OPTIMIZATION OF SYSTEM LAYOUT OF THERMAL ENERGY STORAGE WITH MULTIPLE MATERIALS

A Dissertation by

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The following faculty members have examined the final copy of this dissertation for form and content, and recommend that it be accepted in partial fulfillment of the requirement for the degree of Doctor of Philosophy, with a major in Mechanical Engineering.

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DEDICATION

To my wife Sarah Naseem for her constant support and my sweet little son Muhammad Yusuf Khan
If you can find a path without obstacles…it probably doesn't lead anywhere.
ACKNOWLEDGEMENTS

I express my deep sense of gratitude and indebtedness to my PhD advisor Dr. Muhammad Mustafizur Rahman for providing me an opportunity to fulfill my cherished goal of completing this dissertation successfully. I sincerely thank Dr. Muhammad Rahman for his skillful guidance, valuable suggestions and above all for supporting me financially throughout the duration of my dissertation. My PhD degree is the fruit of his precious guidance at every corner of my dissertation. I cannot thank him enough for being my research advisor.

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Last, but not least, I wish to thank Dr. P. Muthukumar, Professor, Indian Institute of Technology, Guwahati, India for his valuable insights on thermal storage systems.
ABSTRACT

The objective of this research was twofold. The first objective was to investigate the performance of a latent heat storage system using multiple phase change materials (PCMs). Three phase change materials namely, Potassium Hydroxide (KOH), Potassium Nitrate (KNO₃), and Sodium Nitrate (NaNO₃) were selected for this study. In this research, the performance of the thermal energy storage system (TESS) is analyzed by evaluating key parameters such as liquid fraction and the amount of energy stored and retrieved during charging and discharging respectively. Two types of PCM layouts, uniform and cascaded, have been employed. The cascaded layout is of two types, slope down and slope up layout. Overall, the cascaded layout excelled in performance when compared to the uniform layout in terms of PCM melting and solidification time and in terms of energy stored and retrieved.

The second objective was to investigate the performance of a combined sensible heat storage-latent heat storage (SHS-LHS) system with Aragonite as the sensible heat storage material and KOH as the latent heat storage material. The performance of the combined SHS-LHS is analyzed and compared with a sensible-only heat storage system by evaluating key parameters such as Heat Transfer Fluid (HTF) exit temperature, average temperature of the system and the amount of energy stored and retrieved. It was found that a combined SHS-LHS stabilizes the HTF exit temperature to around the temperature of the PCM during the discharge cycle which offsets the drawback of a sensible-only heat storage system. The amount of energy retrieved from the combined system is larger than the energy that is retrieved from a sensible-only heat storage system. All these findings point to the fact that using a combined SHS-LHS is highly advantageous as compared to a sensible-only heat storage system.
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<td>ALF</td>
<td>Average Liquid Fraction</td>
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<td>CFD</td>
<td>Computational Fluid Dynamics</td>
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<td>CSP</td>
<td>Concentrating Solar Power</td>
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<td>HTF</td>
<td>Heat Transfer Fluid</td>
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<td>HDPE</td>
<td>High density polyethylene</td>
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<td>KNO₃</td>
<td>Potassium Nitrate</td>
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<tr>
<td>KOH</td>
<td>Potassium Hydroxide</td>
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<td>LHS</td>
<td>Latent Heat Storage</td>
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<td>NaK</td>
<td>Sodium Potassium Alloy</td>
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<tr>
<td>NaNO₃</td>
<td>Sodium Nitrate</td>
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<td>PCM</td>
<td>Phase Change Material</td>
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<td>RTD</td>
<td>Resistance Temperature Detector</td>
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<td>SHS</td>
<td>Sensible Heat Storage</td>
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<td>TC</td>
<td>Thermocouple</td>
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<td>TESS</td>
<td>Thermal Energy Storage System</td>
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<td>TES</td>
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LIST OF NOMENCLATURE

\( A \)  surface area of pellet, m\(^2\)
\( A_o \)  outer surface area of pellet, m\(^2\)
\( C_p \)  specific heat, J/kg K
\( C_{ps} \)  specific heat capacity in solid state, J/kg K
\( C_{pl} \)  specific heat capacity in liquid state, J/kg K
\( d \)  PCM pellet diameter, m
\( D_{ci} \)  pellet inside diameter, m
\( h \)  outer convective heat transfer coefficient, W/m\(^2\) K
\( h_o \)  convection coefficient between the external surface of pellet and HTF, W/ m\(^2\) K
\( k \)  thermal conductivity of PCM, W/m K
\( k_c \)  thermal conductivity of pellet material, W/m K
\( L \)  latent heat of melting, J/kg
\( l \)  length of the PCM bed, m
\( m \)  mass of PCM, kg
\( m_f \)  mass flow rate of heat transfer fluid, kg/s
\( m_f \)  total mass of heat transfer fluid in the bed, kg
\( N \)  number of elements in the bed
\( Nu \)  Nusselt number = \( h d / k \)
\( Q_{ch} \)  charged energy of the tank, kJ
\( Q_{dis} \)  discharged energy of the tank, kJ
\( Q_{total} \)  total energy storage capacity of the tank, kJ
\( Re \)  Reynolds number = \( V d / \nu \)
LIST OF NOMENCLATURE (continued)

\( R_{ext} \)  thermal resistance due to convection on the external surface of the pellet shell, K-m²/W

\( R_t \)  thermal resistance due to conduction through the pellet wall, K-m²/W

\( R_{in(t)} \)  resistance due to the solidified/melt PCM layer inside the pellet, K-m²/W

\( R_{co} \)  pellet outside radius, m

\( R_{ci} \)  pellet inside radius, m

\( T_b \)  bed temperature, °C

\( T_f \)  heat transfer fluid temperature, °C

\( T_m \)  melting temperature, °C

\( T_{final} \)  final temperature of the bed, °C

\( T_{initial} \)  initial temperature of the bed, °C

\( t \)  time, s

\( U_o \)  overall heat transfer coefficient of pellet, W/m² K

\( U_s \)  overall heat transfer coefficient of storage tank outer wall, W/m² K

\( U_v \)  overall volumetric heat transfer coefficient, W/m³ K

\( V \)  fluid velocity, m/s

\( w \)  width of the bed, m

\( z \)  depth of the bed, m

\( z_p \)  pellet thickness, m

\( \Delta x \)  element thickness, m
LIST OF SYMBOLS

$\rho_b$  
density of bed, kg/m$^3$

$\rho_f$  
density of heat transfer fluid, kg/m$^3$

$\varepsilon$  
porosity

$\nu$  
kineastic viscosity of fluid, m$^2$/s
LIST OF SUBSCRIPTS

\( b \)  bed
\( f \)  heat transfer fluid
\( l \)  liquid PCM
\( s \)  solid PCM
CHAPTER 1

LATENT HEAT STORAGE SYSTEM

1.1 Introduction

With the demand for energy growing everyday by leaps and bounds, it is necessary to reduce our dependence on fossil fuels and explore alternate sources of energy. This calls for harvesting non-conventional and renewable energy sources like the solar energy. This is a vital step in limiting our dependency on non-renewable energy sources like the fossil fuels. A limiting factor in case of renewable energy like the solar energy is its intermittent nature. Hence in order to harness the full potential of the non-conventional and renewable energy sources, it is important that we develop a storage system to store this energy that can be used later when the solar source is not available. These types of storage systems are called thermal energy storage systems. In the present work, emphasis is laid on PCMs suitable for the purpose of steam generation. Efficiency of a steam power plant is very much a function of the cycle highest temperature, which in turn requires PCMs with a high melting temperature for thermal energy storage.

When a material melts or vaporizes, it absorbs heat; when it changes to a solid (crystallizes) or to a liquid (condenses), it releases this heat. This phase change is used for storing heat in PCMs. Typical PCMs are water/ice, salt hydrates, and certain polymers. Since energy densities for latent thermal energy storage exceed those for sensible thermal energy storage, smaller and lighter storage devices and lower storage losses normally result.

The main criteria that govern the selection of phase change heat storage materials are [1]:
- Possess a melting point in the desired operating temperature range (temperature range of application).
• Possess high latent heat of fusion per unit mass, so that a smaller amount of material stores a given amount of energy.

• High specific heat to provide additional significant sensible heat storage effects.

• High thermal conductivity, so that the temperature gradients for charging and discharging the storage material are small.

• Small volume changes during phase transition, so that a simple container and heat exchanger geometry can be used.

• Exhibit little or no sub-cooling during freezing.

• Possess chemical stability, no chemical decomposition and corrosion resistance to construction materials.

• Contain non-poisonous, non-flammable and non-explosive elements/compounds.

• Available in large quantities at low cost.

1.2 Phase Change Material Classification

Phase change Materials are broadly classified into three main categories. They are organic, inorganic, and eutectic PCMs. The classification is shown in Figure 1.

Figure 1. Phase change material classification.
Inorganic PCMs have some attractive properties including: high latent heat values, higher thermal conductivity, not flammable, lower in cost in comparison to organic compounds, high water content means that they are inexpensive and readily available. However, their unsuitable characteristics have led to the investigation of organic PCMs for this purpose. These include: corrosiveness, instability, improper re-solidification, suffer from decomposition and super cooling affects their phase change properties. As they require containment, they have been deemed unsuitable for impregnation into porous building materials [2].

Organic PCMs have a number of characteristics which render them useful for latent heat storage in certain building elements. They are more chemically stable than inorganic substances, they are non-corrosive, they have a high latent heat per unit weight, they are recyclable, they melt congruently and they exhibit little or no super cooling i.e. they do not need to be cooled below their freezing point to initiate crystallization [2].

1.3 Literature Review

Agyenim et al. [1] reviewed the developments in the latent heat thermal energy storage systems. The authors have also reviewed the various Phase Change Materials that were investigated since the past three decades, the heat transfer and improvement techniques employed in PCMs to effectively charge and discharge latent heat energy and the formulation of the phase change problem. The authors also have reviewed the geometry and configurations of PCM containers as well as a series of numerical and experimental tests undertaken to evaluate the effects of parameters such as the inlet temperature and the mass flow rate of the heat transfer fluid (HTF). In their study, the authors have drawn a conclusion that most of the phase change problems have been carried out at temperature ranges between 0 °C and 60 °C suitable for domestic heating applications.
Nagasaka and Nagashima [3] investigated the thermal conductivity data for molten NaN03 and KN03. Measuring the thermal conductivity of molten salts is very difficult, mainly due to their corrosiveness and high melting temperatures. These reasons present difficulties in designing an apparatus. Moreover, considerable systematic errors creep in due to radiation and convection. According to the authors, some recent measurements seem to produce more trustworthy values than obtained before. The authors have collected all available data and evaluated them critically. The temperature range that is covered for molten NaN03 is 584 to 662 K and for molten KN03 is 662 to 712 K, with the confidence limits better than ±5%.

Bellan et al. [4] numerically investigated the performance of a latent heat packed bed thermal energy storage system based on encapsulated PCMs. The PCMs used in this case is NaN03 and HTF is a high temperature synthetic oil (Therminol 66). Parameters that influence the performance of the thermal energy storage system have been investigated in this study. They are, capsule size, fluid temperature (Stefan number), tank size (length and diameter) and fluid flow rate. In this study, enthalpy formulation method was used to model the phase change process inside the capsule and the extended brinkman equation was used to predict the flow inside the system. The authors have considered four different capsule sizes for the purpose of this study. The study observed that the temperature of the PCM bed gradually decreased with increase in time. The authors have reported that the heat transfer rate of the bed is high for small size capsules as compared to the larger size capsules. The authors have also reported that the time taken for complete solidification of the PCM decreases with increase in the HTF flow rate. This has been attributed to the increasing heat transfer rate for a higher flow rate.

Zheng et al. [5] carried out an experimental and computational investigation of encapsulated NaN03 for high temperature applications. The authors in this research have studied
the performance of a thermal energy storage system using Encapsulated Phase Change Materials (EPCMs). The PCM used in this case is NaNO₃. The HTF used in this study is compressed air. The test section constructed for the purpose of this study satisfactorily demonstrated that the EPCM capsules have the ability to store and discharge thermal energy during multiple charging and discharging cycles.

Aldoss and Rahman [6] analyzed the effects of using multiple phase change materials having a continuously varying melting temperature. In their work, the authors have introduced three cascaded stages and compared its performance with continuous linear cascading and have concluded that introducing cascading arrangements with multiple PCMs proves to be advantageous when compared to the uniform case. The authors in their study have shown that the time for charging and discharging processes greatly improves when using cascading. They attribute this to the PCM melting and solidifying in a shorter time.

Bauer et al. [7] investigated sodium nitrate (NaNO₃) as a PCM. The authors in their work have evaluated the thermal stability of NaNO₃ by carrying out long duration oven tests. They report that, although some nitrite formation in the melt was detected, results show that the thermal stability of NaNO₃ is adequate for PCM applications. Long-term measurements by the authors show that NaNO₃ at 350 °C is thermally stable and nitrite formation can be neglected. The authors have measured and reported some thermo-physical properties of NaNO₃. These properties include the thermal diffusivity by the laser flash method and the heat capacity by a heat flux differential scanning calorimeter. Further, reliable temperature dependent thermo-physical values of density, heat capacity, diffusivity and conductivity have also been identified. The authors state that their results show that there is a lack of consistent conductivity and diffusivity data in the solid phase.
Sharma et al. [8] reviewed thermal energy storage with phase change materials and their applications. The authors have summarized the investigation and analysis of the available thermal energy storage systems incorporating PCMs for use in different applications. The authors have mentioned the different storage methods employed currently to store heat, viz., sensible energy storage, latent energy storage, and thermochemical energy storage. The authors have reviewed in detail the different latent heat storage materials like paraffins, non-paraffins, salt hydrates, metalics, and eutectics. The thermal, physical, and chemical properties of these materials have also been discussed. They have also reviewed the availability of these materials along with their costs. The authors have also discussed the thermal energy storage systems like solar water-heating systems, solar air heating systems, solar cookers, and solar green house. They have also delved into the applications of the phase change materials with respect to these storage systems.

From the literature review conducted, it can be inferred that most of the phase change problems have been carried out at temperature ranges between 0 °C and 60 °C that are suitable for domestic heating applications. In most studies, both experimental and numerical, Sodium Nitrate and Potassium Nitrate have been researched as phase change materials. But Potassium Hydroxide has not been explored much as a phase change material. Above all, studies on a cascaded TESS that incorporates all these three PCMs have not been conducted either experimentally or numerically to the best of knowledge of this author. These factors provided the motivation for the present work.
1.4 Properties of Phase Change Materials Used In This Study

In the present research, Potassium Hydroxide, Potassium Nitrate and Sodium Nitrate have been selected as phase change materials (PCMs) keeping in view their properties namely melting temperature, thermal conductivity, and specific heat, which make them suitable for high temperature concentrated solar power generation. These properties play a vital role in getting the best out of a PCM. Table 1 summarizes the properties of the selected PCMs.

Since the selected PCMs have high melting temperatures, an appropriate HTF is needed for the charging process. The desired properties that the HTF should possess in this application are as follows [9]:

- melting point of the HTF must be below the night time temperature of a typical concentrating solar power (CSP) site.
- a reasonable specific heat capacity
- and a low vapor pressure

An ideal HTF identified for this application is the eutectic sodium–potassium alloy (NaK). In general, metallic heat transfer fluids possess good heat transfer properties. NaK is a eutectic alloy of sodium and potassium, and has the following properties [9]:

- Composition: 22% Na, 78% K (by mass)
- Melting point: -12.8 °C
- Boiling point@101 kPa: 785 °C
- Density: 724 kg/m³
- Specific heat capacity: 879 J/kg K
- Viscosity: 0.000176 Pa s
- Safety: Reacts violently with water
TABLE 1
PROPERTIES OF THE PHASE CHANGE MATERIALS [10-16]

<table>
<thead>
<tr>
<th></th>
<th>Potassium Hydroxide (KOH)</th>
<th>Potassium Nitrate (KNO₃)</th>
<th>Sodium Nitrate (NaNO₃)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td>Inorganic Compound</td>
<td>Alkali Metal Nitrate</td>
<td>Alkali Nitrate Salt</td>
</tr>
<tr>
<td><strong>Sources</strong></td>
<td>Electrolysis of KOH solution</td>
<td>Mineral Sources</td>
<td>Naturally occurring within mineral deposits / also produced synthetically</td>
</tr>
<tr>
<td><strong>Melting Temperature (°C)</strong></td>
<td>380</td>
<td>330</td>
<td>310</td>
</tr>
<tr>
<td><strong>Heat of fusion (kJ/kg)</strong></td>
<td>149.7</td>
<td>266</td>
<td>172</td>
</tr>
<tr>
<td><strong>Dynamic viscosity (Pa-S)</strong></td>
<td>3.7 x 10⁻³</td>
<td>2.83 x 10⁻³</td>
<td>2.57 x 10⁻³</td>
</tr>
<tr>
<td><strong>Thermal Expansion Co-efficient (1/K)</strong></td>
<td>3.15 x 10⁻⁴</td>
<td>2.23 x 10⁻⁴</td>
<td>2.7 x 10⁻⁴</td>
</tr>
<tr>
<td><strong>Specific heat capacity in solid state (J/kg-K)</strong></td>
<td>1470</td>
<td>1220</td>
<td>1820</td>
</tr>
<tr>
<td><strong>Specific heat capacity in liquid / molten state (J/kg-K)</strong></td>
<td>1481.32</td>
<td>1368.99</td>
<td>1653.98</td>
</tr>
<tr>
<td><strong>Thermal Conductivity in solid state (W/m-K)</strong></td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Thermal Conductivity liquid / molten state (W/m-K)</strong></td>
<td>0.514</td>
<td>0.411</td>
<td>0.514</td>
</tr>
<tr>
<td><strong>Density in solid state (kg/m³)</strong></td>
<td>2044</td>
<td>2110</td>
<td>2260</td>
</tr>
<tr>
<td><strong>Density liquid / molten state (kg/m³)</strong></td>
<td>1765.2</td>
<td>1865</td>
<td>1900</td>
</tr>
<tr>
<td><strong>Corrosiveness</strong></td>
<td>Yes, corrosive in nature</td>
<td>Oxidant, irritant</td>
<td>Oxidant, irritant</td>
</tr>
<tr>
<td><strong>Flashpoint</strong></td>
<td>Non-flammable</td>
<td>Non-flammable</td>
<td>Non-flammable</td>
</tr>
<tr>
<td><strong>Thermal stability</strong></td>
<td>KOH exhibits high thermal stability. Even at high temperatures, does not dehydrate readily</td>
<td>Decomposes at 400°C</td>
<td>Research shows that NaNO₃ is thermally stable at 350°C</td>
</tr>
<tr>
<td><strong>Available form</strong></td>
<td>Melt-cast as pellets or rods</td>
<td>White solid</td>
<td>Colorless crystals</td>
</tr>
<tr>
<td><strong>Applications</strong></td>
<td>Direct steam generation</td>
<td>Direct steam generation</td>
<td>Direct steam generation</td>
</tr>
</tbody>
</table>
1.5 Description of PCM Layouts

In this study, five different types of PCM layouts have been employed. Three uniform layouts and two cascaded layouts. The uniform layouts comprise of uniform KOH, uniform KNO₃, and uniform NaNO₃ layouts. Uniform PCM layout implies that only one type of PCM is used throughout the bed at a given instance. Cascaded PCM layout means having multiple PCMs with different melting temperatures arranged on the bed either in ascending or descending order of their melting temperatures. The cascaded layout is of two types, slope down and slope up layout. Cascaded slope down PCM layout implies that the PCMs are arranged in the descending order of their melting temperatures i.e., KOH(380 °C) - KNO₃(330 °C) - NaNO₃ (310°C). Cascaded slope up PCM layout implies that the PCMs are arranged in the ascending order of their melting temperatures i.e., NaNO₃(310°C) - KNO₃(330 °C) - KOH (380 °C). The schematic of a inline and a staggered system is shown in Figure 2 and 3 respectively.

![Schematic of a inline arrangement.](image)
1.6 Methodology

Three uniform layouts and two cascaded layouts have been employed for this research. Section 1.5 describes each layout in detail along with the schematics. Three pellet diameters 0.01m, 0.02m, and 0.03m and six HTF flow rates (three for the charging cycle and three for the discharge cycle) have been selected for this study. The HTF flow rates during charging are 0.5 L/min, 1.0 L/min, and 1.5 L/min. The HTF flow rates during discharging are 10.0 L/min, 15.0 L/min, and 18.0 L/min. The methodology adopted is common for all five layouts. The computation is carried out using a MATLAB program tailored for the purpose of this analysis. The methodology is as follows:

1. Pellet diameter varying and HTF flow rate constant (refer Table 2)
In this case, the HTF flow rate is constant at 1.0 L/min for charging and 15.0 L/min for discharging. Every run comprises a charging and a discharging cycle. The computation is first carried out for 0.01m diameter pellet. The values for pellet diameter and HTF flow rate are entered in the MATLAB program. Properties of the PCMs and the HTF are embedded within the program. The MATLAB simulates 900 minutes of run time for each cycle. For a complete cycle, i.e., charging and discharging, the simulation represents a run time of 1800 minutes. After computation, the MATLAB program prints out plots of ALF vs time and energy stored vs time. The process is repeated for the discharge cycle too, with the exception of change in the HTF flow rate (see Table 2). In the second run, the pellet diameter is increased to 0.02m and all the other parameters remain unchanged. After this run is complete, a set of plots for ALF and energy stored are obtained. For the third run, the pellet diameter is increased to 0.03m and the entire process is repeated.

2. Pellet diameter constant and varying HTF flow rate (refer Table 2)

In this case, pellet diameter is constant at 0.02m and the HTF flow rate is varied. The computation is first carried out for a HTF flow rate of 0.5 L/min during charging and 10.0 L/min during discharging. The values for pellet diameter and HTF flow rate are entered in the MATLAB program. As discussed in the previous case, the MATLAB program prints out plots of ALF versus time and energy stored versus time. The process is repeated for the discharge cycle too, with the exception of change in the HTF flow rate (see Table 2). In the second run, the HTF flow rates are 1.0 L/min and 15.0 L/min for the charging and discharging cycles respectively. All the other parameters remain unchanged. After this run is complete, a set of plots for ALF and energy stored are obtained. For the third run, the HTF flow rates are 1.5 L/min and 18.0 L/min for the charging and discharging cycles respectively and the entire process is repeated.
NOTE: For the combined sensible-latent heat storage system, the methodology remains the same with the exception of Aragonite being used as the sensible heat storage material and KOH-Aragonite being used for the combined SHS-LHS (refer Table 6).

1.7 Mathematical Model

In this work, a rectangular shaped tank having dimensions $l \times w \times z$ is considered for the purpose of storing thermal energy. The tank is assumed to be filled with $N$ number of pellets. The pellets are cylindrical in shape having an outer diameter $d$ and length $z$, which is equal to the depth of the tank. The properties of all three PCMs are listed in Table 1. Since the objective of using these PCMs is for high temperature applications namely steam generation, the HTF assumed here is eutectic sodium–potassium alloy the properties of which is mentioned in section 1.4.

A schematic of the rectangular thermal storage tank is shown in Figure 4. The packed PCM bed is divided into $N$ number of elements. Each element consists of PCM pellets and is surrounded by HTF. Energy balance is applied to an element of volume $A\Delta x$ having PCM at a temperature $T_b$ and HTF flowing at the rate of $\dot{m}_f$ and entering at a temperature $T_f$.

![Figure 4. Schematic of the rectangular thermal storage tank.](image-url)
This equation can be written as [17]

\[
(\dot{m}C_p)_f T_f - (\dot{m}C_p)_f \left[ T_f + \frac{\partial T_f}{\partial x} \Delta x \right] = U_v A \Delta x (T_f - T_b) + U_s \pi D \Delta x (T_f - T_x) + \
\rho_f (A \Delta x) \varepsilon C_{p,f} \frac{\partial T_f}{\partial x}
\]

(1)

The left hand side of Eq. (1) represents heat flow due to the movement of HTF. The first and second terms on the right hand side represent heat exchange between the PCM pellets and HTF and loss of heat to the environment respectively. The last term of Eq. (1) represents the rate of stored energy of the HTF in the control volume.

If we consider that the heat losses to be negligible based on the assumption that the storage tank is well insulated and the energy stored in the HTF is negligible, the energy balance at any instance is as follows [17].

\[
(\dot{m}C_p)_f T_f - (\dot{m}C_p)_f \left[ T_f + \frac{\partial T_f}{\partial x} \Delta x \right] - U_v A \Delta x (T_f - T_b) = 0
\]

(2)

or

\[
\frac{\partial T_f}{\partial x} = \frac{-U_v A}{(\dot{m}C_p)_f} (T_f - T_b)
\]

(3)

simplifying further, we get

\[
\frac{\partial T_f}{\partial (x/l)} = -NTU (T_f - T_b)
\]

(4)

where NTU=(U_v A l)/(\dot{m}C_p)_f is the number of transfer units. Integration yields,

\[
\frac{T_{fi+1} - T_{bi}}{T_{fi} - T_{bi}} = \exp\left(\frac{-NTU}{N}\right)
\]

(5)

\[
\frac{T_{fi} - T_{fi+1}}{T_{fi} - T_{bi}} = 1 - \exp\left(\frac{-NTU}{N}\right)
\]

(6)

The outlet temperature of the HTF for \(i^{th}\) element is:

\[
T_{fi+1} = T_{fi-} \left[ (T_{fi} - T_{bi}) \left( 1 - \exp\left(\frac{-NTU}{N}\right) \right) \right]
\]

(7)
where $T_{fi}$ is the HTF temperature at inlet to the element and $T_{f_{i+1}}$ is the HTF temperature at outlet from the element, $T_{bl}$ represents the bed temperature of the element and $N=1/\Delta x$ is the number of elements in the packed bed. Eq. (7) can be written for each control volume forming a system of $N$ simultaneous equations. The NTU value and bed temperature of the element ($T_{bl}$) can be determined by knowing the volumetric heat transfer coefficient and the energy transferred into the PCM pellets. This is as explained below:

The volumetric heat transfer coefficient for a thermal storage system can be written as [17]:

$$U_v = 4U_o(1 - \varepsilon)/D_c$$  \hspace{1cm} (8)

For a PCM pellet, the outer surface overall heat transfer coefficient $U_o$, is a function of either charging or discharging, the state of the PCM pellet in the control volume (fully liquid, fully solid, or phase change processes) and the mechanism of heat transfer (conduction, convection or combined conduction and convection).

During the fully liquid or fully solid stages, the overall heat transfer coefficient can be calculated by using thermal resistance concept for each pellet as given below:

$$U_o = (1/A)(R_{ext} + R_c)^{-1}$$  \hspace{1cm} (9)

where $R_{ext}$ is the convective thermal resistance on the external surface of the pellet shell and $R_c$ is the conductive thermal resistance through the pellet wall.

During the phase change process the outer surface overall heat transfer coefficient can be calculated by using thermal resistance concept for each pellet as given below:

$$U_o = (1/A)(R_{ext} + R_c + R_{in}(t))^{-1}$$  \hspace{1cm} (10)

where $R_{ext}$ is the thermal resistance due to convection on the external surface of the pellet shell, $R_c$ is the thermal resistance due to conduction through the pellet wall and $R_{in}(t)$ is
the resistance due to the solidified/melt PCM layer inside the pellet. It is a function of time.

\[ R_{ext} = \frac{1}{(h_o * A_o)}; \quad R_c = \ln \left( \frac{R_{ro}}{R_{cl}} \right) / (2 \pi . z . k_c); \quad R_{in(t)} = \frac{1}{(\epsilon_e * \pi * D_{cl} * z)} \]

The bed temperature is calculated by using the energy balance between the heat transfer fluid and the bed. The energy transferred to the bed, \( U_v A \Delta x (T_f - T_b) \), results in raising the bed temperature at the rate of \( \frac{dT_b}{dt} \) written as

\[ U_v A \Delta x (T_f - T_b) = \rho_b (A \Delta x)(1 - \epsilon) C_{p.b} \frac{dT_b}{dt} \]  

(11)

for simplification, multiply by \( \frac{(Al)}{(mC_p)_f} \) on both sides

\[ U_v(T_f - T_b) \frac{(Al)}{(mC_p)_f} = (\rho C_p)_b (1 - \epsilon) \frac{dT_b}{dt} \left( \frac{(Al)}{(mC_p)_f} \right) \] 

(12)

since \( NTU = \frac{U_v A l}{(mC_p)_f} \), this equation can be written as

\[ \frac{(\rho C_p)_b (1-\epsilon) Al dT_b}{dt} = NTU (T_f - T_b) \] 

(13)

Eq. (13) can be discretized for ‘\( i^{th} \)' element by using simple explicit and first order finite difference formulation, and can be written as

\[ \frac{(\rho C_p)_b (1-\epsilon) Al \Delta t}{(mC_p)_f} = NTU (T_{fi} - T_{bi}) \] 

(14)

\[ (T_{bi+1}^n - T_{bi}^n)(\rho C_p)_b (1 - \epsilon) Al = (mC_p)_f \Delta t . NTU (T_{fi}^n - T_{bi}^n) \] 

(15)

The total energy stored in the ‘\( i^{th} \)' element can then be expressed as the sum of the heat storage of pellets and the heat transfer fluid:

\[ q_{total,i} = q_{PCM,i} + q_{HTF,i} \]  

(16)

The energy stored in the pellets contained in the bed element ‘\( i \)' is given by

\[ q_{PCM,i} = \int_{T_{initial}}^{T_{p-a1}} mC_{ps} dT + \int_{T_{p-a1}}^{T_{p+a2}} mC_{ps} dT + mL_p + \] 

\[ \int_{T_{m-e1}}^{T_{m+e2}} mC_{pl} dT + ml + \int_{T_{m+e2}}^{T_{final}} mC_{pl} dT \] 

(17)
where \( T_{p+a2} \) and \( T_{p-a1} \) are the solidus and liquidus temperatures.

The energy stored in the heat transfer fluid is given by

\[
q_{HTF,i} = m_f C_{p,f} (T_{initial} - T_{final})
\]  

(18)

where \( T_{initial} \) denotes the initial temperature, \( T_{final} \) the final temperature of the process and \( m_f \) is the mass of the heat transfer fluid in the element. The energy stored in the storage comprising of ‘N’ such elements can then be written as:

\[
Q_{storage} = \sum_{i=1}^{N} q_{total,i}
\]  

(19)

1.8 Results and Discussion

In this study, a rectangular tank measuring 1 m in length, 1 m in height, and 1 m in depth is considered. The storage tank is considered to be well insulated and it is assumed that there are no heat losses. Table 2 shows the different combinations of pellet diameter and HTF flow rate used to study the performance of the TESS and applies to all the five PCM layouts described previously as well as for both the in-line and staggered arrangements. The effect of pellet diameter and effect of HTF flow rate on the performance of the thermal energy has been studied. The key parameters evaluated are Average Liquid Fraction (ALF) and total energy stored and retrieved.

**TABLE 2**

DETAILS OF DIFFERENT CASES STUDIED

<table>
<thead>
<tr>
<th>Study</th>
<th>Case #</th>
<th>Pellet diameter (m)</th>
<th>HTF flow rate (L/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Charging</td>
</tr>
<tr>
<td>Effect of pellet diameter</td>
<td>Case 1</td>
<td>0.01</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>Case 2</td>
<td>0.02</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>Case 3</td>
<td>0.03</td>
<td>1.0</td>
</tr>
<tr>
<td>Effect of HTF flow rate</td>
<td>Case 1</td>
<td>0.02</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Case 2</td>
<td>0.02</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>Case 3</td>
<td>0.02</td>
<td>1.5</td>
</tr>
</tbody>
</table>
To study the effect of pellet diameter on the performance of the TESS, simulations were carried out using three different diameter pellets. PCM pellets having diameters 0.01 m, 0.02 m, and 0.03 m were used. The HTF flow rate was kept constant while varying the pellet diameter. The HTF flow rate during the charging process is 1.0 L/min and it is 15.0 L/min during the discharge process. Table 3 shows the operating temperatures of the TESS.

**TABLE 3**

**OPERATING TEMPERATURES**

<table>
<thead>
<tr>
<th>Operating Temperature in °C</th>
<th>Charging</th>
<th>Discharging</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniform layout – KOH</td>
<td>400</td>
<td>360</td>
</tr>
<tr>
<td>Uniform layout – KNO3</td>
<td>350</td>
<td>310</td>
</tr>
<tr>
<td>Uniform layout – NaNO3</td>
<td>330</td>
<td>290</td>
</tr>
<tr>
<td>Cascaded Slope Up</td>
<td>400</td>
<td>290</td>
</tr>
<tr>
<td>Cascaded Slope Down</td>
<td>400</td>
<td>290</td>
</tr>
</tbody>
</table>

Figures 5-10 present the variation of average liquid fraction with time for varying pellet diameter and constant HTF flow rate, for both in-line and staggered PCM arrangements. It can be observed that during charging, the cascaded slope down PCM layout melts completely in the shortest time while the uniform KNO3 PCM layout takes the longest time to melt. During the discharging process, the cascaded slope up PCM layout solidifies in the shortest time while the uniform KNO3 PCM layout takes the longest time to solidify. It can be further mentioned that as the diameter of the PCM pellet increases, the melting and solidifying time also increases. Hence, the melting and solidifying time of the PCM is proportional to the pellet diameter.
Figure 5. Average Liquid Fraction (d=0.01m, Q=1.0L/min, Inline).

Figure 6. Average Liquid Fraction (d=0.01m, Q=1.0L/min, Staggered).

Figure 7. Average Liquid Fraction (d=0.02m, Q=1.0L/min, Inline).
Figure 8. Average Liquid Fraction (d=0.02m, Q=1.0L/min, Staggered).

Figure 9. Average Liquid Fraction (d=0.03m, Q=1.0L/min, Inline).

Figure 10. Average Liquid Fraction (d=0.03m, Q=1.0L/min, Staggered).
Figures 11-16 present energy stored/retrieved as a function of time for varying pellet diameter and constant HTF flow rate, for both in-line and staggered PCM arrangements. It can be observed that of all the layouts, the cascaded slope down and slope up PCM layouts record the highest energy and the uniform KOH layout records the lowest energy. Among the uniform PCM layouts, KNO₃ records the highest energy followed by NaNO₃ and then KOH. We know that heat of fusion is the energy given up by the mass of liquid when it solidifies. Since KNO₃ has the highest heat of fusion, it stores/gives up the highest energy among the three PCMs. The energy level of the cascaded slope down PCM layout reaches its maximum in the shortest time and in contrast, the energy level of the uniform KNO₃ layout takes the longest time. It can be observed that increase in pellet diameter has almost no effect on the amount of energy stored by the PCM layouts. It can be observed that as the pellet diameter increases, the time taken for the energy to reach its maximum level also increases. For the parameters evaluated i.e., average liquid fraction and energy stored/retrieved, overall the cascaded PCM layouts produced the best results as compared to the uniform layouts. The cascaded slope down layout was more efficient during charging while the cascaded slope up layout during discharge. This difference is very negligible as can be seen from Figure 5 to 16. Comparing the performance of the uniform PCM layouts in terms of time, the uniform KOH layout exhibited the shortest melting and solidification time. In terms of energy storage, the uniform KNO₃ layout outperforms both the uniform KOH and uniform NaNO₃ layouts by virtue of its high heat of fusion.
Figure 11. Energy Stored/Retrieved in kJ (d=0.01m, Q=1.0L/min, Inline).

Figure 12. Energy Stored/Retrieved in kJ (d=0.01m, Q=1.0L/min, Staggered).

Figure 13. Energy Stored/Retrieved in kJ (d=0.02m, Q=1.0L/min, Inline).
Figure 14. Energy Stored/Retrieved in kJ (d=0.02m, Q=1.0L/min, Staggered).

Figure 15. Energy Stored/Retrieved in kJ (d=0.03m, Q=1.0L/min, Inline).

Figure 16. Energy Stored/Retrieved in kJ (d=0.03m, Q=1.0L/min, Staggered).
In order to study the effect of HTF flow rate on the performance of the TESS, simulations were carried out by employing three different flow rates. The pellet diameter was kept constant at 0.02 m while varying the HTF flow rate. The HTF flow rates employed are 0.5 L/min, 1.0 L/min, and 1.5 L/min during charging. During discharging, the corresponding HTF flow rates are 10.0 L/min, 15.0 L/min, and 18.0 L/min. These conditions were applied to both in-line and staggered PCM arrangements. Table 2 shows the different combinations of HTF flow rate and pellet diameter. Figures 17-22 show the effect of varying HTF flow rate on the liquid fraction while keeping the diameter constant, for both in-line and staggered PCM arrangements. It can be observed that during charging, the cascaded slope down PCM layout melts completely in the shortest time while the uniform KNO₃ PCM layout takes the longest time to melt. During the discharging process, the cascaded slope up PCM layout solidifies in the shortest time while the uniform KNO₃ PCM layout takes the longest time to solidify. It may be recalled that in the case of varying pellet diameter and constant HTF flow rate, similar trends were observed. It may be further mentioned from the above cases that as the HTF flow rate increases, the melting and solidifying time decreases and this holds true for both the in-line and staggered arrangements.

![Figure 17. Average Liquid Fraction (d=0.02m, Q=0.5 L/min, Inline).](image-url)
Figure 18. Average Liquid Fraction (d=0.02m, Q=0.5 L/min, Staggered).

Figure 19. Average Liquid Fraction (d=0.02m, Q=1.0 L/min, Inline).

Figure 20. Average Liquid Fraction (d=0.02m, Q=1.0 L/min, Staggered).
Figure 21. Average Liquid Fraction (d=0.02m, Q=1.5 L/min, Inline).

Figure 22. Average Liquid Fraction (d=0.02m, Q=1.5 L/min, Staggered).
Figures 23-28 present energy stored/retrieved as a function of time for varying HTF flow rate and constant pellet diameter, for both in-line and staggered PCM arrangements. It can be observed that of all the layouts, the cascaded slope down and slope up PCM layouts record the highest energy and the uniform KOH PCM layout records the lowest energy. Among the uniform PCM layouts, KNO₃ records the highest energy followed by NaNO₃ and then KOH. The energy level of the cascaded slope down PCM layout reaches its maximum in the shortest time and in contrast, the energy level of the uniform KNO₃ layout takes the longest time. While the total energy that can be stored by each PCM does not change with increase in the HTF flow rate, it is worthwhile to observe that as the HTF flow rate is increased the time taken for the energy level of the PCMs to reach its maximum decreases. This trend is observed both during energy storage and retrieval process for both in-line as well as staggered arrangements.

![Energy Stored/Retrieved in kJ (d=0.02m, Q=0.5 L/min, Inline).](image-url)

Figure 23. Energy Stored/Retrieved in kJ (d=0.02m, Q=0.5 L/min, Inline).
Figure 24. Energy Stored/Retrieved in kJ (d=0.02m, Q=0.5 L/min, Staggered).

Figure 25. Energy Stored/Retrieved in kJ (d=0.02m, Q=1.0 L/min, Inline).

Figure 26. Energy Stored/Retrieved in kJ (d=0.02m, Q=1.0 L/min, Staggered).
1.9 Validation of results

The results obtained in this study have been validated using results from experimental studies carried out by Zheng et al. [5]. They have carried out an experimental and computational investigation of encapsulated NaNO₃ for high temperature applications. Zheng et al. have studied the performance of a thermal energy storage system using Encapsulated Phase Change Materials (EPCMs). The PCM used in this case is NaNO₃. In the present research too, NaNO₃ is used as one of the PCMs. To the best of knowledge of this author and from the literature explored for the purpose of this study, a cascaded latent heat storage system comprising KOH, KNO₃, and
NaNO₃ as PCMs, has not be evaluated. Hence the mathematical model in this research is validated taking into consideration the uniform NaNO₃ layout. Since the mathematical model holds good for both the uniform and cascaded layouts, it is sufficient for the mathematical model to be validated just for one PCM. In order to validate the mathematical model, the calculations were run by employing similar dimensions and parameters as the ones used by Zheng et al. in their experimental work. Two key parameters namely energy stored and energy transfer rate were validated. The values obtained for these parameters were compared with the results obtained by Zheng et al. This comparison is shown in Table 4. For the energy stored, the percentage error between the experimental and calculated values is 13.21 % and for the energy transfer rate, the percentage error between the experimental and calculated values is 8.01 %.

TABLE 4
VALIDATION: PRESENT MATHEMATICAL MODEL VERSUS EXPERIMENTAL RESULTS

<table>
<thead>
<tr>
<th></th>
<th>Experimental Results [5]</th>
<th>Present Mathematical Model</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Stored (kJ)</td>
<td>18300</td>
<td>15882</td>
<td>13.21</td>
</tr>
<tr>
<td>Energy Transfer Rate (kW)</td>
<td>6</td>
<td>5.5</td>
<td>8.01</td>
</tr>
</tbody>
</table>
CHAPTER 2
A DETAILED STUDY OF COMBINED SENSIBLE-LATENT HEAT STORAGE SYSTEMS

2.1 Introduction

In order to wean ourselves from non-renewable energy sources, it is important to increase our focus on renewable forms of energy. One of the most abundant and easily available non-renewable forms of energy is the solar energy. Though solar energy is abundantly available, it availability is intermittent in nature. Energy consumption is not constant. It varies based on the demand. In most of the cases, renewable energy sources do not have the capacity to meet peak load demands. This problem can be solved by storing energy and using it later. Thermal energy storage systems have a come a long way in fulfilling our ever growing energy demands. Based on the method of storage, the thermal energy storage systems can be broadly classified as sensible heat storage, latent heat storage, and thermo-chemical heat storage. Each method of storage has its own advantages and disadvantages. In order to offset the drawbacks of the individual storage systems and to get maximum efficiency out of a thermal energy storage system, hybrid storage systems comprising two different storage systems are used. The objectives of this part of the research is to explore in detail combined sensible-latent heat storage systems and highlight their advantages, limitations, applications, heat storage materials and Heat Transfer Fluid used, and the potential of these combined systems to offset the limitations posed by individual storage systems.

Hybrid thermal energy storage systems are those that combine two different types of storage systems. The two main types of hybrid thermal energy storage systems currently being explored and developed are the sensible heat-latent heat storage systems and sensible heat-
thermochemical heat storage systems. Each storage system has its own advantages and
disadvantages. Thermal energy storage technology can be classified into three main types:
sensible, latent and thermochemical storage. The Thermal Energy Storage (TES) can be
categorized based on several parameters. Some of them are temperature range, primary heat
source, storage material, duration of storage and field of application [18]. In sensible heat
storage, a change in the temperature of the storage material allows heat storage. Materials in the
liquid and solid form are most appropriate for sensible heat storage. We need to keep in mind the
volumetric storage density depends on the specific heat capacity, material density and variation
in temperature. Sensible storage is the simplest of the three storage methods [18]. The state of the
art of commercially available heat storages for domestic applications is dominated by sensible
systems, based on water as heat storage medium. Actually, for applications at temperatures lower
than 100 °C, the sensible/water system seems to be the best option thanks to its availability, its
low cost, and sufficiently high specific heat. Nevertheless, it suffers of the intrinsic limit related
to the heat losses to the ambient that causes reduction of energy stored during the stand-by
periods. This leads to the necessity of careful insulation of the vessels, thus reducing the overall
volumetric heat storage density of the systems [19]. In latent heat storage, the heat is stored as a
result of a phase change in the storage material. In case of latent heat storage, the area of interest
is the phase change from liquid to solid state. From a practical perspective, latent storage is used
in combination with sensible storage since a temperature difference is required between the
source and the heat storage material. The main advantage of latent storage stems from the
possibility that heats of condensation and of evaporation can be charged and discharged with
minimized temperature differences and hence minimized exergy losses [18]. The energy density
is quite high in case of latent heat storages, minus the high pressures, unlike the case of steam
accumulators or pressurized water tanks. The LHS systems are not widely used commercially as much as SHS systems due to the poor heat transfer rate during heat storage and recovery processes. This can be attributed to the fact that during phase change, the solid–liquid interface moves away from the convective heat transfer surface (during charging in cool storage process and discharging in hot storage process) due to which the thermal resistance of the growing layer of solidified PCM increases, thereby resulting in poor heat transfer rate [20]. Sensible heat storage systems have a limitation where in the temperature of the HTF at the end of the discharge cycle drops, thereby reducing the efficiency of the storage system. A latent heat storage system cannot store heat within a large temperature range. These limitations can be overcome by integrating the sensible storage with a latent storage. This integration helps in stabilizing the outlet temperature of the HTF during the discharge cycle to around the temperature of the PCM melting point. In the SHS-LHS, benefits can be derived from the high energy density of the PCM and the high power delivering capacity of the sensible storage material. In a SHS-LHS system the PCM minimizes the temperature drop at the outlet during the discharge cycle. In a SHS-LHS system, it is possible to reduce the power loss of the sensible storage. The combination of sensible and latent storage ensures that surge in power demand in other words the peak power requirements can be met all the same satisfying the base load conditions. The sensible storage meets the peak power requirements and the PCM satisfies the base load conditions. The objectives of this review is to study in detail combined sensible-latent heat storage systems and highlight their advantages, limitations, applications, heat storage materials and Heat Transfer Fluid used, and the potential of these combined systems to offset the limitations posed by individual storage systems. In this study, combined sensible-latent heat storage systems pertaining to both low and high temperature applications have been explored.
2.2 STUDY OF HIGH TEMPERATURE SENSIBLE-LATENT HEAT STORAGE SYSTEMS

Zanganeh et al. [21], have experimentally investigated a combined sensible–latent heat for thermal energy storage at 575 °C. AlSi\textsubscript{12} (88% Al and 12% Si by mass) encapsulated in stainless steel tubes is used for storing latent heat, where as rocks are used for storing the sensible heat. The schematic and configuration of the combined sensible-latent thermal energy storage prototype is shown in Figure 29 and 30.

Figure 29. Scheme of the combined sensible and latent heat concept for thermal energy storage, comprising a relatively small layer of PCM on top of a packed bed of rocks [21].

Figure 30. Configuration of the lab-scale prototype [21].
Air is used as the Heat Transfer Fluid (HTF) and a 21 kW electric heater is used to heat the incoming air. During charging, the heated air enters from the top of the prototype and exits at the bottom. During the discharge process, air enters from the bottom and exits at the top. This can be seen in the schematic shown in Figure 30. The operating temperature during charging ranges between 600-700 °C and that during discharge is 25 °C. The authors in their work have investigated two configurations. One configuration consists of the rocks and PCM arrangement and the other configuration consists of only rocks. The purpose of the latter configuration is to compare the performance of the SHS-LHS system with the standalone sensible storage system. Four runs were carried out, two each for “rocks+PCM” and “rocks only” configuration. Runs 1 and 2 correspond to the "rocks+PCM" configuration and runs 3 and 4 correspond to the “rocks only” configuration. The mass flow rates and charging times for “rocks+PCM” and “rocks only” were similar. The ambient temperature of the storage system at the start of the charging process was 25 °C. The discharging process continued till the storage system returned back to the initial ambient temperature i.e., 25 °C.
Figure 32 shows a comparison of the bottom and top temperature profiles obtained from the experiments for run 1 (“rocks + PCM” setup) and run 3 (“rocks only” setup). It can be observed that the bottom temperature profiles are similar for both cases which indicates that the energy stored for both the configurations is comparable. The final top temperature of the charging period for the “rocks + PCM” setup is about 10 °C lower than that for the “rocks only” setup. The authors attribute this to the melting process involved in the “rocks + PCM” setup. It can be further observed that the outflow temperature during discharge drops faster at first for the “rocks + PCM” setup, but stabilizes later. The outflow temperature of the “rocks only” setup drops below that of the “rocks + PCM” setup after about 70 min of discharging. In comparison, in the “rocks + PCM” setup the outflow temperature is stabilized for about 90 min after which the PCM solidifies and the temperature begins to drop. The outlet temperature of air was higher for about 20 min in case of the combined SHS-LHS as opposed to the sensible only system. These observations demonstrate that the combined SHS-LHS system plays a pivotal role in stabilizing the outlet temperature to around the melting temperature of the PCM while the PCM is partially molten.

Figure 32. Comparison of the experimentally obtained $T_{\text{inlet, top}}$ and $T_{\text{outlet, bottom}}$ for “rocks + PCM” run 1 (solid lines) and “rocks only” run 3 (dashed line) [21].
Zavattoni et al. [22], have investigated a combined SHS-LHS system comprising of a packed bed of gravel and AlSi$_{12}$. The packed bed of gravel comprises of a mixture of different rocks types such as limestone, quartzite, sandstone and gabbro. This mixture of rocks is used to store sensible heat whereas AlSi$_{12}$ is used to store latent heat. The authors have evaluated thermo-fluid dynamics behavior of the combined SHS-LHS system by employing a computational fluid dynamics approach. In this work, they have accounted for the effect of radial void-fraction variation, which is also known as channeling. Radial void-fraction variation is caused due to a small value of the characteristic vessel-to-particles diameter ratio. In this study, the authors have developed a 2D computational fluid dynamics (CFD) model to simulate the behavior of the combined SHS-LHS system which uses air as HTF. Further, a lab-scale combined SHS-LHS prototype system was used to validate the numerical model by comparing the CFD simulation results with experimental data. The lab-scale combined SHS-LHS prototype system used for the study is shown in Figure 33.

Figure 33. Schematic of the pilot-scale combined TES [22].
AlSi$_{12}$ is used as the PCM for the latent section. The PCM was encapsulated in AISI 316 steel tubes. The encapsulated PCM was positioned on top of the packed bed and distributed into four layers. Each layer consists of 17 tubes each and the tubes are oriented at an angle of 45°, with an average void-fraction of 0.55. During charging, the HTF which is the high-temperature air, up to 595°C, was fed through the TES from the top of the system. Thermal energy of the HTF is transferred to the entire TES. During discharging, the direction of flow of the HTF was reversed and air at ambient temperature was fed through the prototype from the bottom. The prototype TES is equipped with several K-type thermocouples (TCs) and a mass flow meter to monitor the temperature and the HTF mass flow rate during the experiments. The charging process lasted for 3.25 hours and the system was discharged until reaching dead-state condition. The PCM and tank wall temperatures along with the simulated CFD results are shown in Figure 34. TCs T1 to T4 are located in the latent heat region and internal surface of the tank. Figure 35 shows packed bed temperatures along with the simulated CFD results. TCs T6 to T10 are located in the packed bed and sensible heat region.

Figure 34. PCM and tank wall temperatures: CFD simulation results (solid lines) and experimental data (markers) [22].
This study shows that adding a small amount of PCM at the top of the packed bed allows the HTF temperature to stabilize around the PCM melting temperature. The authors have corroborated this with the numerical model. Further, the authors point out that due to the small tank-to-particle diameter ratio, the thermo-fluid dynamics behavior of the combined TES prototype was significantly affected by the radial variation of the void-fraction.

Becattini et al. [23], have experimentally and numerically investigated the world’s first pilot-scale advanced adiabatic compressed air energy storage plant with combined sensible/latent thermal-energy storage. The combined thermal-energy storage comprises of sensible and latent units with maximum capacities of 11.6 MWh\textsuperscript{th} and 171.5 kWh\textsuperscript{th}, respectively. The latent thermal-energy storage comprises a steel tank with 296 stainless-steel tubes encapsulating an Al–Cu–Si alloy as phase-change material. Four charging/discharging cycles were involved while investigating the combined thermal-energy storage. Each cycle had a duration of about 3 hours and air inflow temperatures of up to 566 °C. The experimental results showed that the latent thermal-energy storage reduced the drop in the air outflow temperature during discharging. A schematic of the pilot plant is shown in Figure 36. During charging, hot compressed air enters the cavern through an insulated pipe that directs the air to the top of the TES. The air is cooled by
flowing through the thermocline TES. The cooled air then exits the TES at the bottom and enters the cavern. During discharging, the flow is reversed: cold air from the cavern enters the TES at the bottom, gets heated, leaves the TES at the top, and exits the cavern through the insulated tube. The cavern is 120 m long and has a diameter of 4.9 m and confined by two concrete plugs and steel doors. Figure 37 shows a schematic of the combined SHS-LHS.

![Figure 36. A schematic of the pilot plant [23].](image)

In this study, the authors have designed and constructed a separate latent storage to store the PCM. They point out to many advantages in doing so. First, the cross-sectional area of the latent storage can be chosen independently of that of the sensible storage to give good heat-transfer rates and hence melting behavior of the PCM. Second, a separate latent storage provides the possibility to switch between experiments either with only the sensible TES or with the combined TES by disconnecting and reconnecting the pipe linking the two storages. Third, at least for the current pilot-scale plant, a separate latent storage was easier to construct and adapt.
than if the encapsulated PCM had been placed in the sensible storage, which would have required the removal of its steel cover and the pipe attached to the cover. Fourth, with a view to the possible use of industrial-scale combined storages, a separate latent storage allows the PCM to be inspected and/or replaced more easily. The experiments with the combined sensible/latent storage consisted of four cycles (charging/discharging). Before the first charging phase, in order to approach steady cycling conditions more quickly, the TES was pre-charged. Figure 38 shows the temperature evolution during the four charging/discharging cycles as a function of time at four locations in the latent TES. The authors observed that the measured PCM temperatures in layer 2 at the end of the discharging phases decreased with successive cycles. At the end of the first discharging phase, PCM temperature has only just entered the melting range and therefore the PCM has only just begun solidifying. At the ends of the second and third discharging phases, the temperature of the PCM is well within the melting range and hence the PCM is partially solidified. At the end of the fourth discharging phase, the PCM temperature is below the melting range, indicating that the PCM is fully solidified. The authors have concluded that the latent TES reduced the decrease in the air outflow temperature during discharging. This demonstrates the potential of sensible/latent TES as an attractive option for industrial-scale high-temperature storage. They also observed that the performance of the latent TES decreased with each cycle. The decrease was traced primarily to thermal losses from the pipe connecting the latent and sensible TES units, to air leakages from the cover of the sensible TES, and to mass flow rates that were smaller in the experiments than during the design of the latent TES. Further, as per their observation, the PCM exhibited degradation and/or phase segregation upon thermal cycling, resulting in a decrease of its heat of fusion. These changes were attributed to the initial off-
eutectic composition of and impurities in the PCM as well as to corrosion phenomena between the liquid PCM and the stainless-steel encapsulation at high temperatures.

Figure 38. Temperature evolution during the four charging/discharging cycles as a function of time at four locations in the latent TES [23].

The authors have emphasized that the eutectic compositions should have minimal impurities. With regards to the encapsulation, the authors have stressed the need to address the large-scale production of leak-proof encapsulations and continue the development of coatings that prevent corrosion phenomena.
2.3 STUDY OF LOW TEMPERATURE SENSIBLE-LATENT HEAT STORAGE SYSTEMS

Zauner et al. [24], have designed and built a prototype hybrid sensible-latent storage to study the heat transfer within the storage system. Among the various designs explored by the authors, shell-and-tube heat exchangers found their interest. A lot of work has been carried out by employing the shell-and-tube heat exchanger design where the PCM is located on the shell side and the HTF flows through the tubes. This concept has been investigated widely by using computational fluid dynamics (CFD) to study the melting of the PCM, exploring different storage geometries, and studying the effect of fins on the heat transfer rate. The authors mention that almost no work has been done on the inverted configuration of this design i.e., the configuration where the PCM is stored in the tubes and the HTF flows around the tubes i.e., on the shell side. The prototype has a shell-and-tube heat exchanger design. High density polyethylene (HDPE) is used as PCM and thermal oil serves the purpose of sensible storage as well as a HTF. Using this design, it is possible to vary the latent and sensible energy contributions over a wide range. In such storages, one can benefit from both, the high energy density of PCMs and the high powers of the sensible storages. The authors mention that their design is the first of its kind, which is a fully integrated solution of a hybrid sensible-latent heat storage based on an inverted shell-and-tube configuration. A shell-and-tube heat exchanger was redesigned and the PCM is encapsulated within the tubes. The thermal oil which is on the shell side, serves the purpose of a sensible heat storage and also a heat transfer medium. The thermal storage concept developed by the authors has the volume of PCM limited to a maximum of 90% in a densely packed staggered tube arrangement. The authors also mention that the oil and PCM volume fractions can be varied. In this type of design, turbulent flow can be achieved more easily which is advantageous. The sensible energy that is stored in the thermal oil can be discharged.
quickly thereby allowing high storage power, while the energy stored in the PCM takes care of constant power requirements. By combining sensible and latent heat storage, the sudden drop in outlet temperature can be minimized. This is attributed to the high energy density of the PCM. The factors based on which the authors selected a HDPE as a PCM are high enthalpy, wide temperature range, ease of availability, ability to be compounded with additives in order to increase the thermal conductivity, and cyclic stability. Marlotherm SH was selected as a sensible storage medium for its higher boiling point and consequently lower pressure which allows enables a thinner tank wall, which in turn reduces material costs. The geometry of the tank and the shell and tube heat exchanger was carefully selected in order to ensure that the oil and PCM contributed almost equally to the total energy of the storage. The volume share of PCM to the total tank volume was 27%. The tank was insulated with three 10 cm thick layers of mineral wool. The storage system comprised of 208.2 kg of PCM and 515.1 kg of thermal oil. The geometry and arrangement of the PCM tubes within the tank is shown in Figure 39.

Figure 39. Geometry and arrangement of the 19 PCM tubes within the tank. Four baffles separate the tank into five compartments [24].
The experiments were conducted for two mass flow rates, 0.7 kg/s and 1.4 kg/s. The mass flow rate was kept constant within each experiment. As seen in Figure 40, a common notable outcome of both the experiments was that the power peaked initially and decreased rapidly, which is mostly related to the sensible part i.e., the thermal oil. The steady part of the plots corresponds to the PCM. This outcome implies that the sensible part is more suitable for peak power demands where as the latent part is suitable for fulfilling the base load conditions.

Figure 40. Temperatures, power profiles and discharging energy for a mass flow of 0.7 kg/s [24].

Another parameter attributed to influencing the storage characteristics is the inlet temperature. The authors here compared the discharging process at different inlet temperatures at a mass flow rate of 0.7 kg/s. This comparison can be seen in Figure 41. The discharging process with a inlet temperature of 110 °C was compared with that of 95 °C. The authors observed that not only the peak power but also the discharging power related to the PCM is increased. They attribute this to a faster crystallization as well as a larger sensible PCM-energy.
Nallusamy et al. [20], have investigated the thermal behavior of a packed bed of combined sensible and latent heat thermal energy storage (TES) unit. In this work, the authors have designed and constructed a TES unit, which is integrated with a constant temperature solar collector in order to study the performance of the thermal storage unit. The phase change material (PCM) used is paraffin which is filled in spherical capsules. The capsules are packed in an insulated cylindrical storage tank. Water is used as heat transfer fluid (HTF) in order to transfer heat from the constant temperature bath/solar collector to the TES tank. Here, water also plays the role of a sensible heat storage (SHS) material. The authors have carried out charging experiments at constant and varying inlet fluid temperatures to study the effects of inlet fluid temperature and HTF flow rate on the performance of the storage unit. Discharging experiments were carried out by employing both continuous and batch wise processes to retrieve the stored heat. In this experimental study, the authors have compared the performance of the combined
sensible and latent heat storage system with that of the conventional SHS system. They found from the discharging experiments that the combined storage system that employs batch wise discharging of hot water from the TES tank is best suited for applications where the requirement is intermittent. A schematic of the experimental setup is shown in Figure 42.

Figure 42. Schematic of the experimental setup (1) solar flat plate collector (varying heat source); (2) constant temperature bath; (3) electric heater; (4) stirrer; (5) pump; (6 and 7) flow control valves; 8. flow meter; (9) TES tank; (10) PCM capsules; (11) temperature indicator; $T_P$ and $T_f$- temperature sensors (RTDs) [20].

The authors have employed two different methods for the charging process. First, using a constant temperature source i.e. a water bath for supplying the inlet HTF and second, using a varying temperature source i.e. an active solar flat plate collector. For the discharging process too, two different methods have been employed. The first method is termed as the continuous process and the second method is referred to as the batch wise process. In the continuous process, the cold water at a temperature of 32 °C is circulated continuously through the TES tank to recover the stored heat energy. In the batch wise process, a certain quantity of hot water is withdrawn from the TES unit and mixed with cold water at 32 °C to attain a temperature of 45±0.5°C. The TES unit is replenished with the same quantity of water that is withdrawn. This is repeated again after 10 minutes till the temperature of the PCM reaches 45 °C. The amount of
heat transfer to the PCM instantly depends on the temperature difference that exists between HTF and PCM at a given time. During the sensible heating of solid PCM, the authors have observed that the temperature of both HTF and PCM increases at a faster rate and the temperature difference between them also increases continuously until the PCM reaches its melting temperature i.e. 60±1°C. The increase in temperature is higher in water than the PCM, as more quantity of heat is absorbed by the water than it gives its heat to the PCM. The authors attribute this to the higher resistance offered by the solid PCM for heat flow. It is observed that the time required for complete charging of the TES unit is decreased as the inlet temperature is increased. The authors have further compared the combined SHS-LHS system with the SHS system. Figure 43 shows a comparison of HTF outlet temperatures during discharging process from sensible heat storage and combined storage systems. It can be inferred from Figure 43 that in case of a combined storage system, the continuous discharging process exhibits a isothermal behavior around 42–45 °C for a about 30 min i.e. from 30 to 60 min as shown in the graph. It can also be seen from the graph that in the case of combined storage system, the batch wise process gives better performance than the continuous discharging process.

![Figure 43. Comparison of HTF outlet temperatures during discharging process from sensible heat storage and combined storage systems [20].](image-url)
The authors have observed that in the case of SHS system, batch wise discharging of hot water is advantageous, since the water outlet temperature remains almost constant at 70 °C throughout the process. On the other hand, it has been observed that in the continuous discharging process the water outlet temperature decreases continuously with time and this type of discharging process has limited practical applications. The authors point out that this limitation can be overcome by using the combined sensible and LHS concept and thereby eliminating the disadvantage of variation in water outlet temperature experienced in the conventional SHS system.

Frazzica et al. [19], have tested a small scale hybrid SHS-LHS system which uses water for sensible heat storage in which macro-encapsulated PCMs were added. The objective of this study experimentally analyze a domestic small-scale heat storage based on the hybrid “sensible + latent” configuration properly sized for space heating and domestic hot water delivery. In this work, sensible heat storage configuration has been experimentally compared to the hybrid heat storage. Two different PCMs were used in the macro-capsules, a commercial paraffin and a hydrate salts mixture. These two PCMs were macro-encapsulated and immersed in the tank for testing. The two PCMs tested are PCM 58, a mixture of hydrates salts, Mg(NO₃)₂.6H₂O and MgCl₂.6H₂O at the eutectic composition 58.7–41.3% and RT 65, an organic compound. The PCMs were selected considering a heat storage for domestic applications to be coupled to solar thermal collectors as well as to other appliances like gas boiler or micro-CHP. The authors tested different volume ratios between the PCM and the water. The tests were designed to simulate the different domestic hot water consumption profiles. The results pointed to an increase in the heat storage capacity per unit of volume. This increase applied even for limited fractions of PCM used thereby reaching up to 10% of heat storage increasing by 1.3 dm³ of hydrate salts mixture
added. The study employs a cylindrical vertical tank for the purpose of experimentation. This tank is a fully mixed system without internal heat exchangers and is made of stainless steel. Figure 44 and 45 show the cylindrical tank storage and the PCM macro-capsules respectively.

![Figure 44](image1.jpg)  
**Figure 44.** Picture of the realized vertical heat storage, before thermal insulation and the schematic of the allocation of the thermocouples inside the tank [19].

![Figure 45](image2.jpg)  
**Figure 45.** Schematic of the macro-capsule employed and its dimensions [19].

The capsule dimensions have been carefully selected in order to enhance the heat transfer between the PCM and the surrounding water. Given the high heat transfer surface to volume ratio, this ensure a high charging/discharging power. In order to test the heat storage, the authors designed and built a test rig. This test rig allows to carry out all the specified tests for the full characterization of a domestic hot water storage. It can also be employed to simulate
different draw-off profiles that represent domestic applications. Figure 46 shows the hydraulic schematic of the test rig. It consists of two sections, the one at high temperature for providing energy, and the one at low temperature for energy retrieval.

![Hydraulic layout of the realized test rig](image)

Figure 46. Hydraulic layout of the realized test rig: (1) heat exchanger connected to electric boiler, (2) high temperature buffer heat storage, (3) heat storage under testing, (4) intermediate heat exchanger between heat storage side and user side, (5) automatic mixing valve [19].

The experiment was conducted in two different phases: the first one aimed at the characterization of the sensible heat storage as reference system, the second phase aims at evaluating the achievable performance by hybrid storage made of water and PCM, employing different kind and amount of PCMs. In order to investigate the heat loss capacity rate, the heat storage was charged at 70 °C and then was cooled to the ambient temperature maintained around 25 °C. For the hybrid SHS-LHS, two types of test have been employed to test the hybrid configuration. In the first test, the discharge is continuous and the process goes all the way till the temperature in the storage falls to 35 °C. The authors mention that there is a stand-by period between 40-60 minutes, during which, in the presence of PCM, there could be a reheating process. After reheating, water is discharged again. The process is continued till the storage system is not able to deliver water at a temperature of at least 35 °C. The second test is similar to
the first one, but consists of different withdrawal patterns of 5 minutes duration each. In this type of discharge, the time gap between two consecutive withdrawals is between 40 and 60 minutes. This process too is continued till the storage system is not able to deliver water at a temperature of at least 35 °C. A stand-by cooling down test has been carried out which is necessary to characterize the sensible heat storage. This test has also been repeated for the hybrid “sensible + latent” heat storage configuration employing PCM 58. The aim of this test is to analyze the effect of the PCM inclusion. Figure 47 shows the charging phase evolution both for sensible and PCM 58 configuration.

![Figure 47. Main process temperatures evolution during low flow rate charging phases for sensible and PCM 58 configuration [19].](image)

This test shows that the sensible takes a longer time to charge than the PCM 58 configuration to reach the same temperature of 70 °C. This difference in charging time makes it difficult to compare them. From the observation of the authors, the phase transition occurs at around the nominal temperature of 58 °C. The authors have also observed that at low temperature, when the PCM is in the solid state, there is an evident temperature difference between the water temperature and PCM temperature. They attribute this to the fact that, during this phase, the dominant heat transfer mechanism is the thermal conduction. Once the melting point is reached, the main heat transfer mechanism now is convection. This enhances the overall
heat transfer coefficient, thus leading to a quick reduction of the temperature difference between water and PCM. Figure 48 shows the temperatures evolution inside the tank in PCM 58 CONFIG during the stand-by period. It is evident that, even though the heat storage is dimensionally small, there is still a certain degree of stratification inside, They attribute it to the presence of the PCM macro-capsules.

![Figure 48. Measured temperatures inside the heat storage during the stand-by cooling down phase [19].](image)

Figure 48 compares discharging powers and the relative integrated energies for three configurations, SENSIBLE, RT 65 CONFIG 2 and PCM 58 CONFIG, during a typical Test A. The authors have observed that the discharging powers during the first stage are comparable and oscillate around 14 kW. The authors mention that this is a confirmation that the system, even in presence of PCM, does not lose its dynamic performance. Hence, the energy discharged after the first discharging stage is almost the same for each of the configuration. After the stand-by period, there is again a brief discharging phase for the configurations employing PCM, characterized by lower power, about 12 kW, due to the lower temperature of the water inside the heat storage. This additional discharging phase allows increasing the total energy delivered to the user by the PCM-based systems.
This experimental investigation carried out by the authors shows an increase in the hot water delivering capacity of the prototype, compared to the sensible hot water system. The authors mention that an increase of about 10% was obtained employing around 1.3 dm³ of PCM 58. Similar results were obtained by employing almost a double volume of RT 65. They attribute this to the noticeably higher density of the PCM 58 mixture compared to the paraffin RT 65. The authors point out that, the presence of an evident sub-cooling effect for the PCM 58 seems to have a reduced effect on the overall achievable performance of the system. Table 2 summarizes all the SHS-LHS systems reviewed in this study. This experimental investigation carried out by the authors shows an increase in the hot water delivering capacity of the prototype, compared to the sensible hot water system. The authors mention that an increase of about 10% was obtained employing around 1.3 dm³ of PCM 58. Similar results were obtained by employing almost a double volume of RT 65. They attribute this to the noticeably higher density of the PCM 58 mixture compared to the paraffin RT 65. The authors point out that, the presence of an evident sub-cooling effect for the PCM 58 seems to have a reduced effect on the overall achievable performance of the system. Table 5 summarizes all the SHS-LHS systems reviewed in this study.
With this detailed study, it can be agreed upon that the coupling of the sensible heat storage with the latent heat storage plays a pivotal role in stabilizing the outlet temperature to around the melting temperature of the PCM. In some cases, adding even a small amount of PCM at the top of the packed bed allows the HTF temperature to stabilize around the PCM melting temperature. Further, experiments by different researchers show that a combined sensible-latent storage system fulfills both the peak as well as base load requirements. Work done on domestic application of combined sensible-latent storage system has shown that having a electric heat and a solar collector together in the storage configuration will ensure a continuous supply of hot water for domestic application. Even though there is a lot of scope for improvement like improving the quality of the eutectics and exploring more coatings for PCM capsules in order to prevent corrosion, overall, the combined sensible-latent heat storage systems hold a promising future for energy storage systems.
**TABLE 5**

**SUMMARY OF SENSIBLE-LATENT HEAT STORAGE SYSTEMS**

<table>
<thead>
<tr>
<th>Institution</th>
<th>Materials / Mass</th>
<th>Melting Temperature (°C)</th>
<th>Operating Temperature Range (°C) And other parameters</th>
<th>Energy Output (kW) / Capacity (kWh)</th>
<th>Nature of System - Prototype/ Commercial</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETH Zurich, Switzerland</td>
<td>Latent Storage: AlSi12 (88% Al and 12% Si by mass) Sensible Storage: Rocks HTF: Air</td>
<td>575 °C</td>
<td>25 °C to 600–700 °C</td>
<td>42 kWh</td>
<td>Prototype Tank position: vertical Heating source: 21 kW electric heater</td>
</tr>
<tr>
<td>Department of Innovative Technologies, Manno, Switzerland</td>
<td>Latent (PCM) storage: AlSi12 Sensible storage: Gravel HTF: Air</td>
<td>573-577 °C HTF Inlet Temperature = 595°C</td>
<td>22°C - 595°C</td>
<td>42.3 kWhth</td>
<td>Prototype</td>
</tr>
<tr>
<td>ETH Zurich, Switzerland</td>
<td>Latent storage: Al–Cu–Si alloy Sensible storage: Rocks (mafic rocks, felsic rocks, limestones, sandstones, and quartz-rich conglomerates) HTF: Air</td>
<td>509–527 °C</td>
<td>Ambient to 566 °C, pressure of 7 bar Maximum operating pressure: 33 bar Sensible - 11.6 MWhth, Latent - 171.5 kWhth</td>
<td>Pilot-Scale Plant Heating source: Electrical Heater</td>
<td></td>
</tr>
<tr>
<td>Austrian Institute of Technology, Wien, Austria</td>
<td>Latent Storage: HDPE Sensible Storage: Thermal oil (Marlotherm SH) HTF: Thermal oil</td>
<td>150 °C</td>
<td>160 °C - 95 °C</td>
<td>&lt;100kW</td>
<td>Prototype</td>
</tr>
<tr>
<td>Sri Venkateswara College of Engineering India</td>
<td>Latent Storage: Paraffin Sensible storage: Water HTF: Water</td>
<td>60°C</td>
<td>70°C</td>
<td>N/A</td>
<td>Prototype Heating sources: 1, 2, and 3 kW electric heaters, active solar flat plate collector</td>
</tr>
<tr>
<td>CNR ITAE lab, Messina, Italy</td>
<td>Latent(PCM) storage: Commercial paraffin and a hydrate salts mixture Sensible storage: Water Macro-capsule material: polypropylene HTF: Water</td>
<td>PCM 58 (Mg(NO₃)₂.6H₂O + MgCl₂.6H₂O): 57.7 °C and RT 65 - a organic compound: 65.8 °C</td>
<td>25-70 °C</td>
<td>12-14 kW</td>
<td>Small-Scale Heating source: Electric Boiler - 24 kW</td>
</tr>
</tbody>
</table>
CHAPTER 3

COMBINED SENSIBLE-LATENT HEAT STORAGE SYSTEM

3.1 Introduction

Sensible heat storage systems have a limitation where in the temperature of the HTF at the end of the discharge cycle drops, thereby reducing the efficiency of the storage system. A latent heat storage system cannot store heat within a large temperature range. These limitations can be overcome by integrating the sensible storage with a latent storage. This integration helps in stabilizing the outlet temperature of the HTF during the discharge cycle to around the temperature of the PCM melting point. In the sensible heat storage-latent heat storage system, benefits can be derived from the high energy density of the PCM and the high power delivering capacity of the sensible storage material. In a SHS-LHS system the PCM minimizes the temperature drop at the outlet during the discharge cycle. In a SHS-LHS system, it is possible to reduce the power loss of the sensible storage. The combination of sensible and latent storage ensures that surge in power demand in other words the peak power requirements can be met, all the same satisfying the base load conditions. The sensible storage meets the peak power requirements and the PCM satisfies the base load conditions.

A combined SHS-LHS system has been evaluated with Aragonite, which belongs to the category of Limestone, as the sensible heat storage material and KOH as the latent heat storage material. The performance of the combined sensible-latent heat storage system is analyzed and compared with a sensible only heat storage system by evaluating key parameters such as Heat Transfer Fluid exit temperature, average temperature of the heat storage system and the amount of energy stored and retrieved during charging and discharging respectively. It was found that a combined sensible-latent heat storage system stabilizes the HTF exit temperature to around the
temperature of the phase change material during the discharge cycle. This has also been corroborated by many researchers in their experimental work. It was also found for both the systems (sensible and combined) that the larger the pellet diameter, the longer is the time taken by the Thermal Energy Storage System to reach the maximum operating temperature. For both the systems, the temperatures remain at the maximum operating temperature for a longer duration at lower HTF flow rates. This helps in maintaining the stability of the temperatures in a TESS for a longer duration, which in turn, to a limited extent, offsets the losses caused due to a rapid reduction in the outlet temperature in a sensible TESS. The amount of energy retrieved from the combined system is larger than the energy that is retrieved from a sensible only TESS. All these findings point to the fact that using a combined sensible-latent TESS is highly advantageous as compared to a sensible only TESS.

3.2 LITERATURE REVIEW

Zanganeh et al. [21] have experimentally investigated a combined sensible–latent heat for thermal energy storage at 575 °C. AlSi$_{12}$ (88% Al and 12% Si by mass) encapsulated in stainless steel tubes is used for storing latent heat, where as rocks are used for storing the sensible heat. Air is used as the heat transfer fluid. The operating temperature during charging ranges between 600-700 °C and that during discharge is 25 °C. One configuration consists of the rocks and PCM arrangement and the other configuration consists of only rocks. The mass flow rates and charging times for “rocks+PCM” and “rocks only” were similar. The ambient temperature of the storage system at the start of the charging process was 25 °C. The discharging process continued till the storage system returned back to the initial ambient temperature i.e., 25 °C. The final top temperature of the charging period for the “rocks + PCM” setup is about 10 °C lower than that for the “rocks only” setup. The authors attribute this to the melting process involved in the
“rocks + PCM” setup. It can be further observed that the outflow temperature during discharge drops faster at first for the “rocks + PCM” setup, but stabilizes later. The outflow temperature of the “rocks only” setup drops below that of the “rocks + PCM” setup after about 70 min of discharging. In comparison, in the “rocks + PCM” setup the outflow temperature is stabilized for about 90 min after which the PCM solidifies and the temperature begins to drop. The outlet temperature of air was higher for about 20 min in case of the combined SHS-LHS as opposed to the sensible only system. These observations demonstrate that the combined SHS-LHS system plays a pivotal role in stabilizing the outlet temperature to around the melting temperature of the PCM while the PCM is partially molten.

Zavattoni et al. [22] have investigated a combined SHS-LHS system comprising of a packed bed of gravel and AlSi12. The packed bed of gravel comprises of a mixture of different rocks types such as limestone, quartzite, sandstone and gabbro. This mixture of rocks is used to store sensible heat whereas AlSi12 is used to store latent heat. During charging, the HTF which is the high-temperature air, up to 595°C, was fed through the TES from the top of the system. During discharging, the direction of flow of the HTF was reversed and air at ambient temperature was fed through the prototype from the bottom. The charging process lasted for 3.25 hours and the system was discharged until reaching dead-state condition. This study shows that adding a small amount of PCM at the top of the packed bed allows the HTF temperature to stabilize around the PCM melting temperature.

Becattini et al. [23] have experimentally and numerically investigated an adiabatic compressed air energy storage plant with combined sensible/latent thermal-energy storage. The latent thermal-energy storage comprises a steel tank with 296 stainless-steel tubes encapsulating an Al–Cu–Si alloy as phase-change material. Four charging/discharging cycles were involved
while investigating the combined thermal-energy storage. The duration of each cycle was about 3 hours and air inflow temperatures of up to 566 °C. The experimental results showed that the latent thermal-energy storage reduced the drop in the air outflow temperature during discharging. During charging, hot compressed air enters the cavern through an insulated pipe that directs the air to the top of the TES. The air is cooled by flowing through the thermocline TES. The cooled air then exits the TES at the bottom and enters the cavern. During discharging, the flow is reversed: cold air from the cavern enters the TES at the bottom, gets heated, leaves the TES at the top, and exits the cavern through the insulated tube. The experiments with the combined sensible/latent storage consisted of four cycles (charging/discharging). Before the first charging phase, in order approach steady cycling conditions more quickly, the TES was pre-charged. In this work, the authors have concluded that the latent TES reduced the decrease in the air outflow temperature during discharging. This demonstrates the potential of sensible/latent TES as an attractive option for industrial-scale high-temperature storage.

3.3 RESULTS AND DISCUSSION

This research was carried out to evaluate the performance of a combined sensible-latent heat storage system and compare it with a sensible only heat storage system in order to determine whether using combined sensible-latent heat storage systems help in minimizing the drastic HTF temperature drop at the exit of the TESS. The study was carried out to evaluate the effect of pellet diameter and HTF flow rate on the HTF exit temperature, average bed temperature, and energy stored/retrieved. Three pellet diameters 0.01m, 0.02m, and 0.03m along with three HTF flow rates 0.01kg/s, 0.015kg/s, and 0.02kg/s were selected. In the first case, the pellet diameter was varied and the HTF flow rate was kept constant at 0.02kg/s. In the second case, the HTF flow rate was varied and the pellet diameter was kept constant at 0.02m. A schematic of the
sensible-only and the combined sensible-latent storage system is shown in Figure 50 and 51 respectively.

Figure 50. Schematic of the rectangular thermal storage tank for the sensible-only heat storage study.

Figure 51. Schematic of the rectangular thermal storage tank for the combined sensible-latent heat storage study.
TABLE 6
DETAILS OF DIFFERENT CASES STUDIED FOR THE COMBINED SENSIBLE-LATENT HEAT STORAGE

<table>
<thead>
<tr>
<th>Study</th>
<th>Case #</th>
<th>Pellet diameter (m)</th>
<th>HTF Flow Rate ㎡ (kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Charging</td>
</tr>
<tr>
<td>Effect of pellet diameter</td>
<td>Case 1</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>Case 2</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>Case 3</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>Effect of HTF flow rate</td>
<td>Case 1</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Case 2</td>
<td>0.02</td>
<td>0.015</td>
</tr>
<tr>
<td></td>
<td>Case 3</td>
<td>0.02</td>
<td>0.02</td>
</tr>
</tbody>
</table>

For the sensible TESS, during charging, as the pellet diameter increases, the time taken for the HTF exit temperature to reach the maximum operating temperature (400 °C) increases and during discharging, the time taken for the HTF exit temperature to return to the initial temperature of the TESS (360 °C) also increases. For the combined TESS, during both the charging and discharging cycles, the HTF exit temperature of the combined TESS stabilizes around the melting temperature of the PCM (380 °C). This can be observed in Figure 52. For the sensible TESS, during charging, as the pellet diameter increases, the time taken for the TESS bed to reach the maximum operating temperature increases and during discharging, the time taken by the TESS bed to return to the initial temperature also increases. For the combined TESS, for both the charging as well as discharging cycles, the temperature of the TESS bed is stable around the melting temperature of the PCM. This can be observed in Figure 53. For the sensible TESS, a large amount of energy is stored in a short duration during charging and the amount of energy that can be retrieved from the sensible TESS is slightly less as compared to the amount of energy that is stored. For the combined TESS, the amount of energy stored and retrieved is almost about the same. This can be observed in Figure 54.
Figure 52. HTF Exit Temperature (d=0.01m, 0.02m, 0.03m, $\dot{m}=0.02$ kg/s, Inline).

Figure 53. Average Bed Temperature (d=0.01m, 0.02m, 0.03m, $\dot{m}=0.02$ kg/s, Inline).

Figure 54. Energy Stored/Retrieved in kJ (d=0.01m, 0.02m, 0.03m, $\dot{m}=0.02$ kg/s, Inline).
At lower HTF flow rates, the sensible TESS takes a longer time to reach the maximum operating temperature. The combined TESS too takes a longer time to stabilize around the melting temperature of the PCM at lower HTF flow rates. As the HTF flow rates are increased, the duration for which both the systems (sensible and combined) remain stable at the maximum operating temperature decreases. For both the systems, the temperatures remain at the maximum operating temperature for a longer duration at lower HTF flow rates, as compared to cases having high HTF flow rates. It can also be seen that the HTF exit temperature for the combined system stabilizes around the PCM melting temperature. This can be observed in Figure 55. For the sensible TESS, during the charging cycle the average temperature of the TESS bed steadily reaches the maximum operating temperature with increase in time, but on the other hand, during the discharge cycle, the temperature drops rapidly to the initial TESS bed temperature. In case of the combined TESS, for both the charging and discharging cycles, the temperature of the combined TESS is stable around the melting temperature of the PCM. This can be observed in Figure 56. In case of both the systems, increase in the mass flow rates leads to a reduced energy storage time. This is more prominent in case of the sensible TESS. For the sensible TESS, the amount of energy that can be retrieved from it is slightly less than the amount of energy that is stored. In case of the combined TESS, the amount of energy stored and retrieved is almost about the same. This can be observed in Figure 57.
Figure 55. HTF Exit Temperature ($\dot{m}=0.01$ kg/s, 0.015 kg/s, 0.02 kg/s, $d=0.02m$, Inline).

Figure 56. Average Bed Temperature ($\dot{m}=0.01$ kg/s, 0.015 kg/s, 0.02 kg/s, $d=0.02m$, Inline).

Figure 57. Energy Stored/Retrieved in kJ ($\dot{m}=0.01$ kg/s, 0.015 kg/s, 0.02 kg/s, $d=0.02m$, Inline).
For the sensible TESS, during charging, as the pellet diameter increases, the time taken for the HTF exit temperature to reach the maximum operating temperature (400 ºC) increases and during discharging, the time taken for the HTF exit temperature to return to the initial temperature of the TESS (360 ºC) also increases. For the combined TESS, during both the charging and discharging cycles, the HTF exit temperature of the combined TESS stabilizes around the melting temperature of the PCM (380 ºC). This can be observed in Figure 58. For the sensible TESS, during charging, as the pellet diameter increases, the time taken for the TESS bed to reach the maximum operating temperature increases and during discharging, the time taken by the TESS bed to return to the initial temperature also increases. For the combined TESS, for both the charging as well as discharging cycles, the temperature of the TESS bed is stable around the melting temperature of the PCM. This can be observed in Figure 59. For the sensible TESS, a large amount of energy is stored in a short duration during charging and the amount of energy that can be retrieved from the sensible TESS is slightly less as compared to the amount of energy that is stored. For the combined TESS, the amount of energy stored and retrieved is almost about the same. This can be observed in Figure 60. It may be recalled that similar trends were observed in case of the inline arrangement.

Figure 58. HTF Exit Temperature (d=0.01m, 0.02m, 0.03m, ṁ=0.02 kg/s, Staggered).
Figure 59. Average Bed Temperature (d=0.01m, 0.02m, 0.03m, ṁ=0.02 kg/s, Staggered).

Figure 60. Energy Stored/Retrieved in kJ (d=0.01m, 0.02m, 0.03m, ṁ=0.02 kg/s, Staggered).

At lower HTF flow rates, the sensible TESS takes a longer time to reach the maximum operating temperature. The combined TESS too takes a longer time to stabilize around the melting temperature of the PCM at lower HTF flow rates. As the HTF flow rates are increased, the duration for which both the systems (sensible and combined) remain stable at the maximum operating temperature decreases. For both the systems, the temperatures remain at the maximum operating temperature for a longer duration at lower HTF flow rates, as compared to cases having high HTF flow rates. It can also be seen that the HTF exit temperature for the combined system stabilizes around the PCM melting temperature. This can be observed in Figure 61. For
the sensible TESS, during the charging cycle the average temperature of the TESS bed steadily reaches the maximum operating temperature with increase in time, but on the other hand, during the discharge cycle, the temperature drops rapidly to the initial TESS bed temperature. In case of the combined TESS, for both the charging and discharging cycles, the temperature of the combined TESS is stable around the melting temperature of the PCM. This can be observed in Figure 62. In case of both the systems, increase in the mass flow rates leads to a reduced energy storage time. This is more prominent in case of the sensible TESS. For the sensible TESS, the amount of energy that can be retrieved from it is slightly less than the amount of energy that is stored. In case of the combined TESS, the amount of energy stored and retrieved is almost about the same. This can be observed in Figure 63. It may be recalled that similar trends were observed in case of the inline arrangement.

Figure 61. HTF Exit Temperature (ṁ=0.01 kg/s, 0.015 kg/s, 0.02 kg/s, d=0.02m, Staggered).
Figure 62. Average Bed Temperature ($\dot{m}=0.01 \text{ kg/s}, 0.015 \text{ kg/s}, 0.02 \text{ kg/s}, d=0.02\text{m}, \text{Staggered})$.

Figure 63. Energy Stored/Retrieved in kJ ($\dot{m}=0.01 \text{ kg/s}, 0.015 \text{ kg/s}, 0.02 \text{ kg/s}, d=0.02\text{m}, \text{Staggered})$.

Figure 64 to Figure 66 represent a comparison of inline and staggered arrangements for both the sensible and combined systems. This comparison was carried out for a pellet diameter of 0.02m and HTF flow rate of 0.02 kg/s. During the charging cycle for the staggered sensible TESS, the HTF exit temperature reaches the maximum operating temperature faster as compared to the inline sensible TESS. During the discharging cycle, the temperature of the staggered sensible TESS falls back to the initial TESS temperature faster as compared to the inline sensible TESS. This time difference is very negligible. For the combined TESS, the HTF exit temperature
stabilizes almost at the same time for both the inline and staggered arrangements during both the cycles. This can be seen in Figure 64. The average bed temperature of the TESS for both the inline and staggered arrangements takes about the same time to reach the maximum operating temperature. The average bed temperatures of the TESS for both the inline and staggered cases fall back to the initial TESS temperature in about the same time. For the combined TESS, the average bed temperature stabilizes almost at the same time for both the inline and staggered arrangements during both the cycles. This can be observed in Figure 65. The time taken by both the inline and staggered sensible TESS to store the maximum energy is about the same. The time taken by both the inline and staggered combined TESS to store the maximum energy is about the same too. This can be seen in Figure 66. To summarize, the difference in the overall performance level of the inline and staggered systems (combined as well as sensible) is minimal.

Figure 64. HTF Exit Temperature – Inline vs Staggered at d=0.02m and m=0.02 kg/s.
Figure 65. Average Bed Temperature – Inline vs Staggered at d=0.02m and \( \dot{m}=0.02 \) kg/s.

Figure 66. Energy Stored/Retrieved in kJ – Inline vs Staggered at d=0.02m and \( \dot{m}=0.02 \) kg/s.
CHAPTER 4

CONCLUSIONS

The diameter of the PCM pellets has an effect on the melting and solidification time of the PCM in both the uniform and cascaded layouts. As the diameter of the pellets increases, the time taken for the PCM to melt and solidify also increases. The melting and solidification time in case of the cascaded PCM layout is significantly less when compared to the uniform PCM layouts. The cascaded PCM layouts record the highest energy and the uniform KOH PCM layout records the lowest energy. Among the uniform PCM layouts, KNO₃ records the highest energy followed by NaNO₃ and then KOH. As the pellet diameter increases, the time taken for the energy to reach its maximum level also increases. In cases of varying HTF flow rate, as the HTF flow rate increases, the melting and solidifying time decreases. It is worthwhile to observe that as the HTF flow rate is increased the time taken for the energy level of the PCMs to reach its maximum decreases. If the objective of the TESS is to obtain a large amount of energy with time being secondary, then the uniform KNO₃ layout is ideal as it yields the highest energy among the three PCMs. If the objective is to obtain a large amount of energy in a short time, then using the cascaded layout will be ideal. This study also shows that using small diameter pellets and a high HTF flow rate would be the best combination as this will reduce the melting and solidification time as well as decrease the time taken to store and retrieve energy. In case of both the inline and staggered arrangements, the cascaded layout melts and solidifies 72% and 66% faster respectively as compared to the uniform KNO₃ layout. The energy storage and retrieval rate of the cascaded layout is 64% and 60% faster respectively as compared to the uniform KNO₃ layout for both the inline as well as the staggered arrangement. On an average, 51% more energy is
stored and retrieved in case of the cascaded layout as compared to the uniform KNO₃ layout and at a 67% faster energy storage rate.

Temperatures in TESSs with sensible storage materials are known to increase and decrease rapidly as compared to combined sensible and latent TESSs. This trend can be observed in the HTF exit temperature plots. The temperatures in a combined sensible and latent TESS are less prone to rapid fluctuation and this trend too can be observed in our work. One of the main disadvantages of the sensible TESSs is the drastic fall in the HTF exit temperatures during the discharge cycle. This can be avoided by using a combined sensible and latent TESS, which is one of the main objectives of using this type of combined system. It is clearly evident from the HTF exit temperature plots that the HTF exit temperature is stabilized to around the temperature of the PCM during the discharge cycle. It can be appreciated that the HTF exit temperature for the combined sensible and latent system during the discharge cycle does not fall back to the initial TESS temperature of 360 ºC, but on the contrary it continues to be stable around the PCM melting temperature. This trend has been proven by Zanganeh et al. [21], Zavattoni et al. [22], and Becattini et al. [23] in their experimental work. In case of the inline arrangement, on an average, the SHS system stores 6% more energy than the combined SHS-LHS system and the energy retrieved from the combined SHS-LHS system is 19% more than that of the SHS system. On an average, the energy storage rate of the SHS system is 15% higher than that of the combined SHS-LHS system during both charging and discharging. In case of the staggered arrangement, on an average, the SHS system stores 3.8% more energy than the combined SHS-LHS system and the energy retrieved from the combined SHS-LHS system is 21% higher than that of the combined SHS-LHS system during both charging and discharging. On an average, the energy storage rate of the SHS system is 22% higher than that of the combined SHS-LHS system.
during both charging and discharging. It is recommended to use smaller diameter pellets and lower HTF flow rates for optimal performing combined TESS.
CHAPTER 4
SUGGESTIONS FOR FUTURE WORK

For the latent heat storage system, the uniform and cascaded layouts have been evaluated for average liquid fraction and energy stored/retrieved. Overall, the cascaded layout is very efficient as compared to a uniform layout. This is concluded based on the results obtained with cascaded slope down and slope up layouts. It needs to be seen whether the cascaded layout performs with the same efficiency if the PCMs are arranged randomly based on their melting temperatures. Future work could also include evaluating the TESS with just two PCMs instead of three to observe if there is a drastic difference in the performance level of the TESS. Since the computation results are promising and have been validated with experimental work, a lab scale prototype could be developed based on the work carried out in this research to explore the possibility of implementing this work on a large scale.

For the combined sensible-latent heat storage system, the results of this research agree with the experimental work carried out by researchers. Hence a lab scale prototype could be developed based on this work to explore the viability of large scale implementation. Moreover, to the best of knowledge of this author and based on the literature explored, Aragonite has not be evaluated as a sensible heat storage material. Future work could also be aimed at evaluating a combined sensible-latent heat storage system with Aragonite and KNO3/NaNO3 especially KNO3 as the PCM as it yielded the highest amount of energy when used in a latent heat storage system.

In this work, the corrosive effects of the PCMs on the pellets have not been evaluated. Future research could also include a investigation of the corrosive effects of the PCMs on the pellets. One suggestion is to explore the possibility of coating the inner surface of the pellets
with high temperature anti-corrosion coatings. This is important in order to prevent the damage of the pellets and subsequent damage to the TESS itself due to the corrosive effects of the PCMs.

Future work could also include evaluating the service life of the PCMs and carrying out a cost-benefit analysis.

Using the present concept, a air-conditioning/heating system for domestic applications can be explored too.
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