Experimental Analysis of Thermal Energy Storage System with different Phase change materials (PCM).

A Dissertation submitted to the

Delhi Technological University

in partial fulfilment of the requirements

of the award of the degree of

Masters of Technology

(Thermal Engineering)

By

Praween Kumar Dhiraj

Roll No. 2K20/THE/15

Under the supervision of

Dr. Anil Kumar
Associate Professor
Mechanical Engineering Department

Delhi Technological University
(Formerly Delhi College of Engineering)
Shahbad, Daulatpur, Bawana Road Delhi-110042

DEPARTMENT OF MECHANICAL ENGINEERING

DELHI TECHNOLOGICAL UNIVERSITY

DECLARATION OF ORIGINALITY

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no materials previously published or written by another person nor any materials presented for the award of any degree or diploma of Delhi Technological University or any other institution of higher learning. Any contribution made to this research by others is explicitly acknowledged in the dissertation.

Place: *Delhi Technological University.* **_Praween kumar Dhiraj_**

Date: *31.05.2022* *2K20/THE/15*

DEPARTMENT OF MECHANICAL ENGINEERING

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering) Bawana Road, Delhi-110042

May, 2022

CERTIFICATE

This is to certify that the work presented in this dissertation "***Experimental Analysis of Thermal Energy Storage System with different phase change materials (PCM)***" *by Praween Kumar Dhiraj*, Roll No. 2K20/THE/15, is a record of original research carried out by him under my supervision and guidance in partial fulfilment of the requirements for the degree of *Master of Technology* (*Thermal Engineering)*. Neither this dissertation nor any part of it has been submitted earlier for any degree or diploma to any institute or university in India or abroad.

Supervisor's Signature

Dr. Anil Kumar

Associate Professor

Mechanical Engineering Department

Delhi Technological University

(Formerly known as Delhi College of Engineering)

ACKNOWLEDGEMENT

It is a matter of great pleasure for me to present my dissertation report on **"Experimental Analysis of Thermal Energy Storage System with different phase change materials (PCM)".**

First and foremost, I am profoundly grateful to my guide **Dr. ANIL KUMAR, Associate Professor, Mechanical Engineering Department** for his expert guidance and continuous encouragement during all stages of thesis. I feel lucky to get an opportunity to work with him. Not only understanding the subject, but also interpreting the results thereon from the graphs was very thought provoking. I am thankful to the kindness and generosity shown by him towards me, as it helped me morally complete the project before actually starting it.

I would like to extend my gratitude to **Prof. S.K. GARG, Head, Mechanical Engineering Department** for providing this opportunity to carry out the present thesis work.

Finally, and most importantly, I would like to thank my family members and seniors for their help, encouragement and prayers through all these months. I dedicate my work to them.

Place: Delhi | Praween Kumar Dhiraj
Date: 31/05/2022 | (2K20/THE/15)

ABSTRACT

Thermal energy storage systems (TESS) are recently undergoing a revolution, owing to their significant impact on modern technology and wide range of applications, including space and water heating, waste heat utilization, cooling, and air conditioning. But there is a lag between energy demand and supply, so energy storage is important to fulfill this lag. Increasing energy demands, scarcity of fossil fuels, and the continued rise in greenhouse gas emissions are primary motivators for focusing on renewable energy sources. Due to the irregular and unexpected nature of solar energy, which is a very efficient, inexpensive, and reliable energy source, solar thermal energy storage devices require more investigation and research.

Purpose of this work is to study the actual working, experimental analysis of thermal energy storage system using organic phase change materials i.e. Paraffin wax, Fatty acid, and cascading system. The exchange of heat between HTF and the PCM is analysed and different temperature curves have been plotted to see the variation. The energy equations are used between heat exchanging materials with appropriate assumptions to see the real time working condition of the TES system.

The constancy of Phase Change Materials (PCM) in latent heat storage makes them a favored option among the various types of energy storage systems that use various materials. PCM is a good way to store thermal energy since it has a high storage density and is isothermal in nature.

TES system is designed, manufactured, and commissioned in this experiment to collect data on the thermal performance of the thermal energy storage tank. The cylindrical capsules in this TES tank are coated with phase change materials like paraffin wax and fatty acid. Heat transfer fluid (HTF) is used as a medium for transferring heat.

In this study, the charging (melting of PCM) and discharging (solidification of PCM) characteristics of phase change material in a TES tank are investigated and further future scope of work has been discussed.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

TES	Thermal Energy Storage
PCM	Phase Change Material
PUF	Polyurethane Foam
DHC	District Heating and Cooling
ESS	Energy Storage System
LHS	Latent Heat Storage
SHS	Sensible Heat Storage
TCS	Thermochemical Energy Storage
HTF	Heat Transfer Fluid
FPC	Floating Point Calculation
SEC	Solar Energy Collector
LHSU	Latent Heat Storage Unit
RTD	Resistance Temperature Detector
THSS	Thermal Energy Storage System
PCHES	Phase Change Heat Energy Storage System
MS	Mild Steel

CHAPTER 1
INTRODUCTION

1.1 General

The word "Energy" is the most valuable and expensive word for existence of living beings on this planet. Energy has been always a matter of study and research for its effective utilization and impactful application. But the fact remains that it has been never valued and utilized properly. Most of countries lack in knowledge of proper utilization of energy and this is the main reason for its exploitation. Energy can be obtained by different means, broadly can be classified into conventional and non-conventional sources of energy.

The conventional energy sources are that is been used from long past and comes from fossil fuels. These kinds of energy are also recognized as non- renewable sources of energy, it has certain period of utility which will last for a certain period of time and after that it can't be replenished whereas non-Conventional sources are the sources which can be used again and again. The trend is changing and there has been a shift towards energy conservation and energy management. Storing energy is one of the key features of sustainable development and energy management. The development of energy storage is done in such a way that it has a significant impact on the modern-day technology. Energy storage is really very important in meeting the demands of intermittent energy sources. The contribution of energy storage is significantly into meeting the needs of the society for efficiently using energy in building, heating and cooling, utility and aerospace power application.

Energy storage are classified into various types. One important type of energy storage is TES (thermal energy storage) system. In this type of energy storage, the energy is received by a material when its temperature rises and it loses the energy when its temperature falls. By using this application, it helps to utilise a vast variety of materials with changing thermal properties for obtaining a variety of effects. It also helps to obtain the applications of TES which includes heating or cooling applications. Thermal Energy storage can help in stabilising energy demand and it also helps to supply in thermal systems on a daily basis, monthly basis, and even seasonal basis. While improving overall energy system efficiency, TES can also lower peak demand, CO2 emissions, energy consumption, and reduces prices.

The necessity of TES in future energy systems with large volumes of intermittent renewable energy sources arises from the fact that heat accounts for half of global final energy use (International Energy Agency, 2013). As compared to electrical storage, Thermal energy storage is less expensive. TES also offers the advantage of integrating intermittent sources of renewable energy which includes wind and solar energy and convert it into cooling and heating sector by the help of electric boilers and heat pumps. Heating and cooling networks (DHC) benefit from TES by reducing peak thermal demands, boosting system efficiency, and integrating other heat sources such as industrial waste heat or seawater.

Thermal Energy storage system has been the matter of investigation as it remains unexplored besides being a good opportunity of storing energy. The curve of energy demand and supply never coincides as they are totally independent so to fulfil this need of energy at right time with right amount this device is useful. The purpose of any thermal energy storing device is to store large amount of heat in small confined space so that its effectiveness is maximum [1].

The huge potential of ESS (Energy storage System) is that it can increase the effectiveness by which energy is conserved, size of equipment and facilitates substitution of the fuel on a large scale in world's economy. The demand of energy in public, commercial, industrial and residential sectors varies on daily basis, monthly basis and even seasonal basis. Some applications of Energy Storage are discussed below:

- Industry- In Industries, the heat wasted at high temperature from various industrial processes can be stored. And that heat can be used in pre heating and other heating operations.
- Cogeneration: A cogeneration system's combined heat and power production rarely exactly matches demand.
- Utility- relatively in experience base load electricity can be used to charge ES systems during evening or off peak, weekly or seasonal periods.

1.2 Storage System

Any system that have the ability to keep or store some kind of potential that can be converted or reused for achieving certain goals for performing certain specified task is called storage system. Energy can be stored in various materials so that it can be useful for human application and along with that there are a lot of methods for energy storage. Storing energy has been always a challenging task because of its complex process of charging and discharging. There are a lot of losses that are incurred while attempting these series of processes. The technology of energy storage can be applied to a number of areas that differs in energy and power requirements. Energy storage systems provide a wide range of technological options for managing power supply in order to create a more resilient energy infrastructure while also saving money for utilities and customers. Classification can be done in various ways that are now being used around the world. The classification of energy storage can be done in five broad categories based on the quality of energy been stored and the nature of energy storage.

- **Thermal –** Energy can be stored in the form of heat in a confined space with proper insulation and used at demand place and time. These heat energies have various practical application like air-conditioning and air heating, water heating etc.
- **Batteries** - Innovative chemical batteries are the storage system for charge some other devices are also available that has the capability to store charge these are commonly called electrochemical storage methods ex- capacitors and flow batteries.
- **Mechanical Storage -** Mechanical storage is another new approach for capturing kinetic energy and utilising where there is need for power or compensate the energy requirement. Some new mechanical techniques are also been introduced which can be used as energy bank. Gravitational energy is the new technology on which research are carried out for its effective utilization.
- **Hydrogen** – Methods have been adopted to store energy in the form of hydrogen. Electrolysis is a method to store the excess electricity that is not been used, in the form of hydrogen. These methods are not general methods, it requires high end technologies and high accuracy to perform.
- **Pumped hydropower –** Water stored in a confined space has the power of potential that can be used to generate electricity or run a turbine so hydropower or the reservoir power is also an energy storage system.

These are some basic classification of storage systems that have the ability to store any kind of useful energy. The useful energy that can be utilized for various human comfort purposes. Other classification can be based on the utility and the bulk system.

1. Battery Energy Storage

Batteries are electrochemical devices made up of either one or more than one cells with a cathode and an anode. These are the most basic and popular easily available and cheapest storage option. Batteries employ a wide range of chemistries. The most common among them which are generally used everywhere are lead acid and lithium-ion. Other solid battery types include nickel-cadmium and sodium-sulphur, with zinc-air gaining prominence. Another type of battery can be a flow battery is liquid electrolyte solutions which uses liquid electrolyte for their operation of charge storage. While supercapacitors are not technically batteries, their application in sub-minute level responsiveness qualifies them as an electrochemical technology.

2. Thermal Energy Storage

Thermal storage system involves storing or capturing energy in the form of cold or heat by the help of any heat storing material either PCM's and then releasing it when needed. There are different methods by which the heat or cold energy can be stored like cryogenic storage, liquid air, phase change or molten salts. This is very basic technique in which a heat transfer fluid that temporarily stores energy exchanges it with the PCM or some heat capturing material and then this energy is kept intact with the help of insulators like PUF (polyurethane foam). Now this energy can be used for further use or when needed.

3. Mechanical Energy Storage

These kinds of energy storage technique are the most basic and oldest method by which energy are used which used kinetic forces to store energy. However, nowadays new technologies have also been introduced and are required for practicality and for fulfilling the increasing demand of energy.

The most prevalent energy storage technologies are flywheels (energy stored by the virtue of rotational motion of an object that has definite mass) and compressed air systems (the energy of pressure, when air is compressed in a confined space and released as per requirement), some new technologies are also been taking up the market which includes gravitational energy storage system.

4. Pumped Hydropower Energy Storage

In the last century, energy storage with pumped hydro systems based on vast water reservoirs has been the most common type of utility-scale storage. In such systems, water must cycle between two reservoirs at differing levels, with the 'energy storage' in the upper reservoir's water being released when the water is released to the lower reservoir.

5. Hydrogen Energy Storage

One of the methods by which we can store energy by the help of hydrogen is converting power to hydrogen via electrolysis and store it in the tanks, which is still in its infancy. It can then be re-electrified or provided as an alternative to gas in new uses such as residential, industry, and transportation.

1.3 Thermal energy storage (TES) system

Thermal energy storage (TES) system is a modern yet simple technique of storing heat energy in a confined system or space. Storing heat either at lower temperature or higher temperature so that it can be used for later various human purposes to make human life easier and comfortable by increasing the standard of living. Cooling or heating a space can be one of the simplest explanations to it. In Thermal Energy Storage (TES) system, the energy to be used at a later time, is supplied to a storage system. It involves three steps which includes charge, discharge and storage, giving a complete storage cycle as shown in fig 1.1. [5].

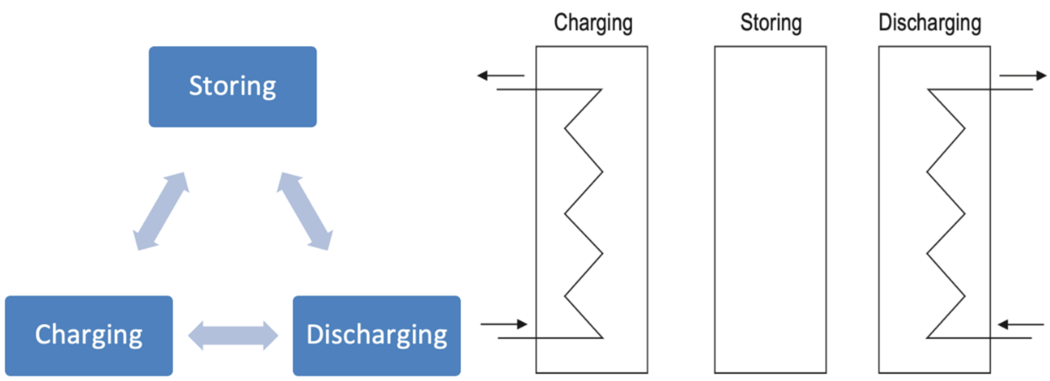

Fig 1.1: Thermal energy storage system cycle

It can be used for various later human comfort purposes such as water and space heating, air conditioning, cooling and waste heat utilization [4]. The fundamental idea is same in all the applications of TES. Energy is sent to a storage system where it can be retrieved and used at a later time. The size of the storage and the method of storing are the key differences. A cycle can be used to describe the process of storing thermal energy in three steps. Charging, storing, and discharging are the three steps. The storage cycle applies to sensible, latent, and chemical storage; the material, operating temperature, and a few other characteristics differentiate these approaches.

The most frequent medium for sensible storage, for example, is water, however this varies according on the application. The amount of time the energy is held is another crucial feature to understand about TES devices. TES is usually categorized as short or long term depending on the length of time that the heat or cold is stored (seasonal storage). Different material qualities may be used in TES applications to achieve energy storage. TES can be categorised into three forms based on the thermal method utilised to store energy: Sensible (e.g., water and rock), Latent (e.g., water/ice and salt hydrates), and Thermo-chemical reactions (e.g., chemical reactions and sorption processes). Sensible storage occurs when a material's temperature is raised or dropped, but latent storage occurs when a material's phase (solid to liquid or liquid to vapour) changes without a temperature change. In the same material, both methods can occur. A chemical reaction, also known as a sorption process, occurs on the surface of a material. Heat can be absorbed or discharged from the substance in all instances.

1.3.1 Classification of TES system

TES systems are basically classified on the basis of their nature or working of the system and it is broadly classified as: latent heat storage (LHS), sensible heat storage (SHS) and thermochemical storage (TCS) [5].

1 **Latent heat storage**
2 **Sensible heat storage**
3 **Thermochemical energy storage**

a) **Sensible Heat Storage (SHS):** - The primary goal of a SHS system is to store the energy produced by increasing the temperature of a solid or liquid medium. During the charging and discharging operation, the heat capacity and temperature change of the material are used in this system. The amount of heat stored is highly influenced by temperature changes, medium specific heat, and the amount of storage material. [3].

$E = mc_p(\mathbf{\Delta}\mathrm{T})$ .... (1.1)

$E = mc_p(T_1 - T_2)$.. (1.2)

$E = \rho V c_p(T_1 - T_2)$.. (1.3)

The ability of a material to store sensible heat is highly influenced by the value of the quantity ρc_p Water has a high value and is cheap, but because it is liquid, it must be kept in a higher-quality container.

b) **Latent heat storage (LHS):** - The core of a latent heat storage system is Phase Change Materials (PCM). The chemical bonds in the PCMs break up when the source temperature rises, and the material goes through a phase transition. In the case of solid-liquid PCMs, this transition is from solid to liquid. Because it seeks heat, this phase change is an endothermic process. In the process, the PCM absorbs heat. This heat is stored in the storage substance, which begins to melt when the phase transition temperature is achieved. The temperature remains constant until the melting process is completed. [3].

$$Q = \int_{T_i}^{T_m} mc_p\, dT + ma_m\Delta h_m + \int_{T_m}^{T_f} mc_p\, dT \qquad (1.4)$$

$$Q = m\left[c_{sp}(T_m - T_i) + a_m\Delta h_m + c_{lp}(T_f - T_m)\right] \qquad (1.5)$$

c) **Thermo-Chemical Storage (TCS)**: - Thermal energy storage is seen as a supporting technology in a wide range of applications. They include energy efficiency, waste management, and renewable heat generation. In this scenario, thermo chemical storage materials outperform SHS and LHS in terms of storage capacity per mass or volume.

When compared to water storage, which is the most common type, it is frequently by a factor of ten or more. In terms of feasibility and cost, methods for storing heat for a short period of time are becoming more popular. Without insulation, TES materials can hold heat for a long time. As a result, it is considered a fundamental technique for infinitely long storage and heat transport. Thermo chemical storage systems, like latent heat storage systems and sensible heat storage systems, must meet particular features and parameters, making them a critical component of TES systems. Cycle efficiency, cycling stability, and power density are some of these metrics. Among these, cyclic stability, as well as storage capacity, are critical. [3].

Thermal Energy Storage (TES) systems is broadly categorised into Sensible heat storage, Thermochemical energy storage and Latent heat storage, and for our experimental analysis in this thesis latent heat storage based thermal energy storage system is been used.

1.3.2 Application of thermal energy storage (TES) system

Some areas of application of thermal energy storage (TES) system is highlighted below:

- Solar water heater system
- Solar cooker
- Air heater
- Green house
- Building
- Trombe wall
- Refrigerator and air conditioning
- Cold storage

- Defence

1.3.3 Advantages of thermal energy storage system

The prerequisites of designing a Thermal Energy Storage System are good heat transfer between the HTF and the storage material, high energy density in the storage material (storage capacity), compatibility of the storage material and the container material, mechanical and chemical stability of the storage material, complete reversibility of a number of cycles, low thermal losses during the storage period, and ease of control. The operation strategy, the maximum load required, the nominal temperature and enthalpy decrease, and the integration into the entire application system are other essential design requirements.

The following are some of the advantages of integrating storage in an energy system:

- Improved system reliability & performance
- Improved economics: It will help me in lowering the capital and operating costs
- Increased efficiency: It provides much more energy efficient consumption
- Less pollution of the environment.

1.4 Phase Change Materials (PCM)

PCMs (phase change materials) can exist in two different phases at least which includes amorphous and crystalline, and back and forth transition occur between them. The physical quantities that are used to distinguish among the phases includes mass density, thermal conductivity, electrical conductivity and optical reflectance. These variations, as well as the consistency of the switching, allow these materials to retain information and energy [8]. Phase change materials are broadly categorized as:

A) Organic PCM
B) Inorganic PCM
C) Eutectic PCM

Fig 1.2 represents the classification of Phase Changing materials on the basis of their nature.

1.4.1 Organic PCM:

Paraffin and non-paraffin compounds are the two types of organic materials. The only thing that is common in all the organic Phase Change materials includes congruent melting which means that no phase deterioration or segregation in latent heat of fusion even after a large amount of charge and discharge cycles. The organic PCM is also non-corrosive and has a strong self-nucleation property, which means the crystallisation process requires little to no supercooling.

- **Paraffin Compounds:** These compounds are the mixture of straight chain n-alkanes found in chemical molecules. With increasing chain length, the latent heat of fusion and melting point both rises. During discharging, the crystallisation of the CH_3 chain releases a lot of latent heat. Paraffin compounds have large range of melting temperature so they are considered to be more reliable. The nature of paraffin compound is non-corrosive.
- **Non-paraffin Compounds:** It contains the biggest group of Phase Changing Materials with wide range of properties. Several experiments have been done to see which alcohols, esters, fatty acids, and other compounds can be employed for latent heat storage.

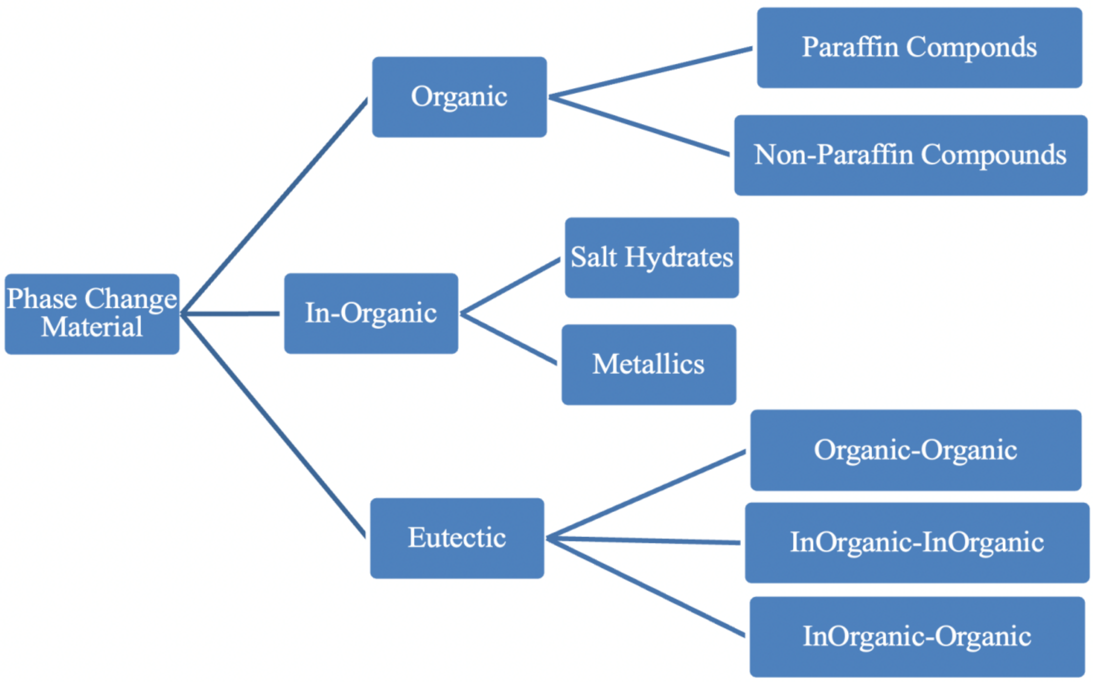

Fig 1.2 Classification of PCM (Phase change materials) on the basis of their nature

1.4.2 Inorganic PCM:

Salt hydrates and metallic PCMs are the two forms of inorganic Phase Change Materials. Metallic PCMs are generally not considered for thermal storage which includes low-temperature melting metallic eutectics, due to a slew of unique engineering issues that can arise during system design.

The appealing features of inorganic PCMs are:

(a) high latent heat of fusion per unit volume,
(b) salt hydrates are one of the most investigated PCM for application in latent heat storage.
(c) strong thermal conductivity (nearly twice that of paraffin)
(d) toxicity is less
(e) compatible with plastic containers
(f) changes in volume is very less when it is melted

It also has some significant flaws, which includes phase segregation and supercooling. supercooling occurs when solidification in certain salt hydrates can begin much below the melting point and phase segregation occurs when the released water of hydration cannot dissolve all of the solid phase at the melting point. This causes inconsistency in the material's heating, which is undesirable for thermal storage.

1.4.3 Eutectics PCM:

There are other PCMs available with a variety of melting temperatures, but they lack the remaining desirable features of a Phase Change Materials. Eutectics is used to remedy this problem. A eutectic is a minimum-melting combination of two or more components, each of which melts and freezes in the same way during crystallisation, resulting in a mixture of component crystals. Without phase separation, these materials always freeze and melt together forming a complicated mixture of crystals with difficult-to-separate components.

Based on the various demands for a latent heat storage unit, PCM may be selected from a wide variety of available compounds and materials. The following are a few examples of uses for these PCM-based thermal storage units:

- Controlling the internal heat load and building energy management with building walls which are integrated with PCM.
- PCM can be used as a storage unit to improve the system's performance for concentrated solar power plants.
- Application of PCM in solar water heating and solar cooking.

1.5 Desirable properties for a PCM

While working on a thermal energy storage device the PCM need to selected according to our requirement and demand. The selection of PCM are generally based on the material by which our device is made up of and the condition where the experiment is to be carried out. The most desirable properties that a PCM should have is discussed below:

- Thermal attributes include an acceptable phase change temperature, good heat transfer qualities, and a high latent heat of transition.
- The physical features of a PCM include good phase stability, high material density, small change in volume, and low pressure of vapour.
- The chemical properties include compatibility with container material, long-term chemical stability, low toxicity, and non-flammability
- The kinetic properties include supercooling is not allowed and crystallisation rate is proper for providing safety from fire hazard.
- Affordability: The material should be readily available in big quantities at a low price (for cost-effectiveness of the storage system)

1.6 Outline of Dissertation

The dissertation consists of following chapters:

Chapter 1: In this chapter introduction to the energy, storage systems, thermal energy storage system, PCM's and their desirable properties are discussed. Along with this, the applications and advantages of TES system and their future scope is discussed.

Chapter 2: In this chapter, literature survey is carried out. Work done in the field of thermal energy storage system and different phase change materials is observed.

Chapter 3: In this chapter, the experimental setup of TES (Thermal Energy Storage) System is described and the working of various components present in the system is explained. Along with that, the general working of TES system is also discussed.

Chapter 4: In this chapter, different temperature profiles at different flow rates of HTF (Heat Transfer Fluid) is plotted and discussed.

Chapter 5: In this chapter, and future scope of work is determined.

CHAPTER 2
LITERATURE REVIEW

2.1 General

Thermal energy has been introduced in late 19th century but its practical application has been introduced in 20th century. Many research is been done to increase the effectiveness of this system. While working on this experimental work lot of literature survey was done to check the road map of thermal energy storage system which gives us the future map or scope of work which can be done. Literature survey has been helpful in knowing the insights of the Thermal energy storage system and carrying out the experimentation with full pace.

In order to get a complete grasp of the thermal storage system's operation, the below mentioned literatures were referred and studied to get an insight about the past history of the TES system. It helped me understand how far thermal storage technology has progressed and what are the challenges and gaps which need to be rectified. It was also helpful in learning how to conduct an experimental examination of the thermal energy storage based on the principle of LHS (latent heat storage) effectively.

In the very beginning the research on phase transition focused on pure substances (water-ice). The ice formation was initially studied by Lamé and Clapeyron (1831) [5] & some of the analysis was done by Stefan (1891) [6]. In 1912 F. Neuman contributed his study on phase change materials and provided results on phase change problem. After that in mid 90's two researchers London and Seban [7] investigated about some ice production process for a variety of shapes (flat, spere and cylinder). But their research lag and was questionable as there was solidification issue because of 1-dimensional approach which was found by Shamsundar and Srinivasan (1978) [8] . As a result, rather than using his 1-dimensional approach method, preference was given to use the 2-dimensional approach method which resulted in improved results and its accuracy.

Abhat (1983) [9] conducted a review of phase transition materials, its characteristics, usage as a means of thermal (heat and cold) storage in different energy systems. The effects of melting-freezing heat cycling on several phase change materials were first identified in this review. These studies also demonstrated the great potential for governments and the energy industry to invest in latent heat storage.

Bansal and Buddhi (1992) [10] were the first to contribute their analytical studies in the field of PCM based thermal energy storage system. In his work a "cylindrical PCM" which was integrated with solar FPC for use in household water heating was investigated and assessed. This research laid the groundwork for future PCM research. It also assisted in the development and foundation of a theoretical system for the model under research and investigation.

Lacroix et al. (1993) [11] open his work in the field of materials changing phase and storing energy. The multi-dimensional phase transition is one of the first studies to formulate & address heat transport problems. This research contributed significantly to the development of the enthalpy approach while also taking into account the contribution of convective heat transport. It was expected that the flow rate would be affected, radius, and heat transfer fluid inlet temperature could affect the working and performance of this phase change material heat storage system. These guesses was proved after extensive study and later his findings were verified and accepted.

The usefulness of a PCM based TES system was examined by Yagi and Akiyama (1995) [12]. Six different PCM's (Phase change materials) were used during their experimentation out of which four were metallic and the rest two were inorganic type. They used a packed bed storage form to conduct thermal storage. The research for the heat transfer analysis was made and on both system single spherical phase transition material storage and other one being the packed bed of PCMs (phase change materials). The final result was concluded that during this analysis metallic one performed in a better way than the other one that is the inorganic one. Concurrent flow produced superior findings in the investigation of packed bed storage than counter current flow.

A computer based model for checking and analysing the thermal behaviour and predicting the behaviour of multi-layer LHS system which was done by Brousseau and Lacroix (1996) [13]. It is created using the principle of energy conservation in phase change materials and heat transfer fluids. Parametric studies and evaluations were also conducted and presented in order to build a link between the thermal storage unit's behaviour and a number of system-affecting parameters. These experiments were carried out in order to build an energy storage unit that would reduce home electricity usage during peak load periods. In places where firms employ dynamic pricing to provide electricity, such a storage device can be extremely beneficial in lowering the electricity price.

Some more contribution are made by Brousseau and Lacroix (1998) [14] as they also worked on latent heat storage system and by performing numerical simulation based on several layered phase transition materials. Due of the numerous melting points of the distinct layers, the simulation revealed complex isotherm distributions within the phase change material (PCM). As a function of various design and operational parameters, the study provided correlations between total heat stored and output heat at the end of discharge.

Esen et al. (1998) reported their work on the geometric design of solar-assisted latent heat storage systems based on various operational parameters and phase-change material types. The PCM-filled cylinders were used in a residential heating circuit [15]. For two different situations, a numerical simulation based on the enthalpy formulation approach was used to solve the two-dimensional phase transition problem. The first mode of operation would be with PCM-filled cylinders and heat transfer fluid (HTF) flowing parallel in the tube that encloses the cylinders. The second mode involves filling the outer cylinder with PCM and forcing HTF to flow through the inner cylinder. For both configurations, several numerical simulation runs were undertaken to investigate the effect of parameters such as cylinder and pipe radii, total PCM volume, HTF mass flow rate, and so on. They presented the best geometric design for this household PCM coupled heating system based on these research.

By tackling the issue of PCM thermal conductivity, researchers hoped to increase the performance of phase change material (PCM) based latent thermal heat storage devices was given by Velraj et al. (1999) [16]. The results showed that the first two approaches were effective in improving heat transmission during PCM solidification, while bubble agitation was more effective in improving heat transfer during melting.

The effective heat conductivity for a composite phase transition material (PCM) induced with paraffin wax was investigated by Fukai et al. (2000) [18]. The aim to improve the conductivity, the fibres of carbon was mixed. Two scenarios were investigated for getting any improvement or development in the conductivity (thermal) of the PCM (phase change material). First method involved putting disoriented carbon fibre into the PCM, whereas the other method involved use of a fibre brush. In the first case the fibre length has almost negligible effect on the thermal conductivity of phase transition material, whereas in the second case fibre brush increased the thermal conductivity significantly.

Sari and Kaygusuz (2000), for a LHS (latent heat storage) system with heat storage tank, gave an experimental energy study and exergy study. The studies were carried out on a residential heating system. Energy and exergy analyses yield a wide range of outcomes. The authors propose that exergy analysis be used as the primary measure of system performance [19].

Sari and Kaygusuz (2001) discussed the use of stearic acid as a phase change material in a latent heat storage unit. Experimental research was conducted on stearic acid's thermal performance and heat transmission characteristics. The effect of several parameters on the phase change stability of the PCM, such as transition periods, temperature range, and heat flow rate, was investigated and compared to previous literature. The effect of adjusting inlet heat transfer fluid temperature on melting and solidification characteristics was also investigated. The setup was tested in both horizontal and vertical configurations, with the former proving to be more effective and possessing superior phase change characteristics than the latter [20].

A numerical model of a heat storage system made up of a cylindrical packed bed of spherical PCM filled capsules by Ismail and Henrquez (2002). For analysing the system numerically and empirically one- dimensional approach of conduction phase transition model. Both a numerical and an experimental method are used to examine the effect of geometrical and operational parameters on the cyclic process of TES (charging & discharging) system [21].

Anica Trp (2005) Performed an experimental and numerical analysis on LHS (latent heat storage system for checking the direction for design optimization & system performance. Numerical simulations were used to obtain the PCM, temperature profile of the hot fluid that moves inside the TES system, tube wall, and HTF working circumstances and geometric factors [22].

Medrano et al. (2009), During the charge and discharge procedures, the heat transfer parameters was experimentally determined. For each of the five heat exchanger setups, thermal interaction with PCM was estimated using the enthalpy formulation approach. The average heat stored per unit area in a Graphite matrix embedded Phase transition material per unit temperature gradient is largest for the heat exchanger of double pipe type [23].

A mathematical model was developed for the calculation of effect of geometric and operating characteristics on energy conservation equations by Adine and El Qarnia in 2009 [24].

Hosseini et al. (2012) investigated the behaviour of melting temperature of material changing its phase using a combination of experimental and computational methods. The goal of this study is to figure out how phase transition material (PCM's) melts due to buoyancy during the charging cycle. The studies were carried out at various intake of water temperatures (HTF) and see how they are been affected the PCM charging process. The simulation took into account the phase change phenomena of single domain enthalpy formulation. According to the findings, PCM melting begins at the HTF tube and progresses towards the shell side. It also demonstrated that as the temperature of the inflow water (fluid) increased, with a significant decrease in melting time [25].

Hosseini et al. (2014) looked into the thermal properties of paraffin during its melting and solidification inside the heat exchanger (shell & tube type). System performance is verified by both experimental and simulation studies. The findings show a direct link between the performance of system intake and temperature of fluid (HTF), with efficiency increasing dramatically as the temperature of the HTF rises [26].

An experiment for the modelling and investigation of a paraffin wax induced (SEC) solar energy collector was done by Reyes et al. (2015). These researchers made a thermal collector out of empty aluminium soft drink cans. Solar thermal collector setups have been created for testing. One collector is filled with pure 100 percent paraffin wax, while the other is filled with 7.5 percent aluminium stripes collected. When compared from former, the final arrangement had double the thermal conductivity. Water is generally used as a HTF but in this setup air was used in the charging-discharging thermal cycle. The prototype testing yielded promising results, prompting the creation of a bigger resultant version of the prototype. Simultaneously, the experimental data was verified with the simulation model in MATLAB [27].

For predicting the thermal behaviour Mathematical equations were produced for a storage unit (shell and tube type) and fluid that is flowing in the TES system inside the tube by Bechiri and Mansouri (2015). The material that is used as a phase change material is paraffin wax. Qarnia et al. [24] developed a model that was helpful for predicting analytically general performance and the thermal performances [28].

For LHS units (tube shell type), the impact of positioning on the performance of was investigated by Seddegh et al. (2016). Based on the findings, it was seen that during the charging state, horizontal heat exchangers has a better output and performance than the vertical ones. Also, it was seen that the unit's positioning had no effect on PCM solidification and that the hot HTF inlet temperature had a substantial impact on melting time [29].

Chen et al. (2016) conducted an analytical research study on LHS (latent heat storage) using a horizontally oriented and aligned heat exchanger with tubes for HTF flow. This system's PCM was combination of two materials one graphite & the other one paraffin. The experimental setup has distinct advantages over other horizontally oriented LHSUs that have been explored. The heat exchanger is made of materials which gives better and improved output. The material used is composite. The benefits of all this is increased thermal conductivity because of large area for heat transfer. It was researched that how different operating settings affected the system's performance. While comparing it was observed that temp. difference has great effect on the performance of the device rather than mass flow rate of the fluid [30].

Nabat et al. (2020), in his research discussed about the liquid air energy storage which is the most recent technology in energy storage. His some of the major findings were high energy storage density, no geographical limitation, and applicability for large-scale uses. His economic analysis represents a payback period of 3.91 years and a net profit of about 18.6 $M during the useful lifetime of the system [43].

Ahmet Aktaş and Yağmur Kirçiçek (2021), discussed about the usefulness of solar thermal energy storage system and compared its result with conventional non-integrated thermal energy storage system. Thermal energy storage is cost-effective and simple structure compared to other types of storage [42].

Experimental work on horizontal configuration heat exchangers of shell and tube type has been extremely infrequently described, according to the literature reviewed above. Only a few investigations on the shell and tube latent heat storage unit with helical coil tube(s) have been published thus far. This research aims to improve our understanding of the thermal behaviour of such systems.

2.2 Research gap

After some literature survey it has been found that, TES being a good opportunity for energy storage and conservation technique but lot of development in design is required along with that no work has ever been done for comparing the results of any two different PCM's at different flow rates. Our work will justify and validate the comparison of two PCM's (paraffin wax and fatty acid), water being the HTF for the experiment.

A lot of work has been carried out on the thermal energy storage and its exergy and energy analysis has been done by many researchers. Some works are done on the heat exchange capacity, effectiveness and thermal efficiency. But no research works shows the comparison of more than one PCM.

CHAPTER 3
METHODOLOGY

3.1 Introduction

The system is designed to check the pattern of charging, storing and discharging of heat and cold in the phase change material which is inside the three cylinders fitted. The arrangement includes two different kind of PCM's (phase change materials) and one the last cylinder contains the cascading system in which the other two PCM's are combined. The system includes an electronic panel on which every temperature and flow readings can be observed. The basic aim of this setup is to check the charging storing and discharging pattern which is basically based on the principle of heat storing during the phase change of a material. The energy is stored during the phase changing period of the material inside the cylinder which is fatty acid, paraffin wax and cascading system in our case. This thermal energy which is now stored inside the cylinder which contains PCM is preserved by the insulating material which is PUF (polyurethane foam).

Inside the cylinder, there are several components such as the spiral coil tube, which is made of copper and is used for charging storing and discharging the cylinder with HTF, and the shell cylinder, which is used to carry phase change material (PCM) which is made up of stainless steel. Total performance of this heat exchanger system was thoroughly engineered. Normal tap water is utilised as the HTF for charging and discharging the PCM. To limit the loss of heat through PCM cylinder, polyurethane foam (PUF) which is an insulating material which prevents the heat losses to the surrounding. Different Sensors have been incorporated and attached to a control unit for taking the reading of temperature and the flow of the HTF so that correct observation or behaviour of this system can be seen and observed. Along with that the nature of heat storing capacity can be seen properly.

3.2 Experimental setup

The experimental setup of thermal energy storage system is a collection of two PCM's and one cascading system which can be used for storing heat energy in them, along with that it will also help in calculation and plotting of different temperature profiles. The setup consists of a heat source tank, three tanks of PCM (paraffin wax, fatty acid and cascading of both), sensors for the measurement of temperature and flow, valves for controlling the flow, pump and control unit.

3.2.1 Components used in experimental setup:

The components that are used for designing the Thermal Energy Storage System are:

1. **Heat Source Tank:** The heat source tank is of 50 litre capacity which is insulated with help of PUF material from outside and is completely sealed to barricade heat losses from it. There are two electric heaters installed which helps in heating the HTF (Heat Transfer Fluid).
2. **PCM Tanks:** The setup also consists of the 3 tanks which contains two different types of phase change materials and in the third tank the provision of cascading is done which contains the combination of the first two PCM's i.e. (paraffin wax and fatty acid).
3. **Used HTF/ Cold HTF Storage:** Two tanks are installed having same capacity of 120 litre. These tanks contain the HTF in cold state and the return of the water in hot state. Tanks are installed with the provision of portability, so that the fluid can be replaced conveniently.
4. **Temperature & Flow Measurement Sensors/ Control Unit:** The setup has in total of 17 sensors out of which 16 are temperature sensors which are a RTD-based sensors. The last sensor which is also fitted with these sensors is the flow sensor which helps in showing the actual flow rate so that it can be varied for taking the calculations at different flow rates. At last all the sensors are attached to a control unit or the control panel which has the display of all the temperatures that has been calculated and contains 3 switches which operates the two heaters that is fitted at Heat sources tank and one switch for the operation of pump.
5. **Pump:** A pump is fitted with the cold HTF tank so that fluid can be pumped into the heat source tank so that experiments can be carried out. The pump that is used is a centrifugal type which is used for low head.
6. **Insulators:** Pipes and fittings are covered with thermal insulators so that heat losses can be minimized.
7. **Alarm:** Alarms are installed so that water level can be known and overflow of fluid can be prevented.

The components attached in the chassis of the Thermal energy storage system can be properly seen and analysed through the schematic diagram shown in figure 3.1. This schematic diagram is the representation of actual thermal energy storage system on which our experimentation is carried out.

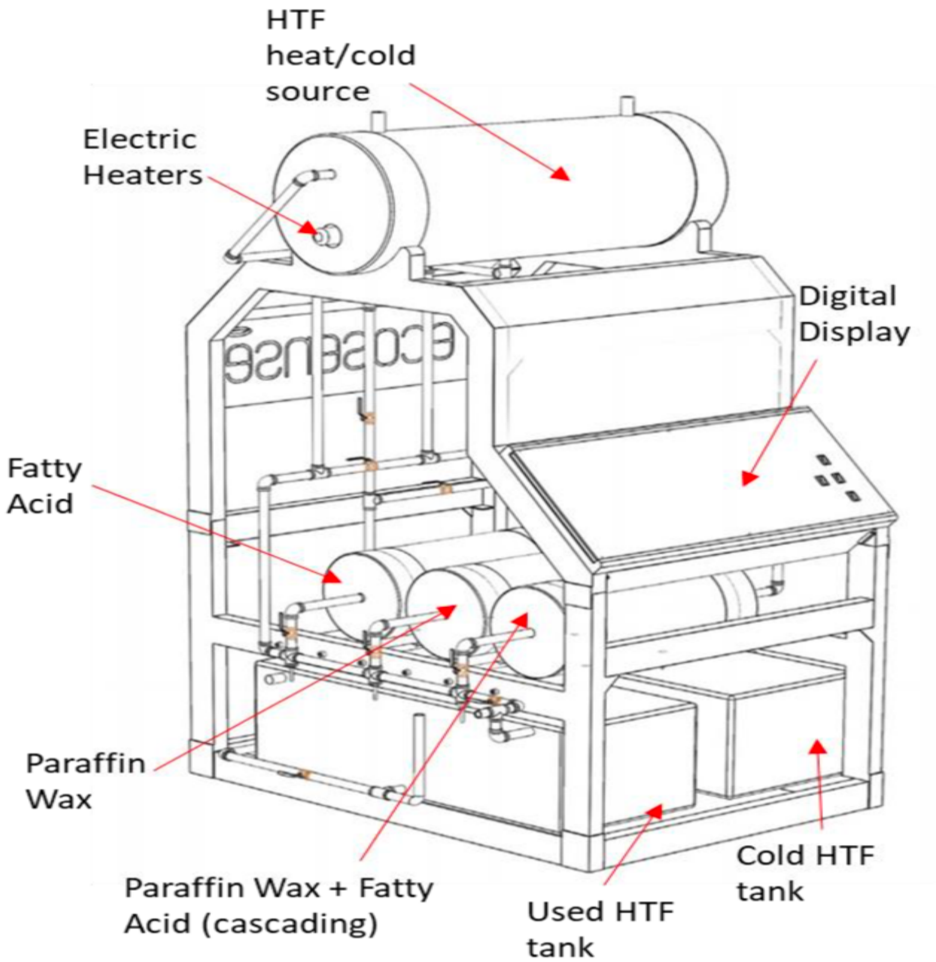

Fig 3.1: Schematic diagram of TES system [31]

The schematic diagram shown clearly shows the components like electric heaters, digital display, HTF heat/cold source, fatty acid cylinder, paraffin wax cylinder, paraffin wax + fatty acid (cascading) cylinder), used HTF tank and cold HTF tank.

Table I Thermophysical Properties of Paraffin Wax and Organic Fatty Acid [31].

Type of PCM	**Organic**	**Organic**
Name of PCM	Paraffin Wax	Organic Fatty Acid
Thermal conductivity in solid state	0.346 W/mK	0.275 W/mK
Thermal conductivity in liquid state	0.167 W/mK	0.162 W/mK
Density in solid state	916 kg/m^3	860 kg/m^3

Density in liquid state	790 kg/m³	833 kg/m³
Specific heat capacity in solid state	2.9 kJ/kg K	0.73 kJ/kg K
Specific heat capacity in liquid state	2.14 kJ/kg K	0.67 kJ/kg K
Heat of fusion	173 kJ/kg	210 kJ/kg
Melting temperature	55-57°C	65-67°C

Table II Specification of TESS [31].

SL.NO	COMPONENTS	SPECIFICATION
1	HTF SOURCE TANK	Material: Stainless Steel Capacity: 50L
2	HEAT EXCHANGERS	Type: Shell & Tube type Numbers of heat exchangers: 3 PCM Carrying capacity of shell: 5kg Materials: - 1) Shell: Stainless Steel 2) Heat exchanger tube: Copper
3	USED HTF STORAGE TANK	HTF holding capacity: 120l Tank material: FRP
4	COLD HTF STORAGE TANK	HTF holding capacity: 120l Tank material: FRP
5	PUMP	Power: 0.12 HP Maximum Head: 6m Maximum flow rate: 33LPM
6	PCM 1	Paraffin based PCM Melting temperature: 55-57°C Heat of Fusion:173 kJ/kg
7	PCM 2	Fatty acid based PCM Melting temperature: 65-67°C

		Heat of Fusion: 210kJ/kg
8	TEMPERATURE MEASURING INSTRUMENT	RTD based class A sensor Range: -200 to 650°C
9	FLOW MEASURING INSTRUMENT	Flow sensor and flow meter: 01 Flow range: 0.5 – 30 LPM
10	VALVES	17 valves ½ Inches valves

In the review of the current study, many strategies were employed to improve the heat transfer rate of the thermal energy storage system (TESS). The focus of this study was on PCM-based thermal energy storage devices, which are more versatile and helpful to energy-saving systems. [4]. A phase change heat energy storage system (PCHES) employing Erythritol as a phase change material (PCM) was tested in an experimental study[32]. The heat transmission characteristics of paraffin wax during melting and solidification procedures were investigated using a vertical annulus energy storage device. [33]. In architectural applications, phase change materials (PCMs) can improve indoor thermal comfort while also increasing energy efficiency. [34]. The theoretical thermal as well as fluid flow characteristics of a phase change material-based thermal energy storage device have been investigated. [35]. In this study researcher investigated both theoretically and experimentally performance enhancing techniques. [36]. It was discovered that raising the fluid flow rate or decreasing the inlet fluid temperature made thermal energy storage system discharge faster, and that changing the flow rate was efficient during charging the discharging time. [37].

HTF storage tank, PCM cylinders, Temperature and flow sensors, control valves, control panel (control unit), Pump and switches constitute the thermal energy storage system. After filling the water storage tank, the water is slowly heated to around 70°C using a steady heat source. Flow control valve is used to control the flow and hot fluid is allowed to flow in control manner in side storage tank. The TES tank is made up of spherical capsules that contain PCM like fatty acid and paraffin wax. Heat is slowly absorbed by phase transition materials until they reach melting point. This is referred to as the charging procedure. Experiments were carried out in this manner for different mass flow rates. For experimentation three flow rates were taken and the values of temperature is taken and different curves are plotted at 3 lit/min, 5 lit/min, and 7 lit/min.

Circuit as well as schematic diagram of TESS is shown in figure 3 and 4 specifies cylindrical system made of mild steel (MS) material and diameter of 60mm. Specifications are discussed in below tables. For, TES tank the specification are discussed in Table I and Properties of phase change material (PCM) is discussed in Table II.

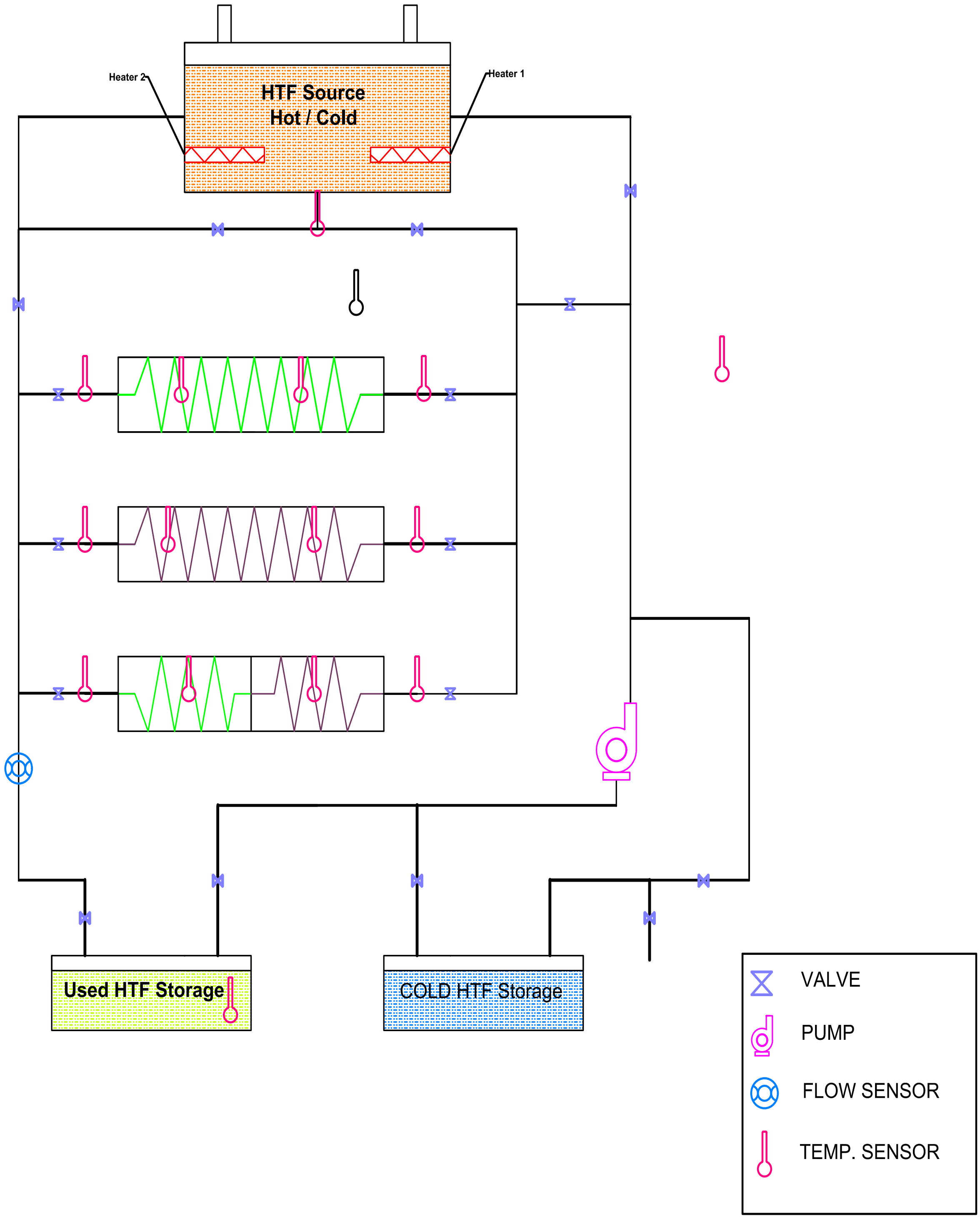

Figure 3.2: Circuit Diagram Thermal Energy Storage System [31].

The circuit diagram shows the actual connection between all the different components of the TES system. Different sensors like flow and temperature sensors are depicted properly and components like pump, valves, HTF storage tank (cold and used), two heaters and 3 PCM cylinders are shown in the circuit diagram. The study becomes easy while analysing the flow from the circuit diagram.

Figure 3.3: Thermal energy storage system

The actual working setup installed at Green Energy Lab., Delhi Technological University, Delhi is shown in figure 4.

3.4 Experimental Procedure

The experiment was carried out in normal working condition at Green Energy Lab, Delhi Technological University. A series of experiments where done to plot the temperature profiles at different stages like charging storing and discharging period. The experimentation and its result was conducted and verified during the period of January'22 to May'22.

The experiment has three basic phase the first phase is called the charging phase in which the HTF is allowed to achieve the desired temperature at which the particular phase change material will be easily melted and gains the ability to store the heat energy during its latent phase change period. The second phase is called the storing period in which the HTF is rotated through the cylinder containing the particular PCM on which the experimentation is carried out.

Now in this period the PCM charges itself with heat energy during its phase change. At last comes the discharging phase when the PCM rejects heat and cools down. These process all together constitutes the overview of the procedure in brief. All the process needs extreme precaution and accuracy to minimize or eliminate any kind of mishappening during the experimentation. Pump and other device should be operated with proper care so that the working is not interrupted. Special attention needs to be given on the sensors so that readings does not gets manipulated so, cleaning of sensors at regular interval of time is necessary. Control panels need to be protected from getting contact with water as it can be easily damaged during experimentation. After getting the brief insights of the experiment and precaution the experiment was carried out.

3.4.1 Charging Process:

The steps that are involved for charging the PCM tank is discussed below:

1. The 120 litre HTF storage tank needs to be filled with regular water.
2. Valves need to be properly opened and switch on the Pump to completely fill the HTF source tank.
3. Now, all the valves that are in flow condition need to be shut off carefully.
4. The two heaters that are present in the HTF storage tank need to be turned on by the two switches (L & R) present on the control unit.
5. Now observe the temperature on the control panel up to which the water is to heated to perform the experiment.
6. Turn off the heaters when the temperature is achieved.

7. All readings need to be noted which is displayed on the control panel at regular interval of time.
8. After achieving the desired temperature that is mentioned for particular PCM, referring the circuit diagram all the required valve needs to be turned on to allow the flow of hot water in the desired cylinder.
9. Flow valve can be adjusted to maintain the flow either constant or variable depending upon the experiment requirement and reading can be observed on the digital display.
10. All readings of temperature and flow needs to be observed and noted properly.
11. After the Heat transfer fluid tank gets empty, all the valves and switches need to be shut off.
12. The process must be repeated to get the average value.
13. At last, after performing the experiment drain all the remaining hot water to the down below storage tank.

3.4.2 Discharging process

The steps for the discharging process in which the system is brought to ambient condition are as follows:

1. In discharging the valves are allowed open according to the circuit diagram.
2. Pump need to be turned on and water is allowed to enter in the upper tank which is the HTF source tank.
3. All the initial readings are to be noted.
4. Referring the circuit flow diagram, the valves respective to the desired PCM cylinder are allowed to open.
5. Flow is allowed and all the readings are taken down at regular intervals.
6. Flow rate are kept constant or variable depending upon the test requirement.
7. After the readings are complete and the temperature comes down to ambient, the rest of the water is drained into the tank situated below (storage tank).

These processes are carried out several times and proper graphs are plotted for all the process and all the three PCM. The fluid being normal tap water, all the data has been drawn. Mass flow rate is also varied from 3litre per minute to 7 litre per minute and the readings are analysed.

In this chapter, discussion about the methodology of the experiment was made and along with that different component of the setup was explained. Circuit diagram, and photograph of the setup is shown. Different tables consisting of design specification of the setup and thermophysical properties of the PCM's are compiled. Proper explanation for the experiment and its procedure is discussed with their safety precautions.

3.5 Calculations

The following equations are calculated for doing the performance and thermal analysis thermal energy storage system (TESS).

3.5.1 Analysis of Heat Exchanger containing Phase Change Materials (PCMs):

The instantaneous heat transfer during charging process of the PCM Is calculated by the help of following equations:

Heat carried by Heat Transfer Fluid at inlet of Phase Change Material Cylinder is given by:

$$E_{in} = \dot{m} * C_{HTF}\left(T_{HTF,i} - T_a\right) Watts \quad (3.1)$$

Heat remaining in Heat transfer fluid which is not absorbed by Phase Change Material is given by:

$$E_{loss,wa} = \dot{m} * C_{HTF}\left(T_{HTF,o} - T_a\right) Watts \quad (3.2)$$

Heat input/ instantaneous heat absorbed by PCM is given by:

$$E_{ch,in} = E_{in} - E_{loss,wa}\ Watts$$

$$E_{ch,in} = \dot{m} * C_{HTF}\left(T_{HTF,i} - T_{HTF,o}\right) Watts \quad (3.3)$$

The heat lost in the atmosphere due to heat transfer losses incurred by various layers of the heat storage cylinder is calculated as:

Heat loss per unit length during charging:

$$\dot{q_1} = \frac{T_{HTF,avg} - T_a}{R_1} \quad (3.4)$$

Where R_1 is thermal resistance and is given as,

$$R_1 = \frac{1}{h_i A_i} + \frac{\ln(\frac{r_2}{r_1})}{2\pi k_1 L_1} + \frac{\ln(\frac{r_3}{r_2})}{2\pi k_2 L_2} + \frac{\ln(\frac{r_4}{r_3})}{2\pi k_3 L_3} + \frac{\ln(\frac{r_5}{r_4})}{2\pi k_4 L_4} + \frac{\ln(\frac{r_6}{r_5})}{2\pi k_5 L_5} + \frac{1}{h_o A_o} \quad (3.5)$$

Calculating $h_i and\ h_o$,

3.5.2 Calculating value of h_i:

Using the relation of Nusselt Number:

$$h_i = \frac{Nu * k_w}{D_i} \quad (3.6)$$

Nusselt number is obtained by the help of empirical relations as given below:

a) For smooth circulation tube (constant heat supply and laminar flow):

$$Nu = \frac{h_i D_i}{k_w} = 4.36 \quad (3.7)$$

b) For smooth circulation tube (constant surface temperature and laminar flow):

$$Nu = \frac{h_i D_i}{k_w} = 3.66 \quad (3.8)$$

c) For fully developed turbulent flow (used in this project):

$$Nu = 0.023 * Re^{0.8} Pr^{0.4} \quad (3.9)$$

Reynold's number is given by the relation:

$$R_e = \frac{\rho_w v D_i}{\mu_w} = \frac{4\dot{m}}{\pi D_i \mu_w} \quad (3.10)$$

And the value of Prandtl number and Reynold's number vary with temperature.

3.5.3 Calculating value of h_o:

Using empirical relations involving Nu, Gr and Pr:
For horizontal cylinder following cases can be considered:

i) $10^4 < Gr.\mathrm{Pr} < 10^9$; $Nu = 0.53(Gr * Pr)^{0.25}$ (3.11)

ii) $10^9 < Gr.\mathrm{Pr} < 10^{12}$; $Nu = 0.13(Gr * Pr)^{0.33}$ (3.12)

Where Gr is the Grashoff Number and is calculated by:

$$Gr = \frac{v_o^3 \rho_{air}^2 g(T_{cy} - T_a)\beta}{\mu_{air}^2} \quad (3.13)$$

From all the above equations, h_i and h_o are calculated and the value of R_1 is obtained. With the help of R_1, value of $\dot{q_1}$(Heat loss per unit length during charging) can be calculated.
Therefore, energy loss from cylinder during charging is given by:

$$E_{loss} = \dot{q_1} * L_4 \; Watts \quad (3.14)$$

The energy accumulated by PCM Cylinder during charging can be given by the help of equations given below:

$$E_{ch} = E_{ch,in} - E_{loss} = E_{in} - E_{loss,wa} - E_{loss}\ Watts \tag{3.15}$$

The charging efficiency of the PCM is given by the help of equation:

$$\eta_{ch} = \frac{Energy\ accumulated\ during\ charging}{Energy\ input\ during\ charging} = \frac{E_{ch}}{E_{in} - E_{loss,wa}} \tag{3.16}$$

These equations are different energy equation for finding different parameters of the system and for doing the performance analysis of the thermal energy storage system. These parameters will help the researcher for doing the performance analysis of this setup.

CHAPTER 4

RESULT AND DISCUSSION

For the charging and discharging operation, the temperature profile of HTF and PCM in the TES tank are examined for varied incoming fluid temperatures and mass flow rates. The effectiveness of the system and the amount of instantaneous heat stored are also evaluated graphically.

4.1 Charging process:

(i) Temperature profile of water and PCM

The temperature profiles of HTF and PCM during the charging process of a TESS encapsulated with PCMs are shown in Figures 4.1 and 4.2. The HTF's input temperature rises at a constant rate until the PCM in the storage tank reaches the phase change temperature. There is no discernible change in temperature between the segments. This is because of that temperature of the water in the storage tank rises gradually in response to the HTF inlet temperature through the steady heat source, and the temperature of the PCM rises in parallel.

As a result, the temperature differential between PCM and HTF is smaller during solid PCM sensible heating and phase change. It may also be observed that the rate of heat transfer from HTF to PCM in the storage tank is greater.

Plotting graphs between temperature (centigrade) and time (minutes) for Heat transfer fluid at different X/L ratio. The considered X/L ratio are 0.25, 0.50, 0.75 respectively.

Where,

L –length of heat storage tank (mm)

X – axial distance from the top of the TES tank (mm)

X/L – dimensionless axial distance from the top of the TES tank.

TABLE III: TEMPERATURE FOR HEAT TRANSFER FLUID (HTF) AT VARIOUS X/L VALUES

Time (Min)	Temperature (℃)		
	X/L=0.25	X/L=0.5	X/L=0.75
10	32.5	33.1	32.2
20	35.12	35.3	34.9
30	42.03	41.8	41.7
40	44.3	43.9	43.5
50	45.1	45.3	44.8
60	45.5	45.6	45.1
70	48.05	47.5	46.9
80	49.9	48.6	48.1
90	51.1	51.2	50.82
100	52.3	52.1	51.7
110	55.2	54.9	57.65
120	56.2	56.1	55.85

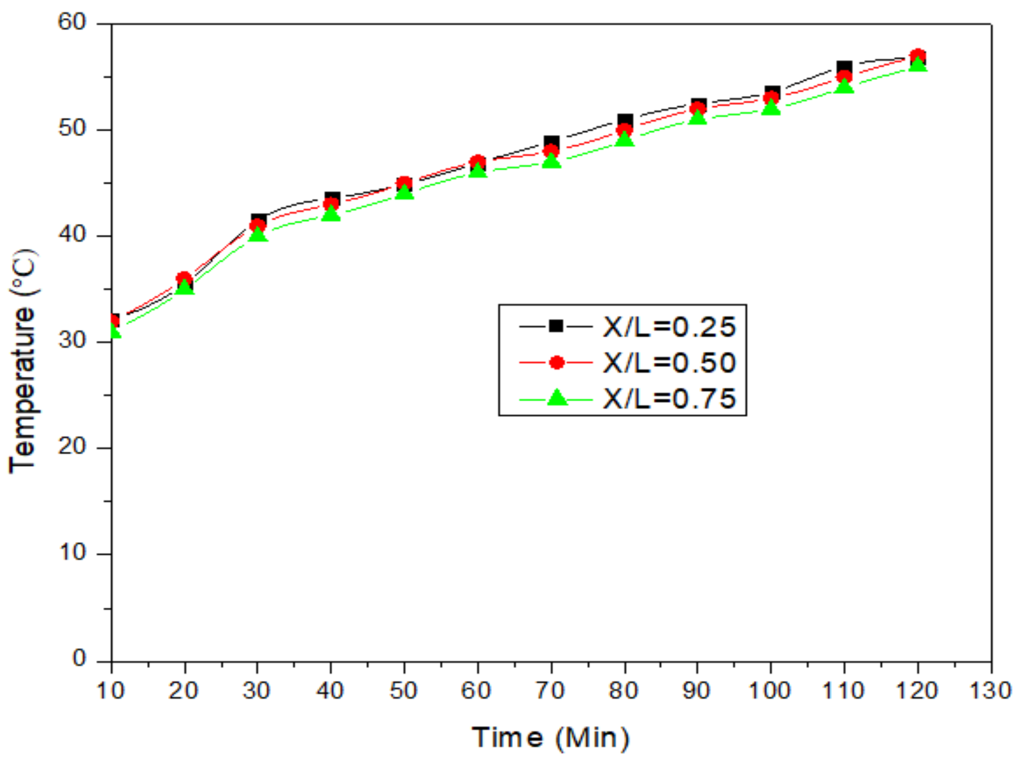

Figure 4.1: Temperature Profile inlet Heat transfer fluid (HTF)

TABLE IV: TEMPERATURE FOR PHASE CHANGE MATERIAL (PCM) AT VARIOUS X/L VALUES

Time (Min)	Temperature (℃)		
	X/L=0.25	X/L=0.5	X/L=0.75
10	32.6	32.8	32.5
20	37.1	37.3	37.0
30	39.2	39.6	39.1
40	41.2	41.4	40.9
50	45.5	45.1	44.8
60	47.6	47.2	46.9
70	49.3	48.9	48.6
80	49.5	49.3	48.9
90	49.7	49.5	49.1
100	50.9	50.4	50.1
110	51.1	50.0	49.4
120	55.4	55.6	55.3

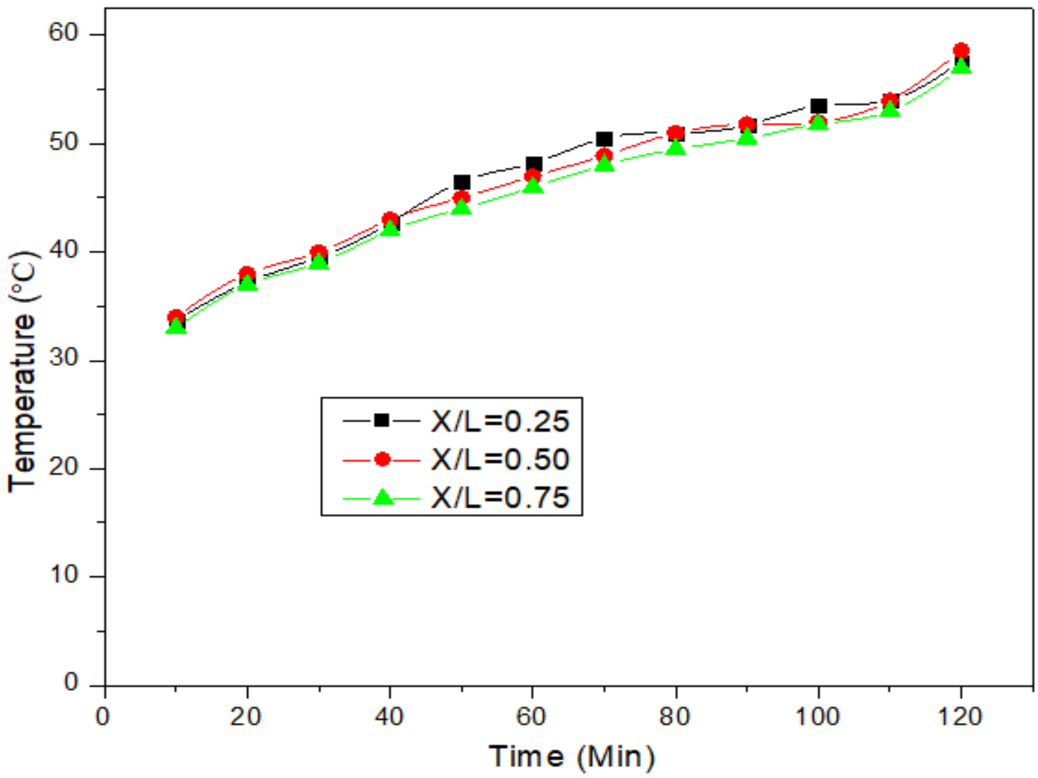

Figure 4.2: Temperature Profile PCM

(ii) Influence of inlet fluid temperature

TABLE V: TEMPERATURE FOR HEAT TRANSFER FLUID (HTF) AT 3 LITRE/MIN

S. No.	Time (Min)	Temperature (℃) at 3 Ltr/min
1.	0	70.0
2.	5	65.0
3.	10	60.2
4.	15	62.1
5.	20	64.9
6.	25	56.2
7.	30	55.8
8.	35	55.1
9.	40	48.3
10.	45	48.4
11.	50	51.1
12.	55	42.4
13.	60	44.8

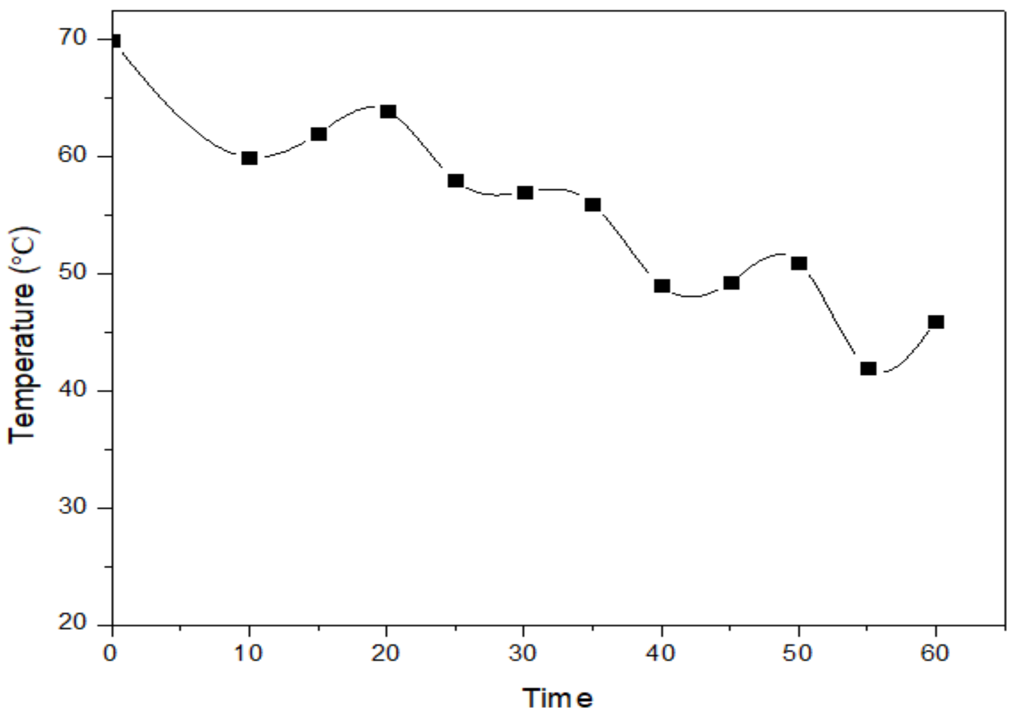

Figure 4.3: Variation in inlet HTF temperature at 3 Ltr/min

TABLE VI: TEMPERATURE FOR HEAT TRANSFER FLUID (HTF) AT 5 LITRE/MIN

S. No.	Time (Min)	Temperature (℃) at 5 Ltr/min
1.	0	70.0
2.	5	64.8
3.	10	60.32
4.	15	62.4
5.	20	65.2
6.	25	57.2
7.	30	57.8
8.	35	56.1
9.	40	50.12
10.	45	50.5
11.	50	51.3
12.	55	45.4
13.	60	46.65

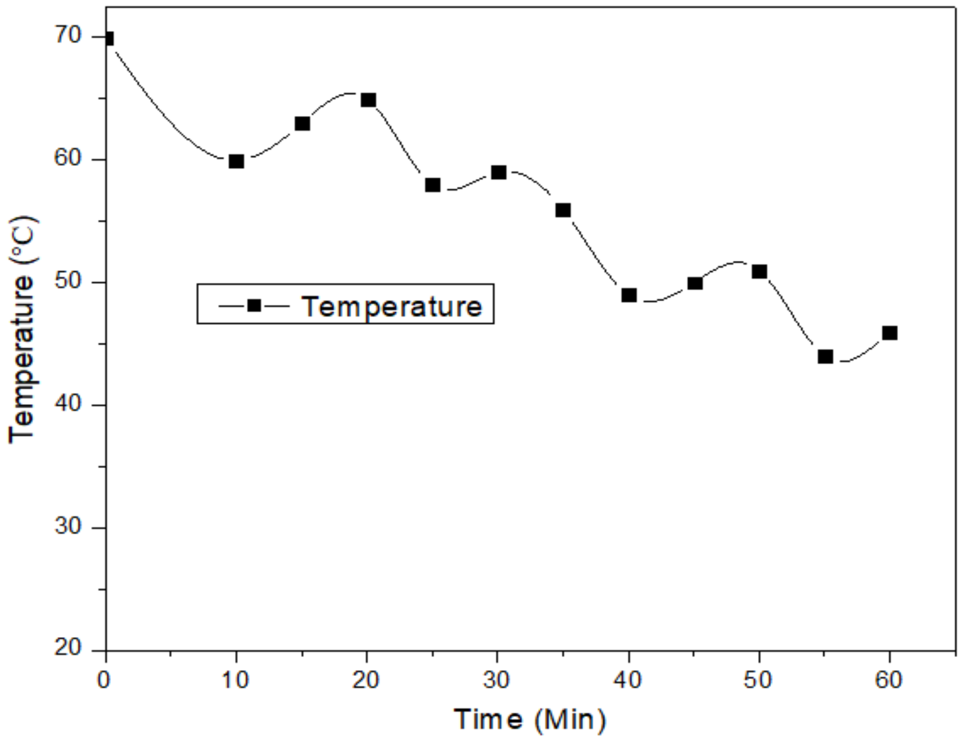

Figure 4.4: Variation in inlet HTF temperature at 5 Ltr/min

Figures 4.3 and 4.4 shows the effect of varying the HTF inlet fluid temperature on charging time for flow rates of 3 and 5Ltr/min, respectively. It can be seen that as the temperature of the input increases, the time required for charging reduces. For flow rates of 3 and 5Ltr/min, the time required for complete charging decreases by 40% as the temperature rises from 65°C to 71°C.

(iii) Instantaneous heat stored

It is determined using the HTF's input and exit temperatures. The immediate heat stored is enormous during the beginning phase of the charging process and reduces as the time passes around (45–50 minutes.) of the charging process. The temperature drops as the charging period progresses because the temperature differential between HTF and PCM diminishes as the PCM melts. Due to the continual temperature difference between the HTF and the storage tank, the temperature becomes practically consistent as time goes on. The instantaneous heat stored (in watts) for a mass flow rate is shown in Figure .4.5

TABLE VII: VALUE OF INSTANTANEOUS HEAT STORED (IN WATTS) FOR VARIOUS MASS FLOW RATE

Time (Min)	Instantaneous Heat Stored (W)		
	3 Litre/min	5 Litre/min	7 Litre/min
0	70	71	68
5	67	67	66
10	63	63.5	64
15	64	65.5	62.5
20	60	64	61.8
25	62	60	60
30	60.5	61.5	58
35	59	61	57
40	55	56	57.5
45	57	58	56
50	55	56	-
55	54	55	-

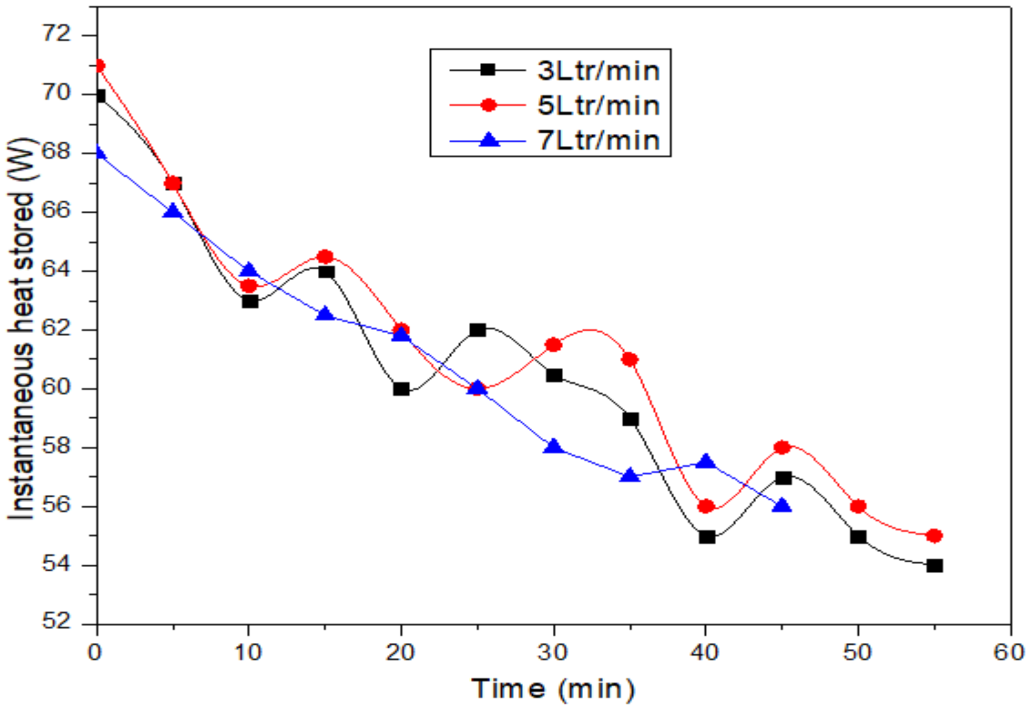

Figure 4.5: Representation of Instantaneous heat stored for various mas flow rate

(iv) System Efficiency

Throughout the sensible heating of solid PCM, the system efficiency increases with time, remains constant during the phase change period, and then increases again during the sensible heating of liquid PCM. Figure 4.6 depicts the efficiency difference between using PCM and not using PCM.

TABLE VIII: SYSTEM EFFECIENCY, η IN % WITH PCM AND WITHOUT PCM

Time (Min)	System Efficiency (η) in %	
	With PCM	Without PCM
20	26.6	3
40	25	4.8
60	25.6	6.1
80	32	13
100	38	15
120	40	17
140	45	21
160	48	24

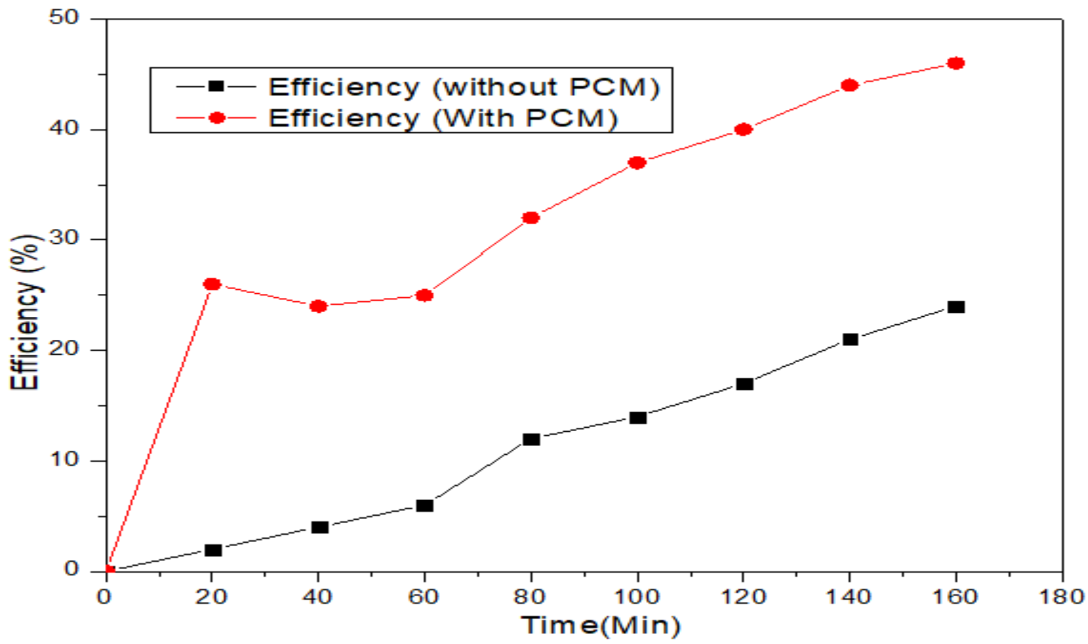

Figure 4.6: Representation of System efficiency with and without PCM

Figure 4.7 shows the relationship between charging time and PCM temperature for mass flow rates of 2, 5, and 7Ltr/min of HTF when flowing from a constant heat source, when PCM is paraffin wax used. The charging time for a mass flow rate of 3Ltr/min is 140 minutes. The charging period for a mass flow rate of 4Ltr/min is 120 minutes. The charging time for a mass flow rate of 7Ltr/min is 110 minutes.

TABLE IX: VALUE OF PARAFFIN WAX TEMPERATURE (IN °C) FOR VARIOUS MASS FLOW RATE

Time (Min)	**Paraffin wax Temperature (℃)**		
	3 Litre/min	**5 Litre/min**	**7 Litre/min**
0	35	35	35
10	37	43	42
20	39	48	48
30	41	52	52
40	43	54	54
50	45	55	55
60	47	57	59
70	50	58	61
80	53	59	62
90	57	62	64

100	58	67	69
110	60	70	70
120	62	-	-
130	65	-	-
140	70	-	-

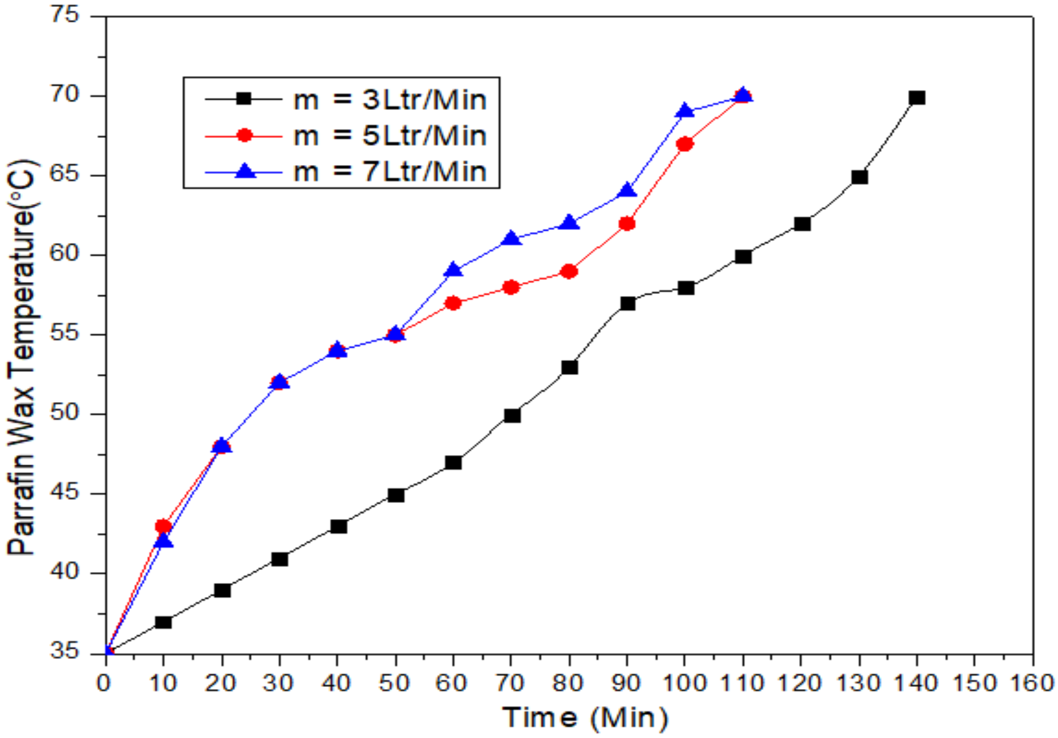

Figure 4.7: Relationship b/w paraffin fax temperature and mass flow rate

Figure 4.8 shows the relationship between charging time and PCM temperature for mass flow rates of 3, 5, and 7Ltr/min of HTF when flowing from a constant heat source and using fatty acid as the PCM. The charging time for a mass flow rate of 3Ltr/min is 130 minutes. The charging time for a mass flow rate of 5Ltr/min is 100 minutes. The charging period for a mass flow rate of 7Ltr/min is 90 minutes.

TABLE X: VALUE OF FATTY ACID TEMPERATURE (IN °C) FOR VARIOUS MASS FLOW RATE

Time (Min)	**Fatty Acid Temperature (°C)**		
	3 Litre/min	**5 Litre/min**	**7 Litre/min**
0	35	35	35
10	40	47	46

20	42	52	50
30	44	54	53
40	46	55	54
50	48	57	58
60	51	59	59
70	55	61	62
80	57	65	67
90	58	68	70
100	60	70	-
110	65	-	-
120	67	-	-
130	70	-	-

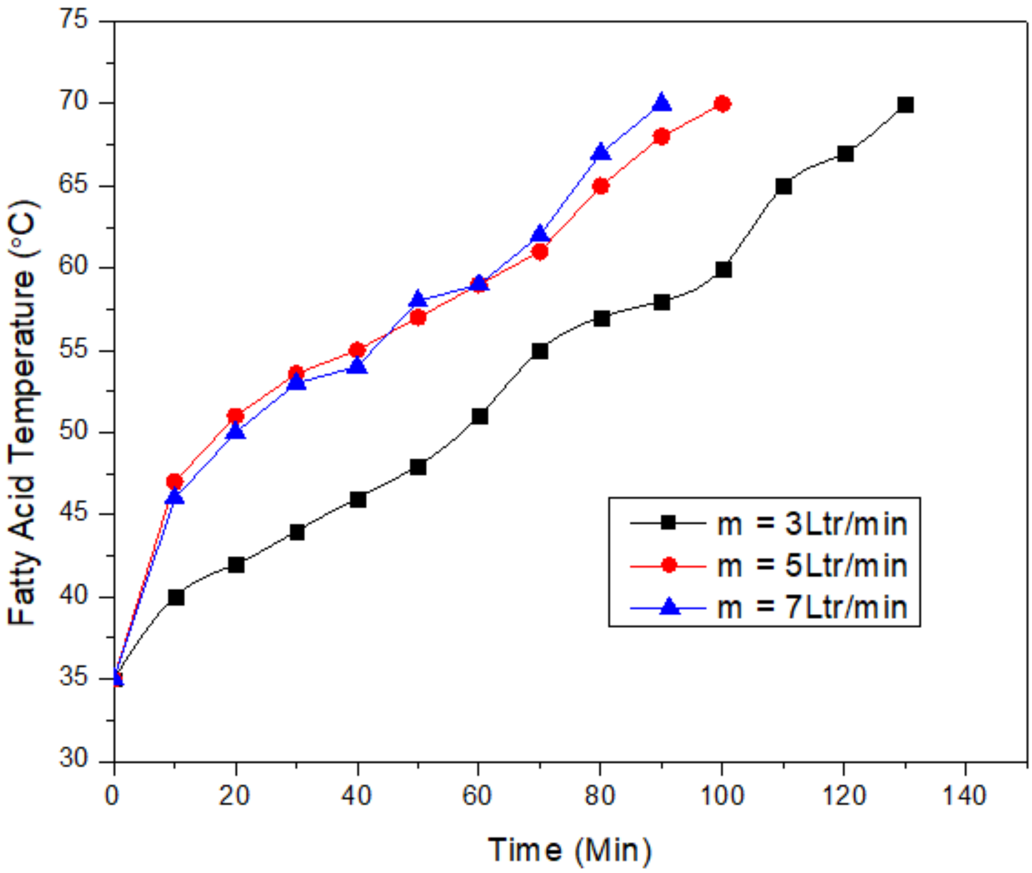

Figure 4.8: Relationship b/w fatty acid temperature and mass flow rate

4.2 Discharging process:

(i) Variation of PCM temperatures

After the TES tank has been fully charged, the discharge is done in batches. In this operation, cold water at room temperature is pumped into the TES tank at a rate of 3Ltr/min, while 50litres of hot water is extracted at the same time. The temperature of the water withdrawn is recorded.

TABLE XI: COMPARISON IN OUTLET TEMPERATURE (IN°C) FOR DIFFERENT BATCH OF WATER BETWEEN PARAFFIN WAX AND FATTY ACID

Batch of Water	Outlet Temperature (°C)	
	Paraffin Wax	Fatty Acid
1	65	65
2	60	62
3	53	57
4	50	52
5	48	51
6	43	47

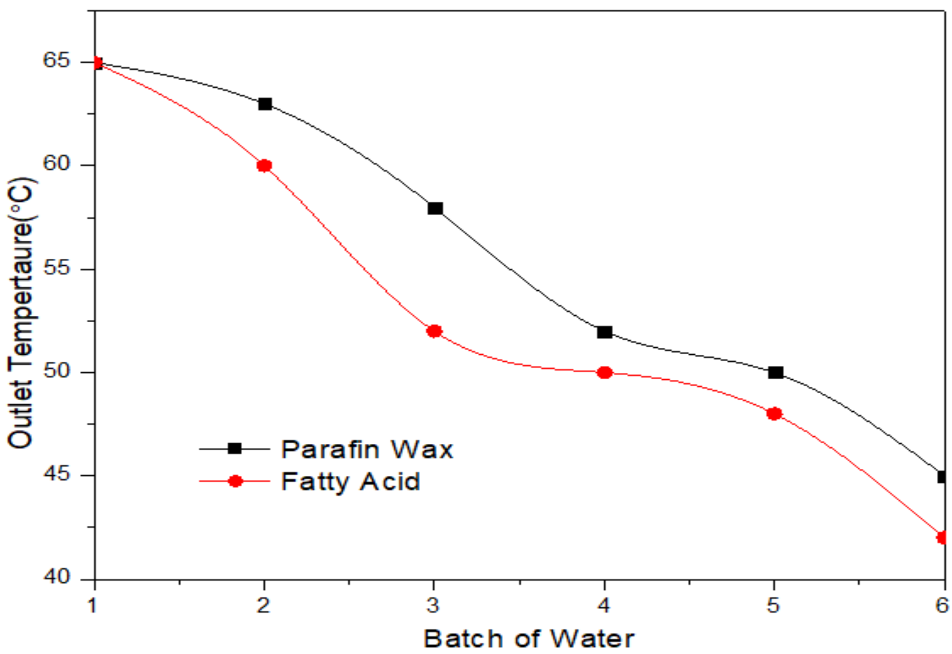

***Figure 4.9**: Comparison between paraffin wax and fatty acid PCM*

The TES tank is refilled with cold water in the same quantity as the water withdrawn. Batch refers to the set amount of 50litres of water that is taken from the TES tank to allow for the filling of fresh cold water.

Another batch of 30 litre of water is removed from the reservoir after a 20-minute time gap to allow for energy transfer from PCM. This process is repeated until the total amount of water containing drawn has reached an average temperature of around 35°C. The temperature of HTF and PCM at various levels of the tank are recorded at regular intervals during the discharge procedure. Figure 4.9: shows the comparison between paraffin wax and fatty acid PCM.

CHAPTER 5
CONCLUSION & FUTURE SCOPE

5.1 Conclusion

The experimentation work was conducted on a Test -Rig of Thermal energy Storage System (TESS). The entire experimental set-up is mounted at Centre of Energy & Environment, DTU, Delhi. The experimental work was conducted in the month of March, 2022. The whole investigation was carried out indoors in Green Energy Lab and used an electric heater to heat the heat transfer fluid (HTF). A no. of set of experiments was done employing different variables i.e. Mass flow rate (3, 5, and 7Ltr/min), and HTF temperature.

During charging and discharging process all readings were noted at regular intervals for different cases of work. Two different types phase change material such as paraffin wax and Fatty acid were used in experimentation.

The outcomes of experiment are listed below:

- Fatty acid has maximum charging storing discharging phase in comparison to paraffin wax.
- Due to greater melting point, the capacity of fatty acid for storing the amount energy is higher than paraffin wax.
- Fatty acid has less amount of heat losses, to store same quantity of heat in comparison to paraffin wax.
- The efficiency of system with and without PCM was 24.8% and 41.25% respectively.
- During the experimentation, it was concluded that rate of increasing the PCM temperature profile is maximum at three different mass flow rates ((3, 5, and 7Ltr/min), because of maximum temperature differences b/w PCM and HTF.
- It was also determined that as mass flow rate increased from 3 to 7Ltr/min charging period of the system was reduced. The reason behind this is that, as flow rate varied from 3 to 7Ltr/min, the amount of thermal energy supplied to the thermal energy storage tank by HTF was increased. This is main conclusion is that as the flow rate increases charging time decreased.

5.2 Future Scope

All storage technologies are being improved to increase efficiency and reduce costs. New materials based on nanoscale principles, such as graphene and others, provide the potential for higher efficiency in supercapacitors and thermal storage, for example. The value and economics of pumped hydro are predicted to improve with the incorporation of renewables such as floating solar and digitization. Cost reductions should be aided by competition and economies of scale. Looking ahead to a net zero energy system in 2050, the Energy Transitions Commission predicts that three storage technologies will win out in the long run, though not at the expense of other solutions, the best combination of which would depend on individual use cases and market conditions.

- In the quest to build TES systems for dealing with climate change issues and energy challenges, it is clear that there is a lot of promise for developing a research route that leads to a more sustainable future. The following are some suggestions and recommendations for future research:
- Heat storage material is the most important component of any TES system. The TES system's operational performance is solely determined by the properties of the heat storage medium or substance. In order to validate simulations based on realistic testing, thorough assessments of thermophysical characteristics, heat interaction mechanisms, and energy performance of heat storage materials are required.
- The inherent inconsistencies discovered in the thermal storage and thermophysical capabilities of energy materials must be addressed by extensive and advanced materials science–based research (e.g., heat transfer studies on nanomaterials for TES)
- Evaluation of various combinations of latent heat storage materials (PCMs) and other sensible heat storage methods to improve overall cooling/heating system energy efficiency.
- The development of hybrid cooling/heating storage systems in conjunction with renewable energy systems in order to maximise energy savings while lowering carbon emissions.
- The use of energy-conserving cold air distribution techniques combined with a hybrid cooling system would contribute to meeting energy redistribution and efficiency requirements for the construction of a sustainable future [2].

REFERENCES

[1] B. Fortunato, S.M. Camporeale, M. Torresi, M. Albano, Simple Mathematical Model of a Thermal Storage with PCM, AASRI Procedia, Volume 2,2012, Pages 241-248, ISSN 2212-6716.

[2] Ansari, Shahid Ali & Deshmukh, Suresh. (2020). An overview: Applications of thermal energy storage using phase change materials. Materials Today: Proceedings. 26. 10.1016/j.matpr.2020.02.247.

[3] Diaz, P.. (2016). Analysis and Comparison of different types of Thermal Energy Storage Systems: A Review. Journal of Advances in Mechanical Engineering and Science. 2. 33-46. 10.18831/james.in/2016011004.

[4] Thamaraikannn R, Kanimozhi B, Anish M, Jayaprabakar J, Saravanan P, Rohan Nicholas A.: Review of Phase Change Materials Based on Energy Storage System with applications, Materials Science and Engineering, 197 (2017).

[5] Akhmetov, B. & Georgiev, Aleksandar & Kaltayev, Aidarkhan & Dzhomartov, A & Popov, Rumen & Tungatarova, Madina. (2016). Thermal energy storage systems – review. Bulgarian Chemical Communications. 48. 31-40.

[6] Stefan, J., 1891, Ann. Phys. Chemie (Wiedemannsche Annalen), Vol. 42, pp. 269-286.

[7] London, A.L. and Seban, R.A., 1943. Rate of ice formation. Trans. ASME, 65(7), pp.771-779.

[8] Shamsundar, N. and Srinivasan, R., 1978. "Analysis of energy storage by phase change with an array of cylindrical tubes", Thermal storage and heat transfer in solar energy systems, pp. 35-40.

[9] Abhat, A., 1983. Low temperature latent heat thermal energy storage: heat storage materials. *Solar energy*, *30*(4), pp.313-332.

[10] Bansal, N.K. and Buddhi, D., 1992. An analytical study of a latent heat storage system in a cylinder. *Energy conversion and management*, *33*(4), pp.235-242.

[11] Lacroix, M., 1993. Numerical simulation of a shell-and-tube latent heat thermal energy storage unit. Solar energy, 50(4), pp.357-367.

[12] Yagi, J. and Akiyama, T., 1995. Storage of thermal energy for effective use of waste heat from industries. *Journal of Materials Processing Technology*, *48*(1-4), pp.793-804.

[13] Brousseau, P. and Lacroix, M., 1996. Study of the thermal performance of a multi-layer PCM storage unit. Energy Conversion and Management, 37(5), pp.599-609.

[14] Brousseau, P. and Lacroix, M., 1998. Numerical simulation of a multi-layer latent heat thermal energy storage system. International Journal of Energy Research, 22(1), pp.1-15.

[15] Esen, M., Durmuş, A. and Durmuş, A., 1998. Geometric design of solar-aided latent heat store depending on various parameters and phase change materials. *Solar energy*, *62*(1), pp.19-28.

[16] Velraj, R.V.S.R., Seeniraj, R.V., Hafner, B., Faber, C. and Schwarzer, K., 1999. Heat transfer enhancement in a latent heat storage system. *Solar energy*, *65*(3), pp.171-180.

[17] Ismail, K.A.R. and Goncalves, M.M., 1999. Thermal performance of a PCM storage unit. *Energy conversion and management*, *40*(2), pp.115-138.

[18] Fukai, J., Kanou, M., Kodama, Y. and Miyatake, O., 2000. Thermal conductivity enhancement of energy storage media using carbon fibers. Energy Conversion and Management, 41(14), pp.1543-1556.

[19] Kaygusuz, A.S.K., 2000. Energy and exergy calculations of latent heat energy storage systems. *Energy sources*, *22*(2), pp.117-126.

[20] Sari, A. and Kaygusuz, K., 2001. Thermal energy storage system using stearic acid as a phase change material. *Solar Energy*, *71*(6), pp.365-376.

[21] Ismail, K.A.R. and Henríquez, J.R., 2002. Numerical and experimental study of spherical capsules packed bed latent heat storage system. *Applied Thermal Engineering*, *22*(15), pp.1705-1716.

[22] Trp, A., 2005. An experimental and numerical investigation of heat transfer during technical grade paraffin melting and solidification in a shell-and-tube latent thermal energy storage unit. *Solar energy*, *79*(6), pp.648-660.

[23] Medrano, M., Yilmaz, M.O., Nogués, M., Martorell, I., Roca, J. and Cabeza, L.F., 2009. Experimental evaluation of commercial heat exchangers for use as PCM thermal storage systems. *Applied energy*, *86*(10), pp.2047-2055.

[24] Adine, H.A. and El Qarnia, H., 2009. Numerical analysis of the thermal behaviour of a shell-and-tube heat storage unit using phase change materials. Applied mathematical modelling, 33(4), pp.2132-2144.

[25] Hosseini, M.J., Ranjbar, A.A., Sedighi, K. and Rahimi, M., 2012. A combined experimental and computational study on the melting behavior of a medium temperature phase change storage material inside shell and tube heat exchanger. International Communications in Heat and Mass Transfer, 39(9), pp.1416-1424.

[26] Hosseini, M.J., Rahimi, M. and Bahrampoury, R., 2014. Experimental and computational evolution of a shell and tube heat exchanger as a PCM thermal storage system. *International Communications in Heat and Mass Transfer*, *50*, pp.128-136.

[27] Reyes, A., Henríquez-Vargas, L., Aravena, R. and Sepúlveda F. Experimental analysis, modeling and simulation of a solar energy accumulator with paraffin wax as PCM. *Energy Conversion and Management, 105*, pp. 189-196.

[28] Bechiri, M. and Mansouri, K., 2015. Analytical solution of heat transfer in a shell-and-tube latent thermal energy storage system. *Renewable energy*, *74*, pp.825-838.

[29] Seddegh, S., Wang, X. and Henderson, A.D., 2016. A comparative study of thermal behaviour of a horizontal and vertical shell-and-tube energy storage using phase change materials. *Applied Thermal Engineering*, *93*, pp.348-358.

[30] Chen, C., Zhang, H., Gao, X., Xu, T., Fang, Y. and Zhang, Z., 2016. Numerical and experimental investigation on latent thermal energy storage system with spiral coil tube and paraffin/expanded graphite composite PCM. Energy conversion and management, 126, pp.889-897.

[31] Product Manual, Ecosense 2.0 latent heat storage experimental test rig.

[32] Cengel, Y., 2014. Heat and mass transfer: fundamentals and applications. McGraw-Hill Higher Education.

[33] Holman, J.P., 2010. Heat Transfer (McGraw-Hill Series in Mechanical Engineering).

[34] Saikrishnan V, Jagadeesh P. S, Jayasuriyaa K. R.: Experimental Investigation of Solar Paraffin Wax Melting Unit Integrated with Phase Change Heat Energy Storage by Using Phase Change Material, Applied Mechanics and Materials, 451-456 (2015).

[35] Stella P. Jesumathy, Udayakumar M, Suresh S.: Heat transfer characteristics in latent heat storage system using paraffin wax, Journal of Mechanical Science and Technology, 26, 959-965 (2012).

[36] Sai Kiran C, Meenakshi Reddy R.: Experimental Analysis of a Thermal Energy Storage System-Waste Heat Recovery, International Journal of Innovative Research in Science, Engineering and Technology, 4, 7768-7774 (2015).

[37] Sachin N. Avghad, Ashok J. Keche, Abhijit Kousal.: Thermal Energy Storage: A Review, IOSR Journal of Mechanical and Civil Engineering, 13, 72-77 (2016).

[38] Lamé, G., and Clapeyron, B. P., 1831. "Memoire Sure La Solidification Par Refroidissement dun Globe Solide", Ann. Chem. Phys., Vol. 47, pp. 250-256

[39] Stefan, J., 1891, Ann. Phys. Chemie (Wiedemannsche Annalen), Vol. 42, pp. 269-286.

[40] London, A.L. and Seban, R.A., 1943. Rate of ice formation. Trans. ASME, 65(7), pp.771-779.

[41] Shamsundar, N. and Srinivasan, R., 1978. "Analysis of energy storage by phase change with an array of cylindrical tubes", Thermal storage and heat transfer in solar energy systems, pp. 35-40.

[42] Ahmet Aktaş, Yağmur Kirçiçek, Chapter 6 - Solar Thermal Systems and Thermal Storage, Editor(s): Ahmet Aktaş, Yağmur Kirçiçek, Solar Hybrid Systems, Academic Press, 2021.

[43] Mohammad Hossein Nabat, Mirhadi Zeynalian, Amir Reza Razmi, Ahmad Arabkoohsar, M. Soltani, Energy, exergy, and economic analyses of an innovative energy storage system; liquid air energy storage (LAES) combined with high-temperature thermal energy storage (HTES), Energy Conversion and Management, Volume 226, 2020.