CHAPTER 3

EXPERIMENTAL INVESTIGATION OF LATENT HEAT STORAGE SYSTEM

An experimental investigation was carried out to study the thermal performance due to stratification. The storage tank integrated with the available solar collectors was used to analyse the stratification performance of the thermal storage system. In the present chapter, the construction of the experimental set up and the procedure adopted in the conduct of the experiments are presented. Initially, the reasons for the selection of the storage tank configuration, the heat transfer fluid and the phase change material are explained in this chapter.

3.1 SELECTION OF THE STORAGE TANK CONFIGURATION

A storage system should be designed to match the intermittent, variable and unpredictable nature of solar radiation along with the fluctuations in the demand for the thermal load of a given application. Storage systems are classified as buffer storage, diurnal storage and annual storage, based on the time interval for which the energy is required. Storage is required only for a short duration of hours in the case of buffer storage. A system larger than buffer storage that has the capacity to store energy for a day or two, is called diurnal storage. A long term storage or seasonal storage is one which stores the excess energy collected in one season for use during the other seasons. In the present research a diurnal storage system is designed and investigated, for
its integration with the solar hot water collector system, suitable for various applications.

Among the various types of storage systems, latent heat thermal storage is chosen, due to its high energy storage capacity and isothermal behaviour during the charging and discharging processes. There are two major configurations studied by researchers for the LHS system.

1. Shell and tube type tubular heat exchanger with PCM on the shell side and the HTF passes through the tubes.

2. Packed bed storage system containing randomly packed PCM containers.

The major problem associated with the first configuration, is cavity formation due to volume change during solidification. This affects the heat transfer characteristics during repeated cycling. Further, the PCM cannot be packed separately inside a storage tank due to its poor thermal conductivity, which varies the resistance for the heat transfer during the charging and discharging processes. The solidified layer of the PCM during its solidification on its convective heat transfer surface, acts as an insulator, and further, as the thickness of the solidified layer increases, the resistance to the heat transfer between the HTF and the liquid PCM increases. This, in turn, decreases the heat transfer rate appreciably, and causes a non-uniform rate of discharging characteristics in the storage tank, which may restrict its usage for any application.

In order to avoid the above said problem, the second configuration consisting of a bed of spheres, randomly packed, and poured into a cylindrical tank, is an attractive option, particularly for solar applications. This type of storage system is very simple in construction, and also increases the heat
storage capacity compared to the SHS system, and eliminates the problems that are usually encountered in a shell and tube type latent heat storage unit.

Further, from the application point of view, the hot water may be required at a high rate for a short duration, and this requirement can be met by the sensible heat of the water in a storage tank. Before its use next time, the temperature of the water in the tank gradually increases again, by the slow extraction of the latent heat from the PCM. Thus, the problem of a non-uniform heat flux during the withdrawal of heat from the LHS system is minimized. Further, a down flow configuration of the HTF flow was selected, considering the need to maintain a high temperature at the top, and the gravitational force aiding the HTF flow through the voids, and to maintain a high level of stratification.

3.2 SELECTION OF HEAT TRANSFER FLUID AND PHASE CHANGE MATERIAL

The HTF, and the storage medium identified, and the PCM properties are presented in this section.

3.2.1 Heat Transfer Fluid

Water is normally used as a storage medium as it is low in cost, and has a high specific heat. The use of water is particularly convenient when it is used also as the heat transfer medium in the solar collector and to deliver the thermal load to the application through heat exchangers. In addition, its properties like the coefficient of expansion, viscosity, thermal capacity, freezing point, boiling point and factors like low cost, larger availability, non-toxicity and the absence of expensive pressure equipment for circulation, favors the choice of water as the HTF.
3.2.2 Phase Change Materials

The selection of the PCM in LHS systems depends on the operating temperature range of the HTF which in turn is based on the application. The packed bed of spheres was designed to operate between the inlet HTF temperatures closer to the PCM melting temperature. Though a variety of PCMs exist as given in Appendix 1, the temperature obtained by the HTF in flat plate collectors, and the desirable PCM properties, are the decisive factors in selecting the PCM. The test facility was meant for an application that demands hot water in a medium temperature range of about 60°C.

The need to maximize the efficiency of the solar system restrains the selection of high melting temperatures of the PCM though higher storage temperatures could be advantageous for several applications. In such cases, the maximum heat gain can be obtained from the solar system and the fraction of high temperature energy requirement can be made available from other sources.

The commercial phase change material (PCM), HS 58, which has a melting temperature of 57-58°C was chosen considering the above factors and procured from Pluss polymers Ltd, India. Table 3.1 summarises the thermo physical properties of the PCM. The disadvantages of the PCMs are their cost and degradation of properties when subjected to high thermal cycling at high temperatures in long term TES applications.
Table 3.1 Thermophysical properties of HS58

<table>
<thead>
<tr>
<th>Property Conditions (if any)</th>
<th>Value</th>
<th>Test Method</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting Temp. (°C)</td>
<td>58</td>
<td>T – History</td>
<td>@ 69 °C (maximum Bath)</td>
</tr>
<tr>
<td>Freezing Temp. (°C)</td>
<td>57</td>
<td>T – History</td>
<td>@ 35 °C (Bath)</td>
</tr>
<tr>
<td>Liquid Density (kg/m³)</td>
<td>1290</td>
<td>ASTM D891-95</td>
<td>@ 68°C</td>
</tr>
<tr>
<td>Solid Density (kg/m³)</td>
<td>1400</td>
<td>PLUSS®</td>
<td>@ 320°C</td>
</tr>
<tr>
<td>Latent Heat (kJ/kg)</td>
<td>250</td>
<td>Calorimetry</td>
<td>Solid PCM is taken at 32°C</td>
</tr>
<tr>
<td>Specific Heat-Liquid (kJ/kg.K)</td>
<td>2.5</td>
<td>Calorimetry</td>
<td>@ 68°C</td>
</tr>
</tbody>
</table>

The PCMs are contained in spherical containers as they offer higher heat storage density. The robust encapsulation material should be capable of resisting leakage and corrosion. A stainless steel encapsulated spherical ball of 0.06 m diameter was chosen taking into account the PCM volume expansion during melting, and it was properly sealed to avoid leakage.

3.3 EXPERIMENTAL SET UP

The experimental set up consisted of an array of solar collectors, an auxiliary heater that heats the HTF to the required temperature level, a pump to circulate the HTF, and the PCM based thermal storage system. Figure 3.1 shows the schematic sketch of the experimental set up. Water was used as the heat transfer fluid, and the heat energy gained from the collector was stored in the TES tank.
3.3.1 Solar Collector System

A solar array consists of seven collectors that are arranged in parallel-series combination. The collectors faced south with an inclination of $17^0$ to the horizontal. Each collector had a length of 1.8 m and a width of 0.9 m, with a window area of 1.62 m$^2$. The photographic view of the solar collectors is shown in Figure 3.2.
Hot water from the solar flat plate collector is stored in an insulated storage tank. A pump with a capacity of 0.25 hp was used to circulate the HTF through the collector and the storage tank. The hot water from the outlet of the collector is fed to the top of the storage tank.

### 3.3.2 Thermal Storage System

The thermal storage system tank size, insulation thickness and storage system configuration are discussed in the present section.

#### 3.3.2.1 Sizing of the thermal storage tank

The thermal storage tank was designed for the purpose of storing 70,000 kJ of energy in the temperature range of 50-60 °C, suitable for hot water bathing requirements for 50 persons in a community building or in a hotel. Further, it is proposed to store 50 % of the energy as latent heat, and the remaining 50 % as sensible heat form, considering the continuous requirement of 50 % of the heat at any time during a day.

The major objective of the present work is to maintain better stratification in the storage tank in order to improve the efficiency of the solar collection system with the use of the PCM encapsulated spherical capsules kept at the top of the tank. To achieve the above objective of better stratification, the bottom 1/3rd height of the tank was maintained at a low temperature, and hence this volume of the storage tank was not considered while designing its heat storage volume.

The size of the storage tank was designed based on the heat requirements as detailed below:
Volume of the PCM to be kept in the container

Heat energy to be stored in the PCM = 35,000 kJ
Latent heat value of the PCM selected = 250 kJ/kg
Mass of the PCM required = 35000/250
= 140 kg

Inner diameter of the spherical container considered for encapsulation = 6.5 cm
Density of the liquid PCM = 1290 kg/m$^3$
Number of balls required = (140/Liquid PCM density)
Volume of single ball = 800

Considering the thickness of the container material and the sealing portion as 15% of the PCM volume,

Volume of the spherical capsule = 0.108 x 1.15
= 0.125 m$^3$.

Volume of water to be kept in the storage tank

The total sensible heat to be stored = 35,000 kJ (Sensible heat of HTF + PCM)
= $c_{HTF} \Delta T_{HTF} + m_{PCM} c_{PCM} T_{PCM}$
= $m_{HTF} \times 4.186 \times 10 + 140 \times 2.5 \times 10$

Mass of water required for heat storage = 752 kg of water
(which is $2/3^{rd}$ of Volume of water in the tank)
Hence the mass of water to be kept in the entire tank = 1128 kg of water

The volume of water in the tank = 1.128 m$^3$.

Total Volume of the tank = 1.128 + 0.125 = 1.25 m$^3$.

Height of the tank considered = 1.2 m

Diameter of the tank = 1.16 m

### 3.3.2.2 Determination of insulation thickness

Thermal insulations are materials or combinations of materials that are used mainly to provide resistance to heat flow. Thermal insulations serve as barriers, and play a major role in the design and manufacture of all energy efficient and energy conservation projects. Minimizing heat leakage from the fluid stream to the ambient through proper insulation, is an important component of the design of a solar thermal charging system. Insufficient or poor insulation work can reduce the thermal performance of solar heating systems significantly. The insulation of the storage tank and the pipes carrying HTF from solar collector to the tank and the return pipe from the tank to the solar collector were designed to ensure lesser heat loss.

The storage tank is insulated using glass wool material and the optimum thickness of insulation is evaluated as below.

The temperature of water inside the PCM tank = 65°C.

Heat transfer coefficient between the outer surface of PCM tank and
ambient (evaluated using empirical formula of Wattmuff et al (1977)) = 7 W/m²K.

The thermal conductivity of glass wool insulation = 0.05 W/mK.

The rate of heat loss from the PCM storage tank is evaluated using the equation.

\[
\dot{Q}_{\text{insulated}} = \frac{T_{\text{inside}} - T_{\text{amb}}}{R_{i} + R_{\text{wall}} + R_{\text{airgap}} + R_{\text{wall}} + R_{\text{insulation}} + R_{o}}
\]

\[
= \frac{T_{\text{PCM}} - T_{\text{amb}}}{\frac{1}{h_{i}A_{i}} + \frac{1}{h_{o}A_{o}} + \frac{\ln(r_{2} / r_{1})}{2\pi k_{m}L} + \frac{\ln(r_{3} / r_{2})}{2\pi k_{\text{air}}L} + \frac{\ln(r_{4} / r_{3})}{2\pi k_{m}L} + \frac{\ln(r_{5} / r_{4})}{2\pi k_{\text{ins}}L}}
\]

where, \( T_{\text{PCM}} \) = temperature of water in PCM tank, °C

\( T_{\text{amb}} \) = ambient temperature, °C

\( R_{o} \) = convective resistance on the outer surface K/W

\( R_{\text{ins}} \) = convective resistance inside the tank, K/W

\( h_{o} \) = heat transfer coefficient on outside of tank, W/m²K

\( A_{o} \) = surface area of the tank, m²

\( r_{1} \) = inside radius of tank, m

\( r_{2}, r_{3}, r_{4}, r_{5} \) = radius at various wall thickness of the tank, m

\( k_{\text{ins}} \) = thermal conductivity of insulation material W/mK

\( k_{m} \) = thermal conductivity of tank material, W/mK

\( k_{\text{air}} \) = thermal conductivity of air, W/mK

\( L \) = length of PCM tank, m
The optimum thickness of insulation required for the thermal storage tank is evaluated by calculating the heat loss at various thicknesses of the insulation. Figure 3.3 shows the heat loss incurred from the storage tank for the thickness of insulation, varying from 0 to 15 cm. Considering the appreciable reduction in the heat loss upto 10 cm thickness and as reduction is much less beyond this thickness, an insulation thickness of 10 cm is provided in the thermal energy storage tank.

![Figure 3.3 Variation of heat loss with insulation thickness](image)

**Figure 3.3 Variation of heat loss with insulation thickness**

### 3.3.2.3 Storage system configuration

The storage tank had the inner dimensions of 1200 mm height and 1152 mm diameter and was insulated with 100 mm thick glass wool. The tank has a storage capacity of 1250 litres, with 800 spherical capsules made of stainless steel kept inside the TES tank. The spherical capsules were filled with the commercial phase change material (PCM), HS 58, which has a melting temperature of 57-58°C, procured from Pluss polymers Ltd, India.
The spherical capsules were surrounded by water that acts as a sensible heat storage material and heat transfer fluid. A perforated plate of thickness 8 mm was kept at a height of 370 mm from the bottom of the storage tank. The spherical capsules were kept above the perforated plate, ensuring high thermal mass at the top of the storage tank to promote stratification. The spherical capsules were filled up to a height of 600 mm above the perforated plate. Figure 3.4 shows the photographic view of thermal storage tank.

![Figure 3.4 Photographic view of the thermal storage tank](image)

3.4 INSTRUMENTATION

The temperature variations of the HTF at different locations of the tank were monitored continuously to study the stratification inside the storage tank. T type thermocouples were kept at five different heights of the storage tank, and also at the inlet and outlet of the storage tank, to measure the temperature of the HTF at various locations. The temperature measurements
were with an uncertainty of ± 0.1 °C. The water volume flow rate was measured with a flow meter, with an accuracy of ± .075 % of the reading. The intensity of solar radiation was measured, using the Pyranometer during the experimentation. The errors associated with the primary experimental measurements, and the calculation of the performance parameters are detailed in Appendix 2.

3.5 EXPERIMENTAL PROCEDURES

Experiments were conducted to analyse the charging and stratification behavior in the storage tank. During the experiment, the HTF was allowed to circulate through the solar collectors, and the hot fluid enters at the top of the storage tank. The experiments were conducted for different mass flow rates and the measurements are taken until 5 PM. It is observed from several trials during the experiment, that after 3 PM, the exit temperature of the HTF from the collector decreases appreciably, and it becomes lesser than the temperature of the HTF available at the top of the storage tank. During the experiments, the intensity of solar radiation along with the ambient temperature was also recorded. Several experiments were conducted to check the repeatability of the values.