the total charging time. The lower inlet coolant temperature could reduce the sub cooling of water and the total charging time. In practical situations a low coolant temperature to promote nucleation was often required in order to establish reasonable heat exchange rates during periods of charging and discharging. When the inlet coolant temperature was set below the temperature of 0 % probability of nucleation, the increase of the coolant flow rate did not have any effect on the crystallization of the PCM. On the contrary, the larger flow rate could reduce the time of crystallization under the condition of inlet coolant temperature with 100 % probability of nucleation.

Royon and Guiffant (2001) conducted an experimental investigation on the heat transfer inside a sample of the emulsion of a mixture of alkane in water, which is suitable for thermal energy storage and transport. They reported that the variation of temperature as a function of time, and showed a stabilization temperature below the melting temperature, which was interpreted as a sub cooling phenomenon. They concluded that the fusion and crystallization temperature respectively were 9.5 °C and 3.9 °C which clearly showed sub cooling phenomenon. The same degree of sub cooling was obtained with the cooling rate of 1 K/min and 10 K/min. The latent heat of
fusion arrived through DSC analysis and through calculation matched very well within ± 0.5 % deviation. Experimental data obtained during cooling in an agitated tank were well simulated by a theoretical expression with three characteristic times. Practically, the obtained expression could be used to predict the time of complete crystallization.

Arkar and Medved (2005) conducted a DSC analysis 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 narrower and higher as well, which showed that the greatest part of the latent heat evolves in a narrow temperature range. The rate of PCM temperature change in the LHTES depended on the air flow rate and the temperature conditions at the storage inlet and the temperature difference between the air and the paraffin, respectively. This rate is important during the selection of an apparent heat capacity function, which should be determined based on measurements at approximately the same heating or cooling rate. A comparison of the numerical and experimental results carried out with a cylindrical LHTES system based on spheres with encapsulated paraffin showed that how the latent heat of the PCM evolves over the temperature range by a parameter described as apparent heat capacity, $c_{app}$. The apparent heat capacity included the heating or cooling rate as an additional influential parameter. It was also observed that the best agreement between the measured and numerical results
was obtained when the apparent heat capacity was calculated from DSC measurements at a heating/cooling rate of 0.1 K/min, which was the closest to the experimental conditions, during sensible cooling of the liquid paraffin.

Experimental and simulation study carried out to study the subcooling phenomena during solidification of a PCM by Gunther et al. (2007) observed two effects. Solidification was a process during which molecules from the liquid phase rearranged and became part of the solid phase. For every molecule that became part of the solid phase, a fixed amount of latent heat was released. That heat raised the temperature of the PCM surrounding the phase front. Depending on the transport properties of liquid and solid PCM, this temperature rise can increase the temperature at the phase front at most to the melting temperature. Had the heat transport been fast compared with the solidification, then the melting temperature was not reached during the phase change and the plateau was suppressed. These effects had a strong impact on the storage performance and should be considered in the design of storage systems. The time required for discharging the stored heat increased with increasing degree of subcooling. A second effect of the degree of subcooling was the buffering effect of the PCM, due to a delayed start of the phase change for strong subcooling. A large fraction of the PCM was cooled below the phase change temperature before the solidification was triggered. For the following increase in temperature to the melting temperature, some heat had to be used. This amount of heat was therefore not available to maintain the temperature of the PCM at the end of the plateau and the temperature fell sooner than in a case with less subcooling. For very large subcooling, the heat released by the phase change was not enough to heat the PCM to the phase change temperature and no plateau at all was obtained. The
temperature profile for different experimental criteria had a very good agreement between simulated and measured data.

On studying sub cooling in hexadecane emulsion, Gunther et al. (2010) analysed the effect of sample volume on sub cooling and solidification. The materials that showed macroscopically no sub cooling at all during solidification, sub cooling could be an issue in microencapsulated samples or emulsions. Different volumes of PCM, emulsions were prepared with different techniques, resulting in different droplet size distributions to investigate the effect of size (volume) on sub cooling. In an emulsion, it could be assumed that droplets behaved independent of each other, such that the thermal behaviour of the emulsion was caused by the multitude of its single droplets. They observed that the influence of the droplet diameter on the melting temperature was smaller than 2 K. There was a clear trend to lower melting temperatures with smaller droplet diameters. Apparently the effect increased as soon as the dimension of the droplet got below 2 µm. During solidification the observed influence of the geometric dimension was dramatic and reaches about 15 K for the emulsion with the smallest droplets. There is a clear tendency of an increase of sub cooling with decreasing droplet diameter.

Huang et al. (2010) experimentally studied the effect of sub cooling and nucleation in paraffin-in-water emulsions. The emulsions had a slightly lowered melting temperature and have a distinctly reduced nucleation temperature than the bulk PCM. The finely dispersed paraffins had nucleation temperatures 10 – 13 K lower than the bulk PCM. The nucleating agent used was a paraffin wax with a freezing point of 50 °C. There was a clear trend to lower melting temperatures with higher fraction of nucleating agent, up to 2 K lower for the sample with 10.0 wt% nucleating agent compared to that
without nucleating agent. The emulsion without nucleating agent had only one freezing peak at 2.6 °C. With addition of 0.8 wt% nucleating agent, two nucleation temperatures at 2.6 and 7.7 °C were observed. The nucleation temperatures increased quickly when the fraction of the nucleating agent rose to 3.0 wt%, then the higher nucleation temperature near 13 °C tend to be constant and the lower one between 9 and 10 °C slowly rose when the nucleating agent increases from 3.0 to 10.0 wt%. The sub cooling was reduced by about 12 K when the fraction of the nucleating agent reached 3.0 wt%. Droplet sizes and their distributions played a vital role both in the melting and nucleation temperature. The observed influence of the droplet diameter on the melting temperature was smaller than 2 K and the influence on the nucleation temperature reached about 15 K for the emulsion with the smallest droplets.

The experimental investigation carried out by Gunther et al. (2011) observed that the nucleation rate in small droplets could be dominated by homogeneous nucleation, which again depended on the droplet volume. Comparing hexadecane emulsions with different droplet diameters in the range of 0.5–20 µm, sub cooling was stronger by about 5 K for the smaller droplets. The peak form of the cooling measurements of some of the emulsified samples had differed significantly from their non-emulsified counterparts. For all samples, the freezing peaks were less steep than for the bulk material, the measurements on hexadecane with different surfactants and droplet sizes showed that the nucleation temperature depends on both parameters. The droplets of about 12 µm diameters emulsified with SDS showed a nucleation temperature similar to the droplets of about 1 µm emulsified with Tween 40. This was a clear hint that at least one of the
surfactants had some nucleating activity and a purely homogeneous nucleation that was shifted to lower nucleation temperatures with smaller droplet volumes was not the dominating nucleation mechanism.

Sparrow et al. (1978) performed an experimental investigation of a finned tube using four fins and they concluded that the use of fins could delay the natural convection during a solidification process. According to the authors, the presence of natural convection could delay or interrupt the solidification process and was deemed undesirable for the solidification process. Sparrow et al. (1981) investigated the freezing of a finned vertical tube when either conduction in the solid or natural convection in the liquid controlled the heat transfer using n-eicosane paraffin as a PCM. The authors concluded that the presence of fins brought an enhancement of freezing heat transfer on the tube surface between the fins.

Numerical and experimental investigation carried out by Ismail et al. (2001) in a model of a thermal storage system, with paraffin as PCM, solidifying around a vertical axially finned isothermal cylinder. They inferred that the number of fins, fin length, fin thickness, the degree of super heat and the aspect ratio of the annular spacing were found to influence the time for complete solidification, solidified mass fraction and the total stored energy. The results confirmed the importance of the fins in delaying the undesirable effects of natural convection during the phase change processes. The fin thickness had a relatively small influence on the solidification time, while the fin lengths as well as the number of fins had strongly affected the time for complete solidification and the solidification rate. The aspect ratio of the annular space had a strong effect on the time for solidification and also the
time for complete solidification. Lamberg (2004) used an approximate analytical model to analyse the two phase solidification problem in a finned PCM storage system, and concluded that the solidification was dominated by conduction while natural convection exists only during the beginning of the solidification process. Natural convection effect diminishes with respect to time, and it reaches almost zero as compared to the effect due to conduction.

Tay et al. (2012) experimentally and numerically analysed solidification of PCM (water) filled in a cylindrical tank in which HTF flows through the four coiled tube arrangement. They concluded that the freezing process starts from the bottom and ends at the top of the tank. During the freezing process, liquid PCM surrounding the tubes will be cooled first. Due to the effect of natural convection, the cold liquid PCM moves to the bottom of the tank while the hot liquid PCM moves to the top of the tank. In this way, the PCM at the bottom of the tank will be the first to be frozen. During melting process, since ice has a lower density, it will be floating at the top of the PCM tank, thus the top of the PCM tank will be the last to be melted.

The experimental work by Medrano et al. (2009) investigated experimentally the heat transfer process during melting (charge) and solidification (discharge) of five small heat exchangers working as latent heat thermal storage systems. Commercial paraffin RT 35 was used as PCM filling one side of the heat exchanger and water was circulated through the other side as heat transfer fluid. Average thermal power values were evaluated for various operating conditions and compared among the heat exchangers studied. When the comparison was done for average power per unit area and per average temperature gradient, results showed that the double pipe heat
exchanger with the PCM embedded in a graphite matrix is the one with higher values, in the range of 700–800 W/m²-K, which are one order of magnitude higher than the ones presented by the second best. On the other hand, the compact heat exchanger is by large the one with the highest average thermal power (above 1 kW), as it has the highest ratio of heat transfer area to external volume.

Experimental investigation carried out by Tay et al. (2012) on a three different configuration of tube-in-tank design filled with PCM for cold storage applications. The PCMs used were salt hydrate with phase change temperature of -27 °C and water. The average heat exchange effectiveness of the storage tank was determined and a characteristic design curve has been developed as a function of the measured average NTU.

The experimental validation for a computational fluid dynamics (CFD) model developed by Tay et al. (2013) for tubes coiled in a phase change thermal energy storage system has been conducted initially. Then using the validated CFD model, three CFD models were analysed for the freezing process. The first model was developed having pins embedded on a tube with heat transfer fluid (HTF) flowing in it, with PCM surrounding the tube and the second model developed was similar to the first model; however, fins were embedded instead of pins and the last model developed was a plain copper tube surrounded by PCM with HTF flowing in it. It was concluded that fins on the tube is better than pins on the tube.
2.5 INFERENCES FROM THE LITERATURE SURVEY

In recent years, the concept of free cooling has gained momentum in the field of Heating, Ventilation and Air Conditioning and green buildings. Since the temperature difference available for free cooling application is quite less, in the range of 3 °C to 4 °C, for both the discharging and charging sides, the sub cooling, suppression of free convection in sensible cooling, and the addition of fins have a great impact on heat transfer. Also, limited literature is available pertaining to the solidification heat transfer performance of PCM, whose melting / freezing temperature ranges from 20 °C to 25 °C. Considering the above, in the present study the heat transfer enhancement of a paraffinic PCM (having solidification temperature range of 19 °C to 22 °C) during outward cylindrical solidification in a double pipe heat exchanger, with the PCM filled in the annulus along with longitudinal fins, and air as the HTF passing through the inner tube, is experimentally investigated.

2.6 SPECIFIC OBJECTIVES

The specific objectives of the present research work are

i) to study, the heat transfer dynamics during solidification of the paraffinic PCM, with and without fin configuration.

ii) to investigate, the sub cooling effect and other major parameters influencing the solidification characteristics, and phase transition temperature of the paraffinic PCM, with in a short range of temperature that exists in the free cooling applications.
iii) to analyze, the heat transfer performance during solidification of the PCM, under various external conditions of the HTF.

iv) to analyze, the solidification performance with various practical ranges of thermal conductivity of the PCMs and heat transfer coefficient of the HTFs, using the experimentally validated equations, and also to analyse the circumstances where the nano enhanced PCM will be effective.