CHAPTER 2

LITERATURE OVERVIEW

Thermal energy storage, in general and LHS in particular, has gained more popularity in the past two decades, due to its advantages discussed in the previous chapter. In the present work, a detailed survey has been made of the various aspects in this field of research, which includes thermal storage materials, storage system configuration, applications, experimental investigations and modeling of phase change problems.

2.1 THERMAL ENERGY STORAGE MATERIALS

One major area of research in the field of thermal energy storage is the material investigation. Though the present research is not focused on the material side, an overview of the studies made on the LHS 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 co-efficient 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 tetradecane 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 A (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 (RII-56) as PCM enclosed in a polyethylene film bag for short term thermal energy storage unit. Prevention from super cooling is one of the most essential challenges for phase change material (PCM) application. López et al (2012) investigated that the addition of 10% of Cel-ZnO to the hexadecane decreases super cooling around a 30%, providing a promising way of improving the performance of system energy efficiency in building cooling and heating applications. Komiyama et al (2012) reported the preparation method of a new phase change material consisting of paraffin and olefinic block copolymer (OBC), which could keep its shape throughout the phase change cycle of paraffin and retain solid state both above and below the melting point of the paraffin. Such kind of OBC-based phase change material (OPCM) is expected to be applicable to latent heat storage system without encapsulation or to applications where the shape is to be maintained. The OPCM has good processability and large latent heat of fusion.

2.2 STORAGE SYSTEM CONFIGURATIONS

Progress in LHS systems mainly depends on heat storage material investigations and on the development of heat exchangers that assure a high effective heat transfer rate to allow rapid charging and discharging. Latent heat TES systems are broadly classified into the capsule-type and the shell-and-tube type, according to the method of containing the thermal energy storage material and to the mode of exchanging heat energy within the container. The various studies carried out by the researchers on different configurations are classified under i) Tubular exchanger ii) packed bed units iii) system with different heat transfer enhancement techniques.
Green and Vliet (1981) developed a numerical model and provided experimental measurements for a PCM storage unit of a shell and tube heat exchanger. The transient performance of a double pipe heat exchanger as a thermal energy storage container was investigated both experimentally and theoretically by Fath (1991). The results indicated that increasing the HTF inlet temperature and flow rate as well as the heat exchanger length increases the heat transfer rate and stored energy. Ryu et al (1991) studied the heat transfer characteristics of cool-thermal storage units during the charging period using vertical and horizontal tube systems. The two systems were compared with respect to heat transfer rate, coefficient of performance and super cooling of the PCM and it was found that the vertical tube system exhibits better thermal performance than the horizontal tube system. Lacroix (1993a) developed a theoretical model to predict the transient behaviour of a shell-and-tube storage unit with the PCM filling the shell side and the HTF circulating inside the finned tubes. A series of numerical tests were undertaken to assess the effects of the shell radius, mass flow rates and inlet temperature of the HTF.

Anica (2005) studied numerically and experimentally a shell-and-tube type latent thermal energy storage system during charging and discharging processes. A series of numerical simulations is carried out to provide guidelines for system performance and design optimisation, unsteady temperature distributions of the HTF, tube wall and the PCM for various HTF working conditions and various geometric parameters, and the thermal behaviour of the latent thermal energy storage unit during charging and discharging process. Akgiın et al (2007) developed a novel tube-in-shell TES system in which the PCM is stored in an annular space between a tube in which the heat transfer fluid (water) is flowing and a concentrically placed outer shell. The outer surface of the shell is conical in shape, designed with an inclination angle of $5^\circ$ which is desired to attain uniform melting of PCM on
the entire shell. Adine et al (2009) investigated a numerical study of a shell-and-tube latent heat storage unit in which two phase change materials is filled in shell space, P116 and n-octadecane, with different melting temperatures (50 °C and 27.7 °C, respectively). A heat transfer fluid (water) flows by forced convection through the inner tube, and transfers the heat to PCMs. A mathematical model based on the conservation energy equations was developed in order to compare the thermal performances of the latent heat storage unit using two phase change materials and a single PCM, and validated with experimental data. Parametric studies were conducted to analyse the effect of the key parameters, the HTF inlet temperature (ranges from 50 to 60 °C), the mass flow rate of the HTF and the proportion mass of PCMs, on the thermal performances of the latent heat storage units using two PCMs and a single PCM, during melting process.

One of the most effective and compact latent heat TES systems is a packed spherical capsule bed with different diameters. Saitoh (1983) showed that a spherical shape gives the best performance among existing various LHS units including flat plate, helical coil, and cylindrical capsule types. Later, Saitoh and Hirose (1986) performed theoretical and experimental investigation of the transient thermal characteristics of a LHS unit using spherical capsules. The effects of variation in the capsule diameter, the flow rates of the heat transfer fluid, the inlet temperature difference, the capsule material and the PCM on the performance of this storage unit were studied in detail. The authors investigated the effect of capsule material on the thermal performance and recommended that the plastic materials can be considered as a promising candidate for practical application. Advantages and disadvantages of different geometries of PCM encapsulation with different materials and their compatibility were discussed by Lane (1986).
An experimental and numerical study was carried out by Ismail and Henriquez (2002) on LHS system composed of spherical capsules filled with water as PCM placed inside a cylindrical tank. The authors studied the effect of spherical capsule materials such as copper, PVC and polyethylene and found that the use of polyethylene or PVC for spherical capsule facilitates the construction of the storage and reduces its costs. Barba and Spiga (2003) analyzed the discharge process of the LHS system, for constant temperature conditions, in three different geometrical configurations, i.e. PCM encapsulated in slab, cylindrical or spherical polyethylene containers and found that the shortest time for complete solidification is matched for small spherical capsules. Nallusamy et al (2007) have investigated experimentally the thermal behavior of a packed bed of combined sensible and latent heat TES unit. The TES unit contains paraffin as PCM filled in spherical capsules, which are packed in an insulated cylindrical storage tank. The water used as heat transfer fluid (HTF) to transfer heat from the constant temperature bath/solar collector to the TES tank also acts as sensible heat storage material. Charging experiments are carried out at constant and varying (solar energy) inlet fluid temperatures to examine the effects of inlet fluid temperature and flow rate of HTF on the performance of the storage unit. Discharging experiments are carried out by both continuous and batch wise processes to recover the stored heat. It is found from the discharging experiments that the combined storage system employing batch wise discharging of hot water from the TES tank is best suited for applications where the requirement is intermittent.

Fang et al (2010) carried out an experimental investigation on operation characteristics of cool storage air-conditioning system with spherical capsules packed bed. They concluded that the cool storage air-conditioning system with spherical capsules packed bed has better performances and can stably work during charging and discharging period.
Shuangmao (2011) analyzed the thermal characteristics of a packed bed LHS system containing spherical capsules integrated with a solar heating collector. Myristic acid is selected as PCM and water is used as HTF. The latent efficiency, which is defined as the ratio between the instantaneous released latent heat and the maximum released heat, is introduced to indicate the thermal performances of the system. The influences of inlet temperature of HTF, flow rate of HTF and initial temperatures of HTF and PCM on the latent efficiency and heat release rate are discussed. Izquierdo-Barrientos et al (2012) compared the performance of a fluidized bed and a fixed bed storage system using sand and a granular phase change material. In case of fluidized bed, the bed temperature along the heights of the tank was found to be uniform, whereas, variation in temperatures was observed along the height of the fixed bed thermal storage system.

There are several methods to enhance the heat transfer in LHS systems. Since shell and tube heat exchangers are commonly used in LHS systems, phase change around tubes with fin configurations has attracted many researchers. Most of the studies are concerned with PCM on the shell side and HTF on the tube side. The use of finned tubes with different configurations has been proposed by various researchers such as Eftekhar et al (1984), Padmanabhan and Krishnamurthy (1986), Sadasuke (1991), and Lacroix (1993b). Velraj et al (1997) have presented theoretical and experimental work for a thermal storage unit consisting of a cylindrical vertical tube with internal longitudinal fins and this tube assembly is, in turn, placed inside another cylindrical vessel containing water. The authors have concluded that this configuration, which forms a V-shaped enclosure for the PCM, gives maximum benefit to the fin arrangement. Ismail et al (2001) presented the numerical and experimental results of PCM storage system using finned tubes. Dincer and Rosen (2002) dealt with the problems of heat transfer with phase change materials in simple and complex geometries and
around isothermal finned cylinders. The results are presented and validated with actual and existing data. Lamberg et al (2003) presented a simplified analytical model to predict the solid-liquid interface location and temperature distribution of the fin during the solidification process of an internally finned PCM storage. Pandiyarajan et al (2011) carried out an experimental investigation on heat recovery from diesel engine exhaust using finned shell and tube heat exchanger and thermal storage system.

Several other heat transfer enhancement techniques such as inserting a metal matrix into the PCM, using PCM dispersed with high conductivity particles and micro-encapsulation of PCM have been studied and reported by various researchers. Hoongendoorn and Bart (1992) have reported that the low value of the thermal conductivity of the PCMs could be greatly improved by embedding a metal matrix structure in them. Chow et al (1996) have evaluated two thermal conductivity enhancement techniques. The first technique focuses on placing PCM in capsules of various shapes in a liquid metal medium. The second technique involves a metal/PCM composite. Bugaje (1997) investigated methods of enhancing the thermal response of paraffin wax heat storage tubes by incorporation of aluminum thermal conductivity promoters of various designs into the body of the wax. In this study, significant reductions in melting and freezing times were obtained by the use of aluminum sheet metal and expanded aluminum matrices. Velraj et al (1999) studied the influence of rasching rings dispersed in paraffin on the performance of LHS unit of 50 litre capacity. Banaszerk et al (1999) studied experimentally the solid-liquid phase change in a spiral TES unit. Fukai et al (2002) used carbon-fiber brushes to improve the thermal conductivities of PCMs packed around heat transfer tubes. Cabeza et al (2002a) performed an experiment in a small thermal energy storage device to study heat transfer improvement in PCM with three different heat transfer enhancement methods. Koizumi (2004) made an attempt to enhance the LHS rate of a solid PCM in a
spherical capsule and found that by inserting the copper plates into the capsules is an effective technique for enhancing the LHS rate, especially in larger spherical capsules. Marin et al (2005) investigated the improvement of TES system using plates with paraffin-graphite composite. Mettawee et al (2007) studied the heat transfer characteristics of a latent heat storage system by the addition of aluminium-powder of 80 μm particle size to paraffin wax to enhance the thermal conductivity. The tested mass fractions in the PCM-aluminium composite material were 0.1, 0.3, 0.4 and 0.5 of aluminium. Nakaso et al (2008) studied the heat transfer enhancement by stretching carbon fiber cloths among heat transfer tubes to extend the heat transfer area in latent heat thermal energy storage tanks. The experimental results show that the carbon fiber cloths of only 0.4 % of total volume had improved the heat exchange rate in the tanks. Moreover, the effect of the carbon fiber cloths on the thermal performance for a practical scale tank is numerically discussed. Zhao and Wu (2011) investigated the feasibility of using metal foams and expanded graphite to enhance the heat transfer capability of PCMs in high temperature thermal energy storage systems. The results show that heat transfer can be significantly enhanced by both metal foams and expanded graphite, thereby reducing the charging and discharging period. Further, it was observed that the overall performance of metal foams is superior to that of expanded graphite.

2.3 APPLICATIONS

TES is one of the key technologies for energy conservation and therefore is of great practical importance. One of its main advantages is that it is best suited for solar thermal applications. Dincer (1999) made a detailed study on the evaluation and selection of sensible and latent heat storage technologies, systems and applications in the field of solar energy. Another significant advantage of TES is that, although it may have been designed
primarily for the storage of solar energy, it is not restricted to that. It may be used to store surplus energy from the power plants, usually in the form of waste water, waste energy from air conditioners, waste energy from industrial processes, and so on. Zalba et al (2003) presented an excellent review on the various applications using PCM based thermal storage systems. Table 2.1 gives literature review of various applications of TES systems.

**Table 2.1 Various applications of TES systems**

<table>
<thead>
<tr>
<th>S.No</th>
<th>Type of application</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>
2.4 EXPERIMENTAL STUDIES

A lot of researchers have conducted experimental investigation to predict the thermal performance of LHS units with different configurations and for various operating conditions. Katayama et al (1981) investigated the characteristic variation of the rate of heat transfer to and from a cylindrical LHS capsule using naphthalene as the PCM. The variation of heat flux was measured using a heat flow meter wrapped around the capsule, as the capsule was subjected to stepwise variations of the capsule-wall temperature. Based on the results, it is concluded that the effects of natural convection within the capsule, the capsule material and the boundary conditions outside the capsule are important in the heat transfer analysis.

Abe et al (1984) developed a direct contact LHS unit using form-stable HDPE rods as PCM and performed series of experiments for different flow rates, PCM initial temperatures and HTF (Ethylene glycol) inlet temperatures to study the charge and discharge characteristics of the storage unit on a lab scale. Dietz (1984) experimentally studied the thermal performance of LHS unit consisting of vertically oriented tubes filled with Calcium Chloride Hexahydrate (CaCl$_2$.H$_2$O) as PCM. The variation of charging and discharging rates were measured for different flow rates and temperatures of HTF (air). These rates decreased with time as a result of decreasing effective heat transfer area and increasing thermal resistance of the PCM. Similar type of experimental work was carried out by Yanadori and Masuda (1986) using a single vertical concentric cylindrical PCM pipe with water (HTF) flowing through the inner pipe. Kamimoto et al (1986) extended the work of Abe et al (1984) and developed a LHS unit of 30 kWh capacity using form stable HDPE rods for solar thermal applications and recovery of industrial waste heat around 140 - 150°C. From the heat transfer experiments and a thermal insulation test, it was confirmed that this storage unit shows
excellent performance due to good direct contact heat transfer and a formation of thermocline.

Sasaguchi and Viskanta (1989) reported an experimental study of the melting/freezing of a PCM around two horizontal cylinders spaced vertically. Experiments have been performed for a single melting/freezing cycle and different cylinder surface temperatures by controlling the temperatures of the working fluids, which are circulated through the cylindrical heat exchangers. Time wise variations of the melt and solidification region contours and temperature distributions in the PCM have been measured and reported. Farid and Kanzawa (1989) and Farid et al (1990) have proposed the use of PCMs with different melting temperatures in a LHS module with air as HTF. The PCM was encapsulated in multirows of vertical cylinders. Both experimental and numerical results showed some improvements in the heat transfer rates during both heat charge and discharge when three types of PCM’s were used. Sozen et al (1991) investigated the thermal energy storage characteristics of a SHS and LHS packed bed consisting of a horizontal channel filled with randomly packed particles of PCM encapsulated spherical capsules. The HTF was refrigerant-12, which was modeled as an ideal gas. The SHS material used was 1% carbon - steel and PCM was myristic acid. The investigations showed distinctly different energy storage characteristics for these two kinds of packed beds. Watanabe et al (1993) extended the experiments of Farid et al (1990) by using water as the HTF and proved that there was obvious enhancement of the charging-discharging rates in the LHS system using three PCMs. Adebiyi et al (1996) reported that the efficiency of storage system using five PCM families in a packed bed LHS system exceeded those using single PCM family by as much as 13-26 percent.

Cool-thermal storage systems have been studied for the efficient use of stored cooling produced during off-peak hours to provide daytime air
conditioning. Bedecarrats et al (1996) presented experimental results of the charge and discharge modes of LHS for air conditioning/refrigeration applications using PCM encapsulated spherical capsules. Cho and Choi (2000) investigated the thermal characteristics of paraffin in a spherical capsule during freezing and melting processes. Experiments were performed with paraffin, i.e. n-tetradecane, and a mixture of n-tetradecane (40%) and n-hexadecane (60%) and water. This study shows that the average heat transfer coefficients were more affected by the inlet temperature and Reynolds number during the melting process than during freezing process due to a free convection effect during the melting process. Wang et al (2001) studied the charging process of a cylindrical LHS capsule with stearic acid, sliced paraffin and lauric acid as PCMs. Experimental results demonstrate that, compared to the capsule with single PCM, the charging rate of the capsule employing three PCMs enhanced obviously.

### 2.5 Modeling of Thermal Energy Storage Systems

#### 2.5.1 Studies on Sensible Heat Storage Systems

Several studies have been described in the literature to investigate and analyze thermal stratification in the sensible heat storage tank. These studies have shown that improving the thermal stratification in a storage device causes a substantial improvement in the whole system efficiency over that of a thermally mixed storage tank. Most of the models proposed in the literature are for simple one-dimensional cases. Zurigat et al (1989) have carried out a survey of the stratified thermal storage one-dimensional models available in the literature. The models include the fully stratified storage tank model, modified version of this model, viscous entrainment model and effective diffusivity model. The model showed varying degree of agreement with thermo cline test data. Ghaddar et al (1989) have 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 thermo cline location in the tank. Biyikoğlu (2002) used the concept of exergy to analyze and optimize a sensible heat cascade thermal energy storage system which is developed for storing exergy and later using it efficiently. First and second law efficiencies and irreversibility sources of the system are compared with the thermal energy storage system's having a unique energy resource. Removing time, optimum storage time and the number of transfer units of the heat exchanger are also determined for different operating conditions by minimizing the irreversibilities in the system. Mawire et al (2009) developed a simplified one dimensional single phase model for an oil pebble thermal energy storage system to examine the thermal performance of three solid sensible heat pebble materials. i.e. fused silica glass, alumina and stainless steel. The model is validated with experimental results. The thermal performance of these materials is evaluated in terms of the axial temperature distribution, the total energy stored, the total exergy stored and the transient charging efficiency. The results indicate that not only is the value of the total amount of energy stored important for the thermal performance of oil-pebble-bed systems but also that the amount of exergy stored and the degree of thermal stratification should be considered. A high ratio of the total exergy to the total energy stored is suggested as a good measure of the thermal performance of the pebble material. The overview of the stratification models of the SHS system found in literature is given in Table 2.2

Another method of SHS is use of packed bed of solids for storing thermal energy. The packed bed provides an effective means of energy storage for many systems and has been satisfactorily employed for various applications. Beasley and Clark (1984) summarized the status of SHS modeling of packed beds, including both analytical and numerical studies, and experimental investigations.
Table 2.2 Thermal stratification models of SHS systems

<table>
<thead>
<tr>
<th>Sl.No</th>
<th>Types of model</th>
<th>Storage medium</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Two-dimensional model (numerical)</td>
<td>Water</td>
<td>Guo and Wu (1985)</td>
</tr>
<tr>
<td>2</td>
<td>One-dimensional model (numerical)</td>
<td>Water</td>
<td>Oppel et al (1986)</td>
</tr>
<tr>
<td>3</td>
<td>Two-dimensional model (analytical)</td>
<td>Water</td>
<td>Issa and Al-Nimr (1989)</td>
</tr>
<tr>
<td>5</td>
<td>One-dimensional model</td>
<td>Water</td>
<td>Wildin and Truman (1989)</td>
</tr>
<tr>
<td>6</td>
<td>One-dimensional model</td>
<td>Water</td>
<td>Zurigat et al (1991)</td>
</tr>
<tr>
<td>7</td>
<td>Transient turbulent two-dimensional model</td>
<td>Water</td>
<td>Al-Najem et al (1993)</td>
</tr>
<tr>
<td>9</td>
<td>Two-dimensional turbulence model</td>
<td>Water</td>
<td>Mo and Miiyatake (1996)</td>
</tr>
<tr>
<td>10</td>
<td>Two-dimensional turbulence model</td>
<td>Water</td>
<td>Spall (1998)</td>
</tr>
</tbody>
</table>

Also the authors developed a numerical model to predict the two-dimensional transient response of a packed bed SHS unit. The influence of radial velocity variation, wall heat capacity and wall thermal losses are considered and the analysis is valid for fluids of various Prandtl numbers. The model is verified by comparison with experimental results of randomly packed bed of natural rock spheres with air as HTF. Saez and McCoy (1982), Torab and Beasley (1987), Sozen (1991) and Dincer (1997) studied the performance of packed bed SHS systems using one-dimensional separate phases models.
2.5.2 Studies on Latent Heat Storage Systems

Modeling of phase change problems has received considerable attention by the researchers, since several years due to the complexity involved due to the moving interface. The studies carried out on various types of modeling and solution methodologies adopted for the phase change problems are summarized in this section.

Viskanta (1983) has discussed the various mathematical formulations available using variable domain method for the one-dimensional phase change problem for various geometry and boundary conditions considering the effect of property variation. Basu and Date (1988) have provided a comprehensive review of the different models adopted by various authors based on both, fixed and variable domain methods and have presented a generalised formulation of melting and solidification problems. Samarskii et al (1993) have modeled the phase change problem based on the conventional Stefan approximation for the evaluation of phase change and the Navier-Stokes equations using Boussinesq approximation for the convective flows within the melt. Since the enthalpy method has been used in the present study for modeling the packed bed with encapsulated PCM balls, a detailed review of this method is presented at the end of this chapter.

As explained in the previous chapter, the numerical methods for phase change problems can be broadly divided into two groups, based on the modeling: (1) The temperature based method (or) Variable domain method and (2) The enthalpy based method (or) Fixed domain method. A comparison of the two methods of modeling for the numerical solution of phase change problem has been done by Griffith and Nassersharif (1990). They have concluded that the interface-following method (temperature based method) is capable of correctly modeling phase change behavior in constant property materials with a discrete melting temperature, in materials that undergo phase
change over a temperature range, and in materials with temperature dependent properties Viswanath and Jaluria (1993) have compared the efficiency of Physical grid method (enthalpy method) and Transformed grid method (temperature based - boundary immobilisation method) by solving phase change problems in enclosures. They concluded that the T-grid method gave better predictions of the flow structure and interface locations than the P-grid method for fixed-temperature phase change problems whereas the P-grid method is ideally suited for alloys and plastics. They also suggested that more work is needed to make the T-grid method more efficient and the enthalpy method more accurate.

2.5.2.1 Temperature based modeling

In the first group of modeling, irrespective of the particular numerical algorithm employed, one of the primary difficulties is in the handling of the phase change boundary. Though this method is not being used in the recent years, the origin and development of this method using various schemes are highlighted in this section. There are five different methods depending on the ways of handling the interface. (i) Fixed grid method, (ii) Variable space grid method. (iii) Variable time step method, (iv) Boundary immobilisation method, (v) Isotherm migration method.

In the fixed grid method a special finite difference scheme based on unequal grid space interval is written near the interface considering the interface as the boundary. Lazaridis (1970) has used this method in multidimensional problems where he has assumed a quadratic temperature profile near the interface to avoid the singularity of the finite difference equation. To solve the problem by fixed grid method, Goodrich (1978) has suggested a new solution procedure based on ‘nodal iteration’ which reduces the computation time.
In the variable space grid method, the number of space intervals are kept constant and the space intervals are adjusted in such a manner that the interface lies on a particular grid point. The space interval is thus a function of time. Murray and Landis (1954) have used this formulation to solve the problem of freezing by the explicit method. Rathjen and Jiji (1971) have used this method for two-dimensional problem. This method has also been used by many researchers for finite element analysis (Bannerot and Jamet 1977).

In the method of variable time grid, the time step is calculated in such manner that the interface moves one grid spacing per time-step. This method has been proposed for the one-dimensional melting problem by Yuen and Kleinman (1980). Though this method has been adopted by many authors for temperature based phase change problems, Voller and Cross (1981) have used this method for enthalpy formulation and it is referred to in the study as ‘Node jumping scheme’.

In the boundary immobilisation method the interface remains fixed by transformation of co-ordinates. The moving control volume in the physical plane is brought to stationary in the transformed plane and this result in convective flux in the transformed governing equation. This term is called ‘pseudo-convection’ term. By the co-ordinate transformation, the governing equation that is linear becomes non-linear partial differential equation. This is the most powerful method in the variable domain formulation. Sparrow and Hsu (1981) have adopted this formulation to solve a thermal storage problem. Bernard et al. (1985) have used this method to study the effect of convection during melting in a rectangular enclosure. Bernard et al. (1986) have suggested two important conditions for applying the quasi-stationary assumption that is very useful for phase change problem with convection. Viswanath and Jaluria (1993) have compared this method with the source term based enthalpy formulation. They studied the melting of gallium and tin...
in a rectangular cavity with isothermal side walls and adiabatic top and bottom walls. The study indicates the range of applicability and computational complexity of the two methods.

The isotherm migration method consists of exchanging one of the spatial co-ordinates with temperature, making the former a dependant variable and temperature the independent variable. This method is analogous to the Lagrangian formulation of fluid flow problems. The isotherm migration method was first used for phase change problems by Chernous’ko (1970) for the melting of an ice slab. Crank and Crowley (1978) have used the method in conjunction with orthogonal flow lines to solve multidimensional freezing problems. A modified isotherm migration method has been described by Talmon and Davis (1981) which can be applied when there is more than one moving phase-transformation front and when there are external surface resistances.

2.5.2.2 Enthalpy based modeling

The enthalpy method was introduced in the 1940s, and since then a lot of work has been done using this method for modeling phase change problems. In all the earlier work on two-dimensional phase change studies using the enthalpy model, the curve of enthalpy versus temperature for the phase change substance was assumed to have a finite slope at the phase change temperature, i.e., the phase change was assumed to occur over a small range of \( 2\varepsilon \) even for the case of pure metals which change phase at a fixed temperature. Meyer (1973) has solved a two dimensional problem using the above model, with \( \varepsilon = 0.5 \) and \( 10^{-6} \) and showed that the computed results were independent of the choice \( \varepsilon \), and hence concluded that their model was suitable for problems where phase change occurs at a single temperature. However, Voller et al. (1979) have later showed that this conclusion is not valid for all cases and that, when \( H(t) \) is defined as in Equation (1.2), smooth
(non-oscillatory) temperature and heat flux histories will be predicted only when at least two nodal temperatures lie in the phase change range at all time-steps. This means that the accuracy of the above scheme is critically dependent on the choice of \( e \). In a discretized procedure, the choice of \( e, \Delta V \) (elemental control volume), and \( \Delta t \) should be consistent. Voller and Cross (1981) bring about this consistency in their ‘node-jumping scheme’, in which, the time-step \( \Delta t \) is iteratively selected, for a chosen value of \( e \), such that the interface moves from one node to the next in one time-step. By this scheme, they were able to eliminate the characteristic waviness observed in the heat flux predictions. This scheme was able to cope with phase change problems where the phase change occurs either at a single temperature or over a range of temperatures. However, since the time-step has to be iteratively chosen, it was restricted to one-dimensional problems. Bell (1982) has concluded that the undesirable step-like behaviour produced by the enthalpy approach is merely a consequence of the quasi-steady nature of the temperature distribution.

Shamsunder and Sparrow (1975) have developed an integral relation for the enthalpy model, without assuming any phase change temperature range i.e. \( e \) for the analysis of multidimensional conduction phase change problems where the phase change occurs at a fixed temperature. The solution method developed by them is applicable, both for substances that change phase at a discrete temperature and for those that change phase over a range temperatures. They employed fully implicit finite difference scheme to solve for the case of solidification in a two-dimensional phase change problem. They solved the resulting finite difference equations by Gauss-Siedel point-by-point iteration scheme. A detailed analysis has also been made by them on the results such as heat flux, boundary temperatures, solidified fraction, and interface position. However, the limitation of their
scheme was that, it could be applied only for the case of the phase change material being initially in a saturated condition.

In the above approaches, since the values of temperature are recovered from enthalpy temperature relations, ‘book keeping’ is required to identify the phase change and the single phase nodes. This precludes the possibility of using line by line integration to solve the finite difference equations. Date (1991) has generalized the enthalpy temperature relationships in such a way that no book keeping is required and solved the finite difference equations by the Tri-Diagonal matrix Algorithm (TDMA). He further proposed a method to eliminate the waviness in the heat flux predictions. This, he achieved by assuming a specific temperature profile in the solid region such that, the condition \( \frac{dT}{dt} = 0 \) is satisfied at the interface. However, this formulation is restricted to small Stefan numbers and an initial condition of saturated liquid. For higher Stefan numbers, the assumed temperature profile in the solid region should be of a higher order.

Date (1992) later made an improved formulation for predicting smooth, non-wavy temperature histories which is independent of the magnitude of the Stefan number and the initial conditions. The prediction of wavy temperature histories is caused by holding the temperature of a two-phase node constant at \( T_m \). Date devised a simple procedure for estimating (i) the exact location of the interface within the phase change node, and (ii) the appropriate nodal temperature at the phase change node. The exact location of the interface is determined from the value of the solid fraction. A second order profile is then assumed for the variation of temperature from the node previous to the phase change node to the interface location. Using this profile, while estimating the temperature from the H-T relation after each iteration, correction is made, and exact nodal value of the temperature at the phase
change node is determined. This procedure yields non-wavy profiles for
temperature and heat flux, for both one and two-dimensional problems.

The above said generalized H-T relation developed by Date, which
eliminated book-keeping and simplified the task of locating the interface, is
suitable only for problems where the phase change occurs at a fixed
temperature. Velraj et al. (1997) have modified this relationship to
accommodate materials having either constant or a range of phase change
temperatures. They have solved a two dimensional problem in cylindrical co-
ordinates (for a finned vertical tube) and have analyzed results such as, the
effect of fins on the heat flux and solidified fraction for a study on heat
transfer enhancement using fins.

Voller (1985) has proposed a new formulation for the enthalpy
method based on separating the enthalpy into latent and sensible heat
components. The latent heat contribution is represented in the formulation as
a source term. On seeking an implicit finite difference solution this fact
ensures that the non-linerity associated with the latent heat is isolated and thus
can be dealt with efficiently. The advantage gained is that only one variable
(i.e. temperature) is to be explicitly solved for in the resulting iterative
scheme. This methods reduces the computing requirements. However,
problems such as waviness in temperature histories are not solved by this
method, and schemes like the node- Jumping scheme have to be employed to
tackle them.

Voller (1990) later developed a new implicit enthalpy solution
scheme that requires no under or over relaxation, and depending on the
problem it is 1.5 to 10 times faster than the previous schemes. In this scheme
also, the latent and sensible heat terms are identified, and the latent heat is
written in terms of the local liquid fraction. TDMA solver is used to
determine the sensible enthalpy fields. The fact that the nodal sensible
enthalpy is zero in all the phase change nodes is utilized while updating the liquid fraction from the sensible enthalpy fields at the end of each iteration. This results in a speed up in the CPU performance. Further modifications have also been suggested to increase the computational speed. While extending the scheme to two-dimensional problems, the performance depends critically on the solver, and alternative solvers are required to improve the performance.

Swaminathan and Voller (1993) have provided a comprehensive and unifying treatment of the enthalpy methods for phase change problems. They have obtained a generalized enthalpy method that includes as subsets both the apparent heat capacity and source based methods that are two commonly used fixed grid enthalpy methods and identified an optimal enthalpy scheme. They demonstrated the superiority of this scheme by solving sample phase change problems. Teng and Akin (1994) have discussed the various approaches of the effective heat capacity method and proposed a new line integral effective capacity approach which is more efficient than the other techniques. Fikiin (1996) presented a numerical solution for a generalized Stefan problem which covers a great variety of unsteady heat conduction cases accompanied by phase transformations. A mathematical model is developed for determination of the unsteady-state temperature and enthalpy fields and of the cooling and freezing times of food materials and other bodies. An improved enthalpy method is proposed by which all non-linearities, caused by the temperature dependence of the thermo physical coefficients, are introduced in a functional relationship between the volumetric specific enthalpy and the Kirchhoff function, suitable for both isothermal and non-isothermal phase change.

Duan et al (2002) performed a numerical study on the investigation of the solidification of a pure n-hexadecane inside a rectangular enclosure
based on an enthalpy formulation of the energy equation. A vertical wall of the enclosure is maintained at a constant temperature below the melting temperature of the n-hexadecane while all other sides are adiabatic. The effects of the cold wall temperature, initial liquid superheat and aspect ratio of the enclosure are studied in terms of the solid fraction and the shape of the solid–liquid phase front.

Bilir and Ilken (2005) investigated the inward solidification problem of a PCM encapsulated in a cylindrical and spherical container. The enthalpy method and control volume technique with the third kind of boundary condition were used to formulate and solve the governing dimensionless equations. Correlations were presented to determine the total solidification time of the PCM in terms of the Biot number, Stefan number and superheat parameter. Vyshak and Jilani (2007) presented a comparative study of the total melting time of a phase change material (PCM) packed in three containers of different geometric configurations, viz. rectangular, cylindrical and cylindrical shell, having the same volume and surface area of heat transfer by employing a slightly modified enthalpy method, which enables decoupling of the temperature and liquid fraction fields. The governing equation for one dimensional isothermal phase change is discretized using the Crank–Nicholson finite difference scheme and the resulting system of algebraic equations for temperature is solved using the Thomas algorithm, the liquid fraction field is updated explicitly using the currently known temperature field. The results are presented for different masses of PCM filling the containers and inlet temperature of the heat transfer fluid (HTF). Tan et al (2009) made an experimental and computational investigation by considering the buoyancy-driven convection during constrained melting of PCM inside a spherical capsule. The computations are done on an iterative, finite-volume numerical procedure that
incorporates a single-domain enthalpy formulation for simulation of the phase change phenomenon.

### 2.5.2.3 Studies on PCM based packed bed storage system

The studies carried out for packed bed storage systems are classified under two groups based on the type of heat transfer fluid being used namely Liquid and air. Regin et al (2008) made an extensive review on the heat transfer characteristics of thermal energy storage system using PCM capsules.

Chen and Yue (1991a) developed a one dimensional porous-medium model to determine the thermal characteristics of a cool thermal storage system using water/ice as the PCM. The result was characterized based on five independent dimensionless parameters, such as effective water-to-coolant heat capacity ratio, effective ice-to-coolant heat capacity ratio, Stanton number, Stefan number and Peclet number. Comparisons of the numerical results show good agreement with the experiments, against their previous work on a one dimensional lump model (1991b). Watanabe et al (1993) developed and studied a heat storage system consisted of horizontal cylindrical capsules filled with three types of PCM with different melting temperature. A simplified one dimensional numerical model was used to study the effect of flow rate, initial temperature of HTF and the dimensions of the heat storage module on the thermal performance of the latent heat storage module. Results proved that the charging and discharging rate are improved by the use of multiple PCM. Bedecarrats et al (1996) investigated the performance of the phase change cool thermal storage plant filled with PCM encapsulated spherical capsules, applicable for air-conditioning and refrigeration units. Ismail and Stuginsky (1999) presented a comparative study on four basic models, including continuous solid phase model, Schumann’s model and single phase model, for fixed bed storage system for
PCM and SHS. The governing equations for the different models in their dimensionless forms together with the corresponding initial and boundary condition were discretized using the finite difference approximation.

The implicit method was used in all one dimensional models and the ADI method was adopted in the two dimensional models to obtain similar equations for all the models. The models were first evaluated in relation to the computational time consumed to solve a specific test problem. The models were then compared in relation to the influence of particle size, void fraction, particle material, flow rate variations, HTF inlet temperature variations and finally the wall thermal losses. Kousksou et al (2005) studied an energy storage which consists of a cylindrical tank filled with encapsulated PCM (water/ice) and HTF (glycol). The delay of the crystallization of the PCM, called supercooling phenomenon is considered for the analysis. A two-dimensional porous-medium numerical model has been compared with experimental results for the tank in vertical position. The numerical program developed was used to study the thermal behavior of the tank in horizontal position. They concluded that the optimum running of the charge mode is obtained in the case of the vertical position where the motions due to the natural convection are in the same direction as the forced convection.

Cheralathan et al (2006) performed a numerical analysis and parametric studies on a PCM encapsulated cool thermal energy storage unit integrated with a refrigeration system. They have used the porous medium model with three different time domains as suggested by Chen and Yue (1991a). They have reported the effect of porosity and various non dimensional parameters and conclude that Ste (0.2 – 0.4), porosity (0.4 – 0.49) and St (0.7 – 1.0) are to be chosen for higher and faster energy storage. Regin et al. (2009) numerically investigated the effect of the phase change temperature range, the size of the PCM capsule, inlet heat transfer fluid temperature and fluid flow
rate on the performance of the packed bed latent heat storage system, consisting of spherical capsules for solar water heating applications.

The solid-solid phase change that occurs before the onset of the actual melting phase change was also considered in the numerical solution. Nallusamy et al (2009) have investigated the performance of a cylindrical packed bed thermal storage unit for solar water heating applications using a simple porous medium model. The model accommodates the effect of varying inlet temperature to the storage tank to simulate the hot water coming from the solar collector.

Adebiyi et al (1996) developed a computer model for the packed bed TES system formed by many independent PCM capsules using porous medium approach and presented the results obtained by the model. The model allows investigation of the effect of Temperature and mass flow rate of the HTF (flue gas), porosity of the bed and dimensions of the vessel on the system performance.

The other factors such as the thermal mass of the containment vessel wall have been studied by coupling the model with the heat diffusion equation for the wall. Arkar and Medved (2005) highlighted the influence of the thermal property data of the PCM on the results of the numerical predictions on a latent heat thermal energy storage system in which paraffin (RT 20) is used as PCM and air as HTF. Benmansour et al (2006) carried out a two dimensional numerical and experimental analysis to understand the transient axial and radial thermal dispersion on a cylindrical packed bed storage filled with spherical PCM (paraffin) capsules. Air is used as the heat transfer fluid (HTF). The comparisons were made for different Reynolds numbers of 560 and 1120. The energy equation for the fluid was resolved by finite difference approximation, and solved by the alternating direction implicit (ADI) scheme, whereas the energy equation for PCM was solved by
the finite difference fully explicit scheme. Karthikeyan et al (2011) has investigated numerically and experimentally a packed bed latent heat storage system with spherical encapsulated paraffin capsules for air heating applications. An enthalpy based conduction dominated model which considers the thermal gradient inside the PCM capsule solved in explicit finite difference method was used in the numerical analysis.

2.6 SPECIFIC OBJECTIVES OF THE PRESENT WORK

In the present research, a detailed survey has been made on modeling of phase change problem with different methods and physical assumptions for different configurations. This survey shows that the studies on systems with air as heat transfer fluid for air heating applications are rare. Further, the validity of such models developed and the complexity required for a given problem are not well reported.

Considering the above, the objectives of the present research are:

- To model a cylindrical storage tank filled with paraffin (PCM) encapsulated spherical containers with air as heat transfer fluid using three different mathematical models.
- To conduct experimental investigation for a similar physical configuration stated in the model.
- To investigate the validity of the three different mathematical models suitable for the phase change problems in a packed bed latent heat storage unit using the experimental results.
- To analyse the transient behavior the storage unit and to carry out parametric studies using the best model identified.