CHAPTER 2

LITERATURE REVIEW

The present review includes (i) Studies on solar water heating systems (ii) Thermal energy storage systems (iii) Stratification studies. The following aspects have been the focus of this review: Solar thermal systems, sensible and latent heat storage materials, theoretical and experimental studies on stratification and its applications.

2.1 SOLAR COLLECTION AND STORAGE METHODS

Solar thermal systems are useful in a variety of industrial and domestic applications. Solar thermal systems have been analysed based on energy, environment and economical benefits of its installation by several researchers. Karagiorgas et al. (2001) evaluated the economic and energy equivalent terms for applications of industrial solar thermal systems. Kalogirou (2004) presented several of the most common types of solar collectors and their applications. For low temperature applications, solar water heating is popular. Kalogirou (2009) presented the environmental benefits of thermosiphon solar water heating systems. Researchers have focused on efficiency improvements in solar thermal systems by variation in design and operating variables.

Shukla et al (2013) presented a review on the design aspects of SWH systems to improve the thermal efficiency of solar water heating. The review focussed on literatures pertaining to issues on refrigerant filled solar
collectors in a heat pump system. Raisul Islam et al. (2013) presented an overview of various types, design features, cost effectiveness and market potential of solar assisted water heating systems.

Hobbi and Siddiqui (2009) conducted an experimental investigation of the effect of different passive heat transfer enhancement techniques inside flat-plate solar collectors over a range of flow rates. A comparison of the twisted strip, coil-spring wire and conical ridges that were used as passive heat enhancement devices, showed no appreciable difference in the heat flux to the collector fluid. Michaelides and Eleftheriou (2011) investigated the behavior of the solar water heating system and the effect of temperature stratification in the storage tank under real weather conditions along with the effect of solar energy and hot water flow variations. They have indicated the predictable nature of the system’s thermal behaviour, and the average efficiency of the solar collector and its insensitivity to solar radiation fluctuations. It is inferred from the literature that point to a slight improvement in thermal efficiency of SWH’s by way of design modifications and change in operating variables. There is thus an enormous scope for efficient solar thermal conversion.

Thermal storage is the major technical constraint that inhibits the large deployment of solar thermal system technologies to a wide variety of applications, due to the intermittent and time mismatched demand and availability of energy. The various configurations of solar thermal storage tanks are shown in Figure 2.1. There are several research works on thermal storage systems, considering various aspects of the material, storage capacity, thermal performance, heat transfer studies and enhancement methods, in the case of latent heat thermal storage systems, and the integration of TES systems with the source and applications available in the literature. In the present review, the performance studies on LHS systems, and the
stratification aspects related to LHS and SHS systems are summarized and presented.

![Diagram of different types of solar thermal storage tanks]

**Figure 2.1 Different types of solar thermal storage tanks**

### 2.1.1 Thermal Energy Storage Methods

Energy storage is vital when the energy supply and consumption varies independently with time. Energy is supplied to a storage system for retrieval and use at a later time. There are three methods of storing thermal energy: sensible, latent and thermochemical heat or cold storage. Though thermochemical storage offers a larger heat storage capacity compared to sensible heat storage, the storage technology is still in the development stage. At present, latent heat storage is the most promising, due to the high storage density and isothermal phase transition from storage to retrieval. LHS units are particularly useful in solar thermal applications. Apart from solar energy, LHS units are implemented in building applications (Zhang et al. 2007), Antony Aroulraj and Velraj (2011), Zhou et al. (2012)), cold storage applications (Hasnain 1998, Cheralathan et al. 2007)). Velraj et al. (2006) explained the concept of using spherical capsules filled with PCM in a water/brine solution tank, that is successfully being adopted in storage based central air conditioning applications. The subsequent section deals in detail with various aspects of the solar thermal system.
LHS units are used in several solar thermal applications, such as Solar air heating (Fath (1995), Saxena et al (2013)), solar cooking (Buddhi and Sahoo (1997), and Muthusivagami et al (2010)), and green house heating (Kurklu (1998b)). A detailed description of the various aspects of thermal storage systems is presented by Dincer and Rosen (2002). Dincer and Dost (1996) presented the economical and technical evaluations of the storage techniques for solar thermal applications with TES. The solar thermal storage sizing is determined by the ratio of maximum to minimum monthly radiation. N’Tsooukpoe et al (2009) have presented the state of the art on sorption (absorption and adsorption) long-term solar heat storage and barriers in its implementation.

A review of the methods available for the seasonal storage of solar thermal energy in residential applications and the reduction in self discharge in sensible heat stores, have been discussed by Pinel et al (2011). Arteconi et al (2012) indicated that stratified water tanks can effectively be used as a load management technique due to the higher thermal efficiency of the storage tank. Li et al (2012) provided generalized charts for the design of thermal storage tanks. The need to develop a compact and economical storage system with maximum storage potential have thus been the focus of the researchers.

A packed bed latent heat storage system offers the advantages of higher storage density and lesser space. Saitoh’s (1983) investigation revealed that the spherical capsule performed better in comparison to other capsules of different shapes. Saitoh and Hirose (1986) performed transient thermal characteristics analysis of a LHS unit. The authors recommended the use of plastic as capsule material for practical applications. For cost reduction, Ismail and Henriquez (2002) too have advocated the use of PVC material for PCM encapsulation. Barba and Spiga (2003) found that small spherical capsules have the shortest time for solidification during the discharge process.
of the LHS system. Felix Regin et al (2008) presented a review of various PCM encapsulation techniques and heat transfer studies in a packed bed system. Nallusamy et al (2009) investigated the thermal performance of a packed bed combined sensible and latent heat storage unit shown in Figure 2.2, integrated with the solar flat plate collector.

Felix Regin et al (2009) numerically investigated the effects of the HTF inlet temperature, the mass flow rate, the phase change temperature range and the radius of the capsule on the dynamic response of a packed bed latent heat thermal energy storage system, using spherical capsules for both the charging and discharging modes. Arias et al (2008) investigated the sensitivity of the long-term performance simulations of solar energy systems to the degree of stratification in both liquid and packed-bed storage units. They observed that only a relatively smaller number of nodes such as five for a water storage tank are needed to accurately simulate the annual performance of a solar system.

Figure 2.2 PCM based packed bed storage system
Source: Nallusamy et al (2009)

Singh et al (2013) analysed various analytical and experimental studies conducted on the performance analysis of the packed bed. Fang et al
(2010) reported better performance, and stable charging and discharging periods of an experimental cool storage air-conditioning system, with a spherical capsules packed bed. Wu and Fang (2011) numerically investigated the thermal discharging characteristics of a packed bed, containing PCM encapsulated spherical capsules and water as the HTF. They concluded that the inlet temperature and mass flow rate have a strong influence on the heat release rate and solidification time. They further added that initial temperature of the packed bed had no significant effect on latent efficiency while there was no significant effect on solidification time and heat release rate.

Karthikeyan and Velraj (2012) compared three numerical models for a packed bed latent heat storage system with air and water at different mass flow rates and ball sizes. Oro et al (2013) compared and validated Brinkman’s equation model and energy equation model of a packed bed storage with PCM, during the cold charging of the PCM. It was concluded that Brinkman’s equation model accurately described the fluid flow of the TES system.

Wei et al (2005) investigated numerically and experimentally a plate heat exchanger that was used as a heat storage tank. The PCM was filled into the channels on one side of the heat exchanger in different arrangements, and the working fluid flowed in the channels on the other side of the heat exchanger. The spherical capsule showed the best heat release performance among the four types of investigated capsules, whereas the tubular capsule with low void fraction was not ideal for rapid heat release of the thermal energy stored in the PCM. For the spherical and cylindrical capsules, the heat release performances were almost independent of the void fractions. The general observations drawn from the various studies demonstrate that, spherical capsules were favoured in a packed bed configuration for efficient storage. It is evident from the literatures that the selection of appropriate PCM
and operating variable such as mass flow rate are crucial for energy efficient storage.

2.1.2 Thermal Energy Storage Materials

In a latent heat storage system used for solar energy storage, energy is stored during melting, and recovered during the freezing of a Phase change material (PCM). Among the various PCMs, paraffins have been widely applied for latent heat energy storage, due to their large latent heat capacity and good thermal characteristics, such as little or no supercooling, low vapour pressure, good thermal and chemical stability, and self-nucleating behavior (Abhat (1983) and Dincer and Rosen (2002)). Hydrated salts are also used as PCM for solar thermal applications. Canbazoglu et al (2005) investigated experimentally by combining SWH with sodium thiosulfate pentahydrate, and theoretically examined the storage performances of other salt hydrates, and compared the enhancement of solar thermal energy storage with the conventional SWH System.

Though the energy storage density is higher in the PCM, poor thermal conductivity is its negative feature. Different enhancement techniques such as the inclusion of fins (Abhat (1981), Velraj et al (1997)), graphite nanofibers (Chintakrinda et al (2011)) are attempted to improve the PCM thermal response. Mettawee and Assassa (2007) investigated experimentally the addition of aluminum-powder to paraffin wax, to improve its thermal conductivity. It was found that the charging time was reduced by approximately 60% by adding aluminum powder in the wax.

Mazman et al (2009) investigated the effect of using PCM modules in a 150 Litre solar hot water tank. PCM-graphite compounds with 80:20 weight percent ratio mixtures of paraffin and stearic acid, paraffin and palmitic acid, and stearic acid and myristic acid, were used for the purpose. In
the cooling experiments, the average tank water temperature dropped below the PCM melting temperature range in 6–12 hours. The percent recovery efficiency of the paraffin and stearic acid was better than that of the Paraffin and Palmitic acid. Tian and Zhao (2013) reviewed various types of solar collectors and the design criteria, materials and heat transfer enhancement techniques for high-temperature thermal energy storage systems. Molten salts were considered to be the ideal materials for high-temperature thermal storage applications and graphite composites and metal foams were found to be the ideal materials for heat transfer enhancement. Jegadheeswaran and Pohekar (2009) presented a review of the performance enhancement in a latent heat thermal storage system, and cited considerable performance enhancement in an LHS system, embedded with fins or with dispersed metal particles. Agyenim et al (2010) reviewed the different heat transfer solution methods employed by different researchers based on the theoretical, experimental and numerical studies that have been conducted considering the thermophysical properties of the phase change materials. Dutil et al (2011) reviewed numerical models based on the first and second law, for various PCM problem geometry and applications. They stressed the need to match the numerical solutions with the experimental results.

Sensible heat storage materials are inexpensive and have higher thermal conductivities, when compared to the PCM for solar applications. The PCM degrades with thermal cycling especially at high temperatures, and thus it cannot be used effectively for long-term TES applications. A single phase sensible heat TES system is usually expensive to operate, as a much larger volume of material is required to store the same amount of energy, in comparison to latent heat storage, and hence, dual phase systems have been applied for different solar thermal applications (Hanchen et al (2011)). Air, water, liquid sodium and heat transfer oil are used as the HTF, and pebbles, rocks, aluminium oxide and other sensible solid materials are used in the dual
phase. Air as the HTF poses the problem of a large-sized heat exchanger and high pump power requirement, to store large amount of heat due to the low density of air.

A liquid offers the advantage of a lower vapour pressure and allows for the use of a low cost storage tank. In the dual phase system, solid pebble bed storage materials are popular, as the pebbles that make up the storage are readily available, cheaper, and pebbles can replace a considerable fraction of the HTF. Water has an excellent heat capacity but is limited to lower temperatures as it vaporises at 100°C, requiring pressurizing equipment to be used for temperatures above its boiling point. Hence, heat transfer oils that have low heat capacities than water are used for TES systems, as applied at the solar thermal power station (Bindra et al (2013)). Though heat transfer oils are expensive, they reduce the need for expensive pressurizing equipment. Gil et al (2010) listed the properties and cost of solid-state, molten salts and thermal oils, that are used as high temperature sensible heat storage materials. The summary of the storage capacity and temperature range for some of the important potential storage materials are given in Appendix 1. Literatures have shown that HTF properties and storage materials characteristics play a key role in the performance of a storage system. However, the performance of the different systems (Sensible and Latent) having similar geometric features have not been studied at length.

2.2 STRATIFICATION IN THERMAL STORAGE

Thermal stratification is essential for storage to be energy efficient as it improved the overall solar thermal system performance. The studies on stratification to maximize storage performance, and hence, the overall system, have received much attention in recent years. All the research works relevant to the stratification performance and parametric analysis, and the modelling and numerical analysis of sensible and latent heat storage systems suitable for
a conventional hot water storage system, are presented under this category. Further, the stratification studies performed on modified storage tank configurations and other applications are also summarized under a separate section.

2.2.1 Stratification Enhancement Studies

The present section deals with reviews of literatures pertaining to different methods adopted by the researchers for stratification enhancements. Most of the researchers have attempted experimental investigations for stratification enhancement through geometrical modifications in the storage tank, such as the inlet, outlet locations, multiple tank configurations, introduction of obstacles, partitioning of tanks and placing diffusers. Recently attempts were also made through phase change systems inside the storage tank, to improve the stratification performance. These studies were summarized under the following two subsections.

2.2.1.1 Geometrical configurations

Several geometrical configurations have been proposed by some of the researchers to minimize mixing and aid thermal stratification. Hugo et al (2010) proposed the use of stratifiers as shown in Figure 2.3 to enhance stratification. Figure 2.4 shows the presence of baffles in the storage tank near the inlet pipe, that lets hot water inside the tank to aid stratification. Mather et al (2002) adopted the use of multi tanks, as shown in Figure 2.5, to improve stratification. They demonstrated the advantageous features of improved stratification and thermal diode effect at the laboratory level, for a multi tank system compared to a single tank system. Multitanks however suffer disadvantage of larger space requirement and higher initial cost. Aiding stratification through fluid inlet design to distribute heat at the correct level, and limiting destratification by the presence of baffle plates, have also been undertaken by researchers. The experimental study of Lavan and Thompson
(1977) on stratified hot water storage tanks concluded, that stratification increased on increasing the height-to-diameter ratio of the tank, increased temperature difference between the inlet and the exit water, increased pipe diameters at the inlet and outlet located near the end walls and reduced flow rates.

Helwa et al (1995) concluded that thermal stratification was dependent on the hot water consumption load pattern, and the thermal performance of a horizontal storage tank was inferior, compared to a vertical one. Ryu et al (1991) have pointed out that a vertical tube system had better thermal performance than a horizontal one, as the thermocline of the HTF in the vertical tube system reduced the thermal resistance of the solidified PCM. Hegazy (2002) tested three different side-inlet geometries: namely, wedged, perforated, and slotted pipe-inlets, as shown in Figure 2.6, using two 50 L capacity electric water heaters of aspect ratios of 1 and 2, and two discharge rates of 5 and 10 L/min. It was reported that the designs were successful in promoting good thermal stratification inside the storage tanks. They further indicated that electric water heaters perform more effectively, using tanks of higher aspect ratios and low draw-rates. Also, it was observed, that slotted inlets exhibited best thermal performances, which were consistently the closest to the perfectly stratified behavior. Literatures reviewed have shown a superior performance by the presence of stratifiers and baffle plate. However yet its benefits and drawbacks on long term operation have not yet been widely reported.
Figure 2.3 Presence of stratifiers to improve stratification

Figure 2.4 Presence of baffle plates to improve stratification
Source: Han et al (2009)
In order to effect thermal stratification, a modified inlet design was made by Li and Sumathy (2002), and the tank was partitioned, with the upper part having one-fourth volume of the entire tank. Four stratified segments under four modes were compared, to study the performance for solar operated air conditioning systems. They have indicated that the system operating in the partitioned mode can provide the solar absorption based cooling effect, much
earlier compared to the conventional whole-tank designs, and achieve a higher system coefficient of performance. Rhee et al (2010) have experimentally measured the stratification in a solar hot water storage tank, employing a double chimney device that acts as a thermal diode. The sketch of the thermal diode employed in the experiment is shown in Figure 2.7.

It was reported that the express elevator method that directs the hot water from the bottom of the tank to the top exhibited better stratification, than a baseline fully mixed tank. However, the single and double-diode configurations exhibited reverse stratification during heating while improved stratification was exhibited during cooling in all the three modified designs. However its effect on a larger capacity system needs to be investigated for implementing in various applications.

Figure 2.7 Thermal diode configurations examined in the study a) fully mixed tank b) single diode c) double diode d) express elevator. Source: Rhee et al (2010)
Mondol et al (2011) described the operating performance of a novel heat exchange unit called ‘Solasyphon’ developed for solar hot water applications. The Solasyphon unit is shown in Figure 2.8. The hot fluid from the solar collector enters into the ‘Solasyphon’ (point B) through the primary flow pipe, circulates through the internal annular section, and returns to the solar collector through the primary flow return (point H). They have indicated that in the ‘Solasyphon’ system, the heat retention in the upper layers within the store is better than that of the ‘coil’ system under the stratified condition, resulting in less disruption to any hot water stored in the upper storage volumes. Complicated system configuration however remains its negative feature.

![Figure 2.8 Schematic Diagram of a Solasyphon unit](source: Mondol et al (2011))

Tests for the stratification of a pressurized thermal storage unit by Al-Marafie et al (2005) revealed that the extraction efficiency for long periods of storage is decreased primarily as a result of thermal loss to the environment.
and, to a lesser extent, the short-circuit between the hot and cold zones, caused by conduction through the walls and thermal storage fluid, and the lack of improvement in thermal extraction efficiency by increasing the ratio of length to diameter larger than 4. Furbo et al (2005) showed that the thermal performance of the solar storage tanks can be increased by using two draw-off levels, from the middle or just above the middle of the solar tanks, instead of one draw off level at a fixed position. Shah et al’s (2005) investigation of Particle Image Velocimetry and temperature measurements on a rigid stratifier, showed that the performance of the system with flaps in the stratifier, is better in comparison with the rigid stratifier. Stratifier with flaps is innovative but its ability to deliver superior performance needs to be investigated for wide range of mass flow rates and temperatures.

Haltiwanger and Davidson (2009) investigated the effect of a cylindrical baffle, on the storage side convective heat transfer of an immersed heat exchanger in a solar thermal storage tank. The baffle presence restricted the growth of the descending plume within the annular region, and minimal thermal stratification was developed within the bulk storage fluid.

Arefmanesh et al (2009) reported a stable thermal stratification in the reservoir throughout the entire withdrawal cycle, in their analysis of the thermal characteristics of an underground cold-water reservoir. Wade et al (2009) have recommended that a divided storage may be used to maintain high outlet temperatures longer, than in a conventional tank of the same total volume, if the NTU of the heat exchanger is greater than 3, whereas baffles are useful regardless of the NTU.

Karim (2011) observed that stratification instability and mixing increases with increasing flow rates. He further added that diffusers should be designed, based on the Froude number = 1 and an equal pressure drop. Lower Froude numbers cause unequal pressure drop and hence, unequal flow from
different openings. It was concluded that octagonal diffusers have better performance than distributed diffusers. Brown and Lai (2011) through the flow visualization experiments concluded, that a porous manifold is able to reduce the shear-induced mixing between fluids of different temperatures, and thus is able to promote and maintain a stable stratification.

The effects of reverse thermosyphoning during periods of low solar input in single storage tanks, and the carryover of energy in a multitank thermal storage were investigated by Cruickshank and Harrison (2011). In a series connected multitank TES, reverse thermosyphoning in the upstream storage tank, will result in heat being removed from the upstream tank leading to destratification in the upstream TES.

A mantle tank is a cylindrical storage tank surrounded by an annulus, through which hot liquid from the collector flows, thereby transferring energy to the tank contents. Knudsen (2002) showed that mixing during draw-offs has a stronger negative impact on the thermal performance of spiral tank systems, than on the thermal performance of mantle tank systems. In tanks fitted with surface heat exchangers, better stratification is expected due to less turbulence. Knudsen and Furbo (2004) suggested improvements in the mantle tank design, by increasing the height/diameter ratio, reducing the mantle height, increasing the insulation thickness on the sides of the tank and using stainless steel instead of steel as the tank material. Vertical mantle heat exchangers are preferable for better stratification.

Kenjo et al (2007) have predicted thermal stratification within a mantle tank of solar domestic hot water systems, by adopting the zonal approach and compared with the experimental results. Dehghan and Barzegar (2011) numerically studied the transient thermal behavior of a vertical storage tank employed in a domestic solar water heating system, with a mantle heat exchanger, during the discharging/consumption operation. It was noticed that
the large tank’s inlet/outlet opening sizes resulted in undesirable mixing in the top hot region of the tank and a rapid drop in the consumption flow temperature, during the discharging period. The study confirmed better thermal stratification for higher values of the Grashof number, and lower inlet Reynolds number.

Experimental results of horizontal mantle heat exchangers by Jannatabadi and Taherian (2012) showed, that the turbulent mixing during the hot water extraction from the storage tank had a significant effect on the thermal performance of mantle tank systems, due to the degradation of temperature at higher flow rates. It was concluded that the thermal efficiency of the storage tank was critically impaired by the effect of the short circuit phenomenon and mixing, caused by turbulence.

2.2.1.2 Phase change systems

Mehling et al (2003) conducted experiments by adding a PCM module at the top of the water tank to enhance stratification. The experimental results were used to quantify the stratification in terms of non-dimensional numbers. This resulted in higher storage density, allowing reheating of the transition layer after partial unloading, and compensation of the heat loss in the top layer for a considerable time. Cabeza et al (2006) showed that the energy density of the hot water storage tank with stratification, increased with increasing amounts of the PCM modules at the top of the tank, as shown in Figure 2.9.

Castell et al’s (2009) experimental comparison revealed a similar stratification between a water tank and a PCM-water tank. It was also stated, that the Richardson number reflected stratification better than the MIX number due to its sensitivity to very small differences in the tank temperature
profile. Ordaz-Flores et al (2011) compared a closed two-phase Change System thermosyphon, to heat water with a conventional domestic solar water heating system. The schematic representation of the experimental Phase Change System is shown in Figure 2.10. The stratification profile in the thermo tanks was higher in the Phase Change System than in the domestic solar water heating system. To obtain a high stratification profile it was suggested to place the coil at the lowest part possible of the thermo tank, to transfer heat at a major temperature difference.

Figure 2.9 PCM to improve energy storage

Source: Cabeza et al (2006)
Huang et al (2011) examined the thermal performance of Phase Change Slurry heat storage, with different rates of heat input, to enable improved system designs to be developed for the intermittent thermal energy storage for residential applications. The test system as shown in Figure 2.11, consists of small micro-encapsulated PCM particles suspended in the carrier fluid termed Phase change slurry inside a helical coil heat exchanger.

They observed thermal stratification above the heat exchanger, and slurries with 50% volume concentration were found unsuitable for the heat storage applications tested, due to the low rates of heat transfer resulting from the suppression of natural convection and mixing in the store. However the stratification performance in phase change system is still under development and more research is required to conclusively prove its benefits.
2.2.2 Theoretical Studies

Theoretical investigations of stratification have been divided into three sections. In the first part, the investigations made, using the mathematical modelling methods are discussed. The second part deals with the stratification performance evaluation by the use of software.

2.2.2.1 Mathematical modelling

Finite difference model and finite volume method were used by various researchers to predict the temperature distribution in forced and natural circulation system of solar water heaters for different operating parameters suitable for domestic applications. A one dimensional explicit finite difference model was developed by Oppel et al (1986) to simulate the behavior of a stratified thermal storage system While some of the models proposed in the literature are simple one-dimensional models (Wildin and Truman (1989), Zurigat et al (1991)) most of the other models are two dimensional turbulence model (Cai et al (1993), Mo and Miyatake (1996),
Spall (1998)) with water as the HTF. Zurigat et al (1989) carried out a survey of the stratified thermal storage one-dimensional models available in the literature. They have validated six models with the experimental data, obtained at their laboratory and from the literature, conducted under both constant and varying inlet fluid temperature conditions.

The models include the fully stratified storage tank model, a modified version of this model, the viscous entrainment model, and the effective diffusivity model. The models showed varying degree of agreement with the thermocline test data. Al Najem (1993) developed a theoretical model based on the integral transform technique to simulate the thermal behaviour of stratification. They have said that thermal diffusion and axial wall heat conduction have led to more heat loss to the ambient, thereby degrading the stratification.

Van Berkel (1996) ascribed mixing inside thermally stratified stores to fluid withdrawal from the thermocline by the viscous drag, and the subsequent mixing to active diffusion by the stretching and folding of fluid particles. Ghadder et al (1989) examined a one-dimensional problem using a numerical finite difference method. They showed that the turbulent mixing factor is greatly dependent on the flow rate, the inlet port design, and the thermocline location in the tank. Ghaddar and Al-maarafie (1997) compared the one-dimensional plug flow model and the two dimensional axisymmetric spectral element simulation with experiment. The numerical analysis on hot water store by Hahne and Chen (1998) revealed, that the modified Richardson number, Peclet number and aspect ratio influenced the charging efficiency and stratification of the store.
Eames and Norton (1998) proposed a transient three-dimensional finite-volume based model on a hot water store, and reported that cross sectional geometries had little influence on the thermocline development, when subjected to low velocity inlet jets. Homan and Soo (1998) computed the relationship of the analytic model to the thermal efficiency of a stratified storage tank under laminar flow conditions. They suggested the use of the effective diffusivity factor to quantify the level of thermal mixing at any stage of the charging and/or discharging processes. Nelson et al (1998) proposed a one dimensional model incorporating axial wall conduction, thermal diffusion, heat transfer with the ambient, and the effects of fluid mixing on temperature. Yoo et al (1999) described the thermal behaviour during charging by analytical solutions to the two-region one-dimensional model of a stratified thermal storage tank with variable inlet temperature as well as momentum-induced mixing.


Zachar et al (2003) in their analysis on the diffuser plate situated opposite the inlet indicated, that the plate diameter had little impact, but moving the thermocline closer to the plates resulted in the diameter having a greater influence, to preserve stratification even at larger inlet flow rates. The numerical simulations by Oliveski et al (2003) on vertical tanks showed the
dependence of the natural convection heat transfer from the tank to the tank aspect ratio, the thermal loss to the environment, and the difference between the average temperature of the tank and the environmental temperature.

Shin et al (2004) through their numerical and experimental works concluded that the increase in charging time lowers the degree of stratification, and that the performance of a larger system is better than that of a smaller one. Spall (1998) employed both $k$-$\omega$ and the full Reynolds stress turbulence closure models for a numerical study of the transient mixed convection in an axisymmetric cylindrical storage tank, and indicated that the latter method resulted in considerable thinning of the thermocline. Numerical simulations on radial diffusers by Chung et al (2008) revealed that the Froude number’s contribution is negligible, and the Reynolds number and diffuser shape play a significant role in the performance of a stratified thermal storage tank. Mawire et al’s (2009) modified version of the Schumann model simulation results indicated, a greater degree of thermal stratification and energy stored, when using constant-temperature charging than when using constant-flow rate charging.

Gopalakrishnan and Srinivasa Murthy (2009) presented a numerical study of transient, two-dimensional, mixed convective heat transfer and flow characteristics in stratified hot water storage. The numerical results indicated that as the Rayleigh number increases, mixing decreases. For a specified Rayleigh number, increasing the flow rate increases the mixing, and hence, this decreases the discharging efficiency. Kousksou and Bruel (2010) stressed the need for mathematical optimization procedures when designing a PCM based practical storage system, due to its complexity and multi-parameter sensitivity. Geczy-Vig and Farkas (2010) developed and installed an internal heat exchanger in the storage tank of a hot water system. An artificial neural
network model was developed to describe the thermal stratification in a solar storage tank and at low flow rates; the thermocline degradation was affected by the axial wall conduction.

Al-Hinti et al’s (2010) experimental investigation of the performance of water-phase change material storage for use with conventional solar water heating systems resulted in extending the effective operational time of the system. The Phase Change Slurries inside the helical coil heat exchanger in a solar storage tank, were unsuitable for a solar heat storage system claimed Huang et al (2011), due to low rates of heat transfer. De Gracia et al (2011) measured the water temperature profiles along the vertical plane, during the heat discharge from the PCM inside the vertical tubes, did not show stratification inside the tank.

Numerical simulations were also carried out by researchers for storage system with different devices/modifications to improve stratification performance. Savicki et al (2011) performed the numerical simulation of a diffuser plate configuration for a horizontal storage tank, and observed better thermal stratification. Glembin and Rockendorf (2012) analyzed the effects of different discharging and charging strategies on the performance of a combined solar thermal system through simulations. They have indicated that while the stratified charging leads to higher solar heat gains, and the net utilized solar energy values in a system with a lower solar fraction, the benefit of stratified discharging is higher for the system with a higher solar fraction. Palacios (2012) conducted experiments and developed a model to study the effects of the hydrodynamic and thermal characteristics of both singular and dual inlet jets on the temperature field in the tank.
They investigated thermal mixing caused by the inflow from one or two round, horizontal, buoyant jets in a water storage tank that was part of a thermal solar installation. Nizami et al (2013) developed a new empirical model and compared its predictions with the experimental results, as well as to detailed CFD modelling results, for a domestic hot water tank system.

2.2.2.2 Use of Software

Software has been employed to study the heat transfer phenomenon in solar collection and storage. Selmi et al (2008) simulated the heat transfer phenomena in flat-plate solar collectors, using commercial CFD codes, and their results achieved good agreement with the test data. Alizadeh (1999) numerically investigated the thermal behaviour of a horizontal tank by one dimensional turbulent and displacement mixing models, and validated it with the experimental results. It was reported that the thermal stratification was enhanced using the divergent conical tube as the inlet nozzle. The CFD simulation using parallel computers as a tool for virtually prototyping thermal storage tanks was adopted by Consul et al (2004). The exergy method of stratification evaluation was suggested as an alternative to the MIX number. Altuntop et al (2005) carried out a numerical analysis of the effect of placing various types of obstacles in a solar hot water tank, as shown in Figure 2.12 for thermal stratification. Obstacle numbered 11 provided the best thermal stratification in the tank, followed by obstacle number 7, while the other obstacle types had little effect on improving stratification. Jordan and Furbo (2005) TRNSYS model in a storage tank after draw-offs showed, that the thermal stratification inside the tanks depends differently on the flow rate, the draw-off volume, as well as the initial temperature in the storage tank.
Figure 2.12 Obstacle geometries and their assembly in the tank proposed by Altuntop et al (2005)

In the CFD simulation on the mantle tank carried out by Altuntop et al (2006) better thermal stratification prevailed, at an increased water flow rate, at the mantle inlet. Andersen et al (2008) presented the thermal behavior of different modern stratification devices with fabric and rigid pipes. They performed numerical calculations using CFD, to predict the thermo-hydraulic behaviour of the device and validated it with measuring methods, such as particle image velocimetry and laser-induced fluorescence, for the assessment of the stratification devices considered. Goppert et al (2009) analyzed the arrangement of the charge system in the tank using a model implemented in Matlab and compared it with the experimental and CFD calculations.

Trinkl et al (2009) developed a Matlab model and identified the collector area and latent heat storage volume as the predominant parameters for dimensioning a solar/heat pump heating system. Simon and Wenxian (2009) conducted a numerical study of the three dimensional flow dynamics in hot water storage tanks, and indicated that increased height/diameter aspect ratios were instrumental in increasing the levels of thermal stratification.

The use of CFD softwares have benefited the researchers in analysing and understanding the complex HTF flows with better prediction and accuracy. MacPhee and Dincer (2009) performed a three dimensional CFD analysis and thermodynamic modeling, on solidification and melting in
an encapsulated ice storage tank. The HTF temperatures which strayed farther from the solidification temperature of water, were most optimal exergetically, but least optimal energetically, and had faster charging and discharging times. In LHS systems, researchers have undertaken studies to understand the thermal behaviour of the HTF and PCM during heat storage and release. Commercial software was applied by Joulin et al (2011) for the computation of the thermal behaviour of the PCM. Koizumi and Jin (2012) performed transient 2D numerical melting simulation of a solid phase change material in a container by the enthalpy-porosity approach of a commercial software.

The TRNSYS results from the study conducted by Lundh et al (2010) showed that the maximum fractional energy savings due to the reduction in auxiliary energy demand by a solar heating system, compared to conventional heating, are found at height-to-diameter ratios of about 2–4 for the different store volumes. Ievers and Lin (2009) developed three-dimensional CFD models, to quantify the level of thermal stratification in a hot water tank. They have analyzed stratification in a storage tank using Fluent software, and concluded that increasing the tank’s height/diameter aspect ratio, decreasing the inlet/outlet flow rates and moving the inlet/outlet to the outer extremities of the tank, results in increasing the levels of thermal stratification.

The transient charging process of an underground storage tank subjected to various water inlet conditions was simulated by a two dimensional CFD model by Papanicolaou and Belessiotis (2009). The temperature distribution in the tank for constant-temperature charging, developed a relatively thick thermocline separating the hot and cold fluid, and whose thickness increased rapidly, at different rates on the upper and lower sides of it, and higher than the analytical studies. A two dimensional CFD
analysis of the effect of encapsulation and arrangement of the PCM spheres on heat transfer, was carried out by Xia et al (2010).

Baek et al (2011) evaluated the thermal performance of the spiral-jacketed thermal storage tank based on CFD model and considering the energy, exergy analyses, and the stratification and heat transfer characteristics. They showed that though a higher flow rate enhances the thermal efficiency, it leads to reduced thermal stratification, whereas higher thermal stratification in the thermal storage tank can be achieved by using a smaller brine flow rate. Nithyanandam and Pitchumani (2013) conducted a three dimensional computational study of an LHS system embedded with heat pipes for storage performance enhancement in energy storage, collected from concentrating solar power.

Rodriguez et al (2009) investigated by means of the CFD and heat transfer numerical simulations, the unsteady laminar heat transfer and fluid flow phenomena, inside a water storage tank during its static mode of operation. The transient numerical CFD simulations have shown that as the cooling process evolves, there is a development of thermal stratification from the bottom to the top of the tank.

Once the stratification of the fluid was completely developed, the cooling process was found to take place in a quasi-steady regime, where three fluid regions were distinguished as clearly stratified zones, with a sharper temperature gradient at the bottom occupying a quarter of the tank volume, an almost uniform temperature region at the top equivalent to a quarter of the total volume, and a transition zone partially stratified between the top and bottom regions. It was reported that thermal stratification advanced from the bottom to the top of the tank due to conduction domination in the bottom region, while on the top and sidewall, convection heat transfer prevailed.
2.2.3 Performance Analysis

The performance of the stratification is evaluated by various indices such as the mix number and the Richardson number. The recent advancement in the computational analysis that predicts the temperature distribution of the entire storage tank paves the way for a detailed exergy analysis. Hence, the combination of the CFD and exergy analysis has gained importance in recent years. The various studies on the stratification performance available in the literature are presented in the following two subsections.

2.2.3.1 Various performance parameters

The experimental measurements of the charging and discharging modes of energy transfer to and from the hot water TES systems, with single entrance and exit ports, have been correlated by Wood et al (1981) in terms of the Archimedes number. At lower values of the Archimedes number, the stratification efficiency progressively reduces towards zero, due to short circuiting of the flow between the inlet and outlet ports. Hegazy and Diab (2002) investigated the performance characteristics of the 50 L electric water heater, using perforated, slotted and wedged pipe inlets.

Their analysis based on discharge efficiency, extraction efficiency and heat recovery revealed, that the slotted inlet performed better compared to a conventional storage system. Panthalookaran et al (2007) have used the SEN storage evaluation number that integrates the first and second law concerns, to characterize storage system performance. The SEN efficiency was found to increase with the increase in the aspect ratio, indicating the improvement of the charging–discharging processes.
Han et al (2009) outlined various types of thermal stratification tanks, and stressed the need for further research on the enhancement of thermal stratification. They have listed inlet and outlet condition, baffle plate, thermal leakage, static or dynamic operating conditions as some of the influencing factors. It was mentioned that the Stratification number, energy efficiency, or exergy efficiency were determined as the evaluating index for the performance of thermal stratification by different researchers. In the dimensionless group analysis, the Richardson number was generally used as the evaluation index.

Castell et al (2010) described the role and significance of non-dimensionless numbers, that characterize stratification in a storage tank. Experimental charging cases to evaluate the thermal stratification parameters of an oil/pebble-bed TES system, were presented by Mawire and Taole (2011). They have identified the temperature distribution and Stratification number, for the quantitative inference of thermal stratification, exergy efficiency and Reynolds number, for qualitative inference for thermal stratification.

2.2.3.2 Exergy analysis

Exergy is popularly used for characterizing the stratified store, and it is reported separately in the subsequent section. Rosengarten et al (1999) have developed a performance measure, based on the exergy method for optimizing the design of thermal energy storage systems. Sari and Kaygusuz (2000) have compared the energy and exergy efficiencies of a latent heat energy storage tank.

They have reiterated the importance of the exergy analysis in the calculation and comparison of the charge and discharge times for a thermal energy storage system. Rosen (2001) has endorsed the use of the exergy
method for rationally assessing, comparing and improving TES, as it reflects
the thermodynamic and economic value of the storage operation. Shah and
Furbo (2003) conducted experiments to measure the temperature stratification
in the tank during the draw-offs with the three inlets, and nine draw-off tests
at different inlet flow rates. The results showed the entropy and exergy
changes in the storage during the draw offs with the variation in the
Richardson number, volume draw-off and the initial tank conditions.

Rosen and Dincer (2003) discussed the applications of exergy to
several TESs, stratified storages and cold TES. They suggested improved
insulation to reduce heat loss, avoiding mixing losses and use of efficient
pumps for performance improvement. The application of exergy to several
thermodynamic benefits, especially the increase in the exergy storage capacity
obtained by stratification, and the use of the exergy analysis for storage
comparisons, have been highlighted by Rosen et al (2004).

They have further indicated that the increase in the exergy capacity
is the greatest for storages at temperatures close to the ambient temperature.
They have stressed the use of stratification in thermal storage designs, as it
increases the exergy storage capacity of thermal storage and an exergy
analysis should be applied in the comparison of stratified thermal storage
systems. Xiaowu and Ben (2005) conducted an exergy analysis on a SWH
system. The study identified the storage tank as the weakest unit of the
system, and revealed that exergy loss can be minimized by maintaining
stratification in the storage tank.

Ji and Homan (2006) utilized the thermal mixing factor, based on
the useful volume fraction, to characterize the level of mixing. In the gravity-
dominated regime, on the outlet side of the gradient layer, significant levels of
entropy generation were produced, whereas in the inertia-dominated regime
appreciable levels of entropy generation are distributed over a much greater
fraction of the enclosure volume. Fernandez-Seara et al (2007) reported the thermal behaviour of a 150 l domestic electric hot water storage tank, for static heating and cooling periods. They have attributed the small values of the heating exergy efficiencies to the high degree of irreversibility in this type of heating processes, by means of electrical heaters. Panthalookaran et al’s (2008) investigation on diffusers revealed, that conical diffusers with smaller angles of diffusion produced the overall best efficiency.

Sole et al (2008) in their assessment of the energy and exergy performances of storage tanks with and without PCMs reported, that the PCM did not destroy stratification, and instead, contributed to higher energy quality. Haller et al (2009) determined the influence of heat losses on stratification efficiency by using the relative entropy generation/exergy loss methods. The exergy analysis by Jack and Wrobel (2009) has shown that stratification delays the mixing of the incoming fluid with that in the storage tank, leading to an increase in the overall second-law efficiency, and a reduction in the optimum charging time compared to the fully mixed case. Bindra et al’s (2013) analysis showed a higher exergy recovery rate in SHS compared to LHS system, under similar high temperature storage conditions. The lower exergy efficiency was attributed to the higher axial dispersion and higher ambient losses.

2.2.4 Applications

Stratification finds application in various hot and cold storage systems. In heating systems, stratification studies are conducted in solar thermal storage and nuclear tanks. Stratification studies are reported in solar water heating systems, integrated collector storage, and solar air heating applications. Stratification studies on solar water heating systems have already been reported in the previous sections. The present section highlights
some of the research works pertaining to ICS, nuclear tanks and chilled water storage systems that are reported in literature.

### 2.2.4.1 Integrated collector storage

Eames and Griffiths (2006) found that the PCM slurry systems collected heat, marginally less effectively than water filled stores; however, higher solar savings fractions were realized, as heat was retained at higher temperatures in the PCM slurry systems. Smyth et al (2006) reported advances in the ICS vessel design in the field of glazing systems, methods of insulation, reflector configurations, use of evacuation, internal and external baffles and phase change materials. Madhlopa et al (2006) conducted experiments in a parallel connected integrated collector–storage solar water heater. The interconnection configuration, in which two insulated hose pipes, of which the lower pipe linked the bottom part of the lower tank to the bottom part of the upper tank, while the upper pipe linked the top part of the lower tank to the top part of the upper tank, exhibited satisfactory temperature stratification in both tanks, during solar collection and hot water draw-offs.

Sridhar and Reddy (2007) developed a modified cuboid solar integrated-collector-storage (ICS) system and found that the stratification factor was higher for lower inclination angles, and increased with the depth of the systems. Reddy (2007) numerically studied the transient response of the PCM-water solar ICS system, with and without fins. The configuration without fins showed the highest stratification, having a more nonuniform water temperature in the enclosure whereas the configuration with nine fins had the highest average temperature. Garnier et al (2009) modified a macro model, by using polynomial functions to incorporate the longitudinal stratification of temperature within the solar collector. Fooladi and Taheriani (2010) presented the experimental results of multitube ICS systems. The tanks
exhibited a very good degree of temperature stratification for the hot water draw off process.

2.2.4.2 Nuclear tank

The possible causes of stratification in the suppression pool due to blow down in their order of importance and analytical models, developed to capture the primary characteristics of the SP thermal behavior, are described by Gamble et al (2001). The analytical method has been developed by them to estimate the stresses caused by the circumferential temperature distribution from thermal stratification, in piping systems in nuclear power plants. The experiment conducted by Kuhn et al (2001) showed that stirring corrected the density variation in the upper compartment, and the separation of the mixed and unmixed regions remained in the lower compartment. The experimental investigation by Niu et al (2007) of conditions simulating those of passive containment cooling systems for passively safe reactors, has revealed that the jet Archimedes number, fluid properties, injection orientation, flow obstructions, and enclosure aspect ratio, control the heat transfer augmentation by forced jets. Zhao et al (2009) have stressed the need to analyze the thermal stratification in pools in nuclear reactor tanks, from the perspective of thermal hydraulics, to improve design optimization and accident analysis.

Chattopadhyay (2009) employed a semi-analytical technique to evaluate the stresses due to thermal stratification that have the potential to produce fatigue failure in pipelines. Kweon et al (2008) examined through a numerical parametric study, the effects of the boundary layer thickness, temperature difference, stratification length, wall thickness, inner diameter, elastic modulus, thermal expansion coefficient and Poisson’s ratio on peak temperature and peak stress intensity, due to non-linear temperature distribution in a pipe cross-section.
2.2.4.3 Air heating applications

Jones and Golshekan’s (1989) experiments on a pebble bed with air as the HTF exhibited the effect of destratification on recovery temperatures, duty cycle and initial temperature differences along the bed. Stamps and Clark (1992) have attributed the thermal destratification in a cylindrical tank filled with glass spheres and saturated with air, to both diffusive and convective effects. Crandall and Thacher (2004) compared a standard and a segmented bed. The numerical solution showed that segmenting a standard rock bed and routing the flow to segments cooler than the inlet air during charging, preserved the stratification throughout the bed. They further mentioned that loss in stratification could be reduced by increasing the number of segments.

Kurian et al (2009) have explored using CFD simulations, the effect of cylinder inclination on thermal buoyancy induced flows, and internal natural convective heat transfer for air, confined in a cylinder with the unity aspect ratio. The results showed that there was more heat transfer for inclination angles in the range of 45–60°, and for inclination angles beyond 90°, the hydrodynamics of the flow changed from a single vortex to a double vortex pattern.

2.2.4.4 Stratification in chilled water systems

Nelson et al (1998) expressed the mixing coefficient as a function of the Reynolds and Richardson numbers. Their experiments on chilled water tanks showed an increase in thermocline decay with an increase in the mixing coefficient, and improved performance was exhibited at an aspect ratio of 3. Sensible heat chilled water storage systems utilizing stratification tanks were studied by Tran et al (1989) and Musser and Bahnfleth (1998). Nelson et al (1999) have pointed out that the percent cold recoverable in a discharge cycle
increases with increasing initial temperature difference, aspect ratio and flow rate. Karim (2011) indicated that partial discharging in one discharge cycle involves a relatively longer residence time of cool water in storage, that leads to a significant decrease in the thermal efficiency, as the temperature of the chilled water in the tank increases because of heat conduction through the walls.

Hence, for any practical requirements the storage system should be designed with several tanks, so that based on the cooling requirement, the required number of tanks can be charged and discharged. The thermal performance of a stratified chilled water storage tank was quantified, using the thermocline thickness, half-cycle figure of merit (FoM1/2) and equivalent lost tank height (ELH) by Bahnfleth and Song (2005).

2.3 COMMENTS ON EARLIER WORKS

From the solar collection and storage aspects, studies are focussed on optimizing the solar collector area and storage volume. Performance studies in a storage system have received the attention of researchers worldwide. The SHS system has reached a maturity stage whereas thermochemical storage is in the developmental phase. In sensible heat storage system, experimental and numerical works have focused on temperature distribution, energy charging and discharging efficiency of storage system at different operating conditions for different configurations of solar hot water storage systems such as conventional hot water system, Integrated collectors storage and mantle tanks. In the stratification enhancement methods, many attempts have been made with various geometrical configuration, such as stratifiers, diffusers and baffles. However, the recent developments with phase change in the storage system, are very promising as the performance enhancement is very high. In phase change
systems, though PCM encapsulated spherical capsules were studied by researchers only very few literatures are available on stratification studies of packed bed storage system.

In recent years, there is a greater awareness, and hence, there exists several stratification studies in SHS units; however, such studies are scarcely available in LHS units. Stratification evaluation is another important part of thermal storage analysis. Richardson number and stratification number have been used as the stratification evaluation index in majority of research works. This would be of significance to designers of thermal storage systems to increase the storage system capacity with minimal mixing loss. Various stratification evaluation techniques have been put forth by different researchers. The use of CFD and exergy analysis has been adopted by some researchers for reliable and better prediction.

2.4 SPECIFIC OBJECTIVES

In contributing to a better understanding, and to demonstrate the potential of stratification in a PCM based packed bed, the research objectives of this dissertation were:

1) To conduct experiments on a PCM based packed bed, to study the charging behavior of the storage system.

2) Though there are several techniques to evaluate stratification available in the open literature, the recent advances in the computational performance made it possible to analyze stratification more accurately through numerical simulations.
Further, considering the need to compare the performance of the SHS system and to analyse the stratification performance through various evaluation methods, the following objectives are formulated:

- To carry out the CFD analysis using the commercially available software for similar configurations used in the experimental investigation, to analyse the temperature variation of the HTF in the storage tank under various mass flow rates.

- To study the stratification performance of the storage tank, using the exergy analysis and other performance parameters.