

NUMERICAL ANALYSIS AND COMPARISON BETWEEN SINGLE PCM AND MULTI PCM BASED HIGH TEMPERATURE THERMAL ENERGY STORAGE SYSTEM

Submitted in partial fulfilment of the requirements for the award of Bachelor of Engineering Degree in Mechanical Engineering

by

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BONAFIDE CERTIFICATE

This is to certify that this Project Report is the bonafide work of **D SAI MANOJ (Reg no: 37150050)** and **CH L S PAVAN (Reg no: 37150040)** who carried out the project entitled “**NUMERICAL ANALYSIS AND COMPARISON BETWEEN SINGLE PCM AND MULTI PCM BASED HIGH TEMPERATURE THERMAL ENERGY STORAGE SYSTEM**” under our supervision from October 2020 to April 2021.

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We, **D SAI MANOJ (Reg no: 37150050)** and **CH L S PAVAN (Reg no: 37150040)** hereby declare that the Project Report entitled “ **ANALYSIS AND COMPARSION BETWEEN SINGLE PCM AND MULTI PCM BASED HIGH TEMPERATURE THERMAL ENERGY STORAGE SYSTEM**” is a record of an original work done by us under the guidance of **Mr. V. JAYAPRAKASH M.Tech., (Ph.D.)** at **SATHYABAMA INSTITUTE OF SCIENCE AND TECHNOLOGY** is submitted in partial fulfilment of the requirements for the award of Bachelor of Engineering degree in Mechanical Engineering.

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ABSTRACT

The work is aimed to analyse the heat storage capacity in the single stage PCM and multi stage PCM based thermal energy storage system. Several numerical models are available to analyse the performance of thermal energy storage system. After thorough literature survey, it has been found that the PCM filling in the shell is around 80 – 85% of the total volume capacity in order to accommodate the thermal expansion and contraction during heating and cooling respectively. Most commonly, the numerical models are performed by considering fully occupied PCM in the encapsulation shell and this will lead to provide unfavourable results. In order to overcome these problems, the proposed work will provide comparative numerical heat transfer analysis in single stage PCM and multi stage PCM by considering void in the encapsulation shell.

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LIST OF ABREVIATON

HTF	Heat transfer fluid
PCM	Phase change material
LHTES	Latent heat thermal energy storage
PCM1	Magnesium Chloride Hexahydrate
PCM2	Magnesium Nitrate Hexahydrate

CHAPTER 1

INTRODUCTION

The world is in need of an alternative, renewable and non-hazardous source of energy, one of the options is to create an energy storing device which is equivalent to developing a new source of energy itself. Thermal Energy Storage (TES) systems prove to have potential to undertake the task as shown by Vincent Morisson and Felix

Thermal energy storage system is like battery which is used to store certain category of energy. Thus, Energy storage plays critical parts in preserving accessible vitality and progressing its utilization, since numerous vitality sources are irregular in nature. Like, sun-oriented vitality is accessible as it were amid the day, and subsequently, its application requires productive warm vitality capacity so that the abundance warm collected amid daylight hours may be put away for afterward utilize amid the night. Moreover, Warm vitality capacity (TES) can be accomplished with enormously varying advances which collectively obliges a wide extend of needs. It allows excess thermal energy to be collected for later use (hours, days even months later). TES is proven to be economical energy storage which plays a key role in electric power systems now and in the future. The storage of thermal energy at high or low temperature can be efficiently done using thermal energy storage system. Thermal energy can be stored by heating, melting or vaporization of material and the energy becomes available as heat, when the process is reversed.

Thermal energy storage system can provide a significant change in energy storage density as it has a diversified capacity of storing both sensible heat as well as latent heat. It is possible for both sensible and latent heat storage to occur in same material. This can be harnessed by using thermic fluids or heat transfer fluids and PCM's respectively. The classifications of storage systems are:

- Sensible Heat Storage System.
- Latent Heat Storage System.

Sensible heat involves rise in temperature without change in phase. The ability to store heat depends upon the density, specific heat and difference in temperature. Materials

which are generally used in this type of storage are water, rock salt, concrete and refractory materials and thermic fluids (HTF).

To balance the energy demand between day and night time, one of the efficient means to harness energy is latent heat storage system as shown by Dušan Medved'. LHTE is acquired at the time of phase change. It has the capability to provide high energy storage density. All though sun's energy provides clean and safe form of energy It fails to provide constant supply of energy hence the need of LHTES becomes liable. This method has been used to improve solar water heating advanced power systems for the past few years. This energy storage system improves the performance of whole setup by improving the supply and increasing reliability. This storage system is attractive due its ability to provide high energy storage density and also can operate at narrow range of temperature. For employing latent heat storage system, we use PCM. The selection of PCM is critical task, so as to meet the constant heat flux demand for the experimental setup. Hence the PCM's are chosen in the hierarchical order of their melting point to fulfil the requirement of the setup. Latent heat storage using various PCMs is shown by Bel_en2 Zalba. Stored heat for phase transition when compared with sensible heat is much greater as shown by Mohammed M. Farid. Effects in using multiple PCM's of a shell and tube has been numerically analysed and it proved that maximum thermal energy charging rate, in order choosing of multiple PCM's is very vital for the performance of latent thermal energy storage. The experimental analysis identified that the constant transfer of heat energy per unit time between the PCM's are maintained at constant. Usage of multiple PCM over single PCM increases the charging and discharging rate.

Also, the type of encapsulation plays an important role in the heat transfer between HTF and PCM's. In this experiment cylindrical encapsulation is used to accommodate all the three PCM's in their increasing hierarchical order of their melting point, to facilitate increasing heat transfer area, reducing PCM's reactivity with the environment, controlling the changes in the storage e material volume as phase change occurs, and constant heat flux density which The present work can provide insights on the optimizations of the storage system configurations and operational strategies for a better energy and exergy efficiency.

1.1 Thermal Energy Storage

Thermal Energy Storage is divided into three branches based on the principal behind the energy storage process. Thus, Energy storage plays critical parts in preserving accessible vitality and progressing its utilization, since numerous vitality sources are irregular in nature. Like, sun-oriented vitality is accessible as it were amid the day, and subsequently, its application requires productive warm vitality capacity so that the abundance warm collected amid daylight hours may be put away for afterward utilize amid the night. Moreover, Warm vitality capacity (TES) can be accomplished with enormously varying advances which collectively obliges a wide extend of needs. In a similar way, thermochemical energy storage systems use reversible endothermic/exothermic reactions to store and release energy. To reduce the cost of the storage system, a material with a high energy storage density should be used. While thermochemical systems have the highest energy storage density of the three forms of TES, research into its usage is still in the early stages and uncertainties in the thermodynamic properties as well as reaction kinetics limit its usage. Currently only sensible heat storage systems are used at operating CSP plants around the world. These systems use either a large volume of a solid material such as concrete, or a single- or two-tank molten salt-based storage system. These systems require an immense volume of material to store enough energy to efficiently operate the power plant for eight hours. For example, 28,500 tons of molten salt is required to operate the Andasol power plant in Spain for 7.5 hours. On the off chance that an inactive heat-based capacity framework was utilized instead, the sum of capacity fabric may be enormously decreased yielding a lower system cost. This would result in a diminish within the levelized taken a toll of power at CSP plants driving to them being not as it were taken a toll competitive with current fossil fuel-based plants but with other implies of renewable vitality as well.

1.2 Phase Change Materials

The most component of a latent heat-based TES framework is the phase change material (PCM) that's utilized. Any material that experiences a state change can possibly be utilized as a PCM for TES applications. Four diverse state or stage changes can happen: solid-solid, solid-liquid, liquid-gas, and solid-gas. Amid a strong stage change the precious structure of a material changes from one grid arrangement to another. While the little volumetric changes that happen amid solids stage changes make them perfect candidates for TES, the moves are regularly moderate and have low change enthalpies relative to the other state changes. The 7-state change that's ordinarily considered for TES applications is that of solid-liquid stage changes due to their generally little volume changes and direct enthalpy changes. In spite of the fact that liquid-gas moves have tall change energies, the expansive volume changes that happen and the complexity of putting away the vaporous medium restrain their utilize for TES applications. The final state change is when a strong material specifically turns into a gas, such as dry ice. Solid-gas moves have the same downsides as the utilize of liquid-gas moves. Hence, the solid-liquid stage change is best suited for TES. While various materials exist that have softening temperatures in any wanted temperature extend, this alone does not make them a reasonable PCMs for TES applications. The material must moreover show other alluring thermo-physical, active, and chemical properties such as a tall latent heat of combination, little volume change, adequate crystallization rate, and chemical solidness, all whereas being copious at low cost. By and large, PCMs can be isolated into three bunches: natural, inorganic, and eutectic materials. A diagram of the classification of PCMs is shown in Figure 1. Extensive research has been conducted into potential materials for use in latent heat-based TES at temperatures below 120 °C that include paraffin waxes, fatty acids, and salt hydrates.

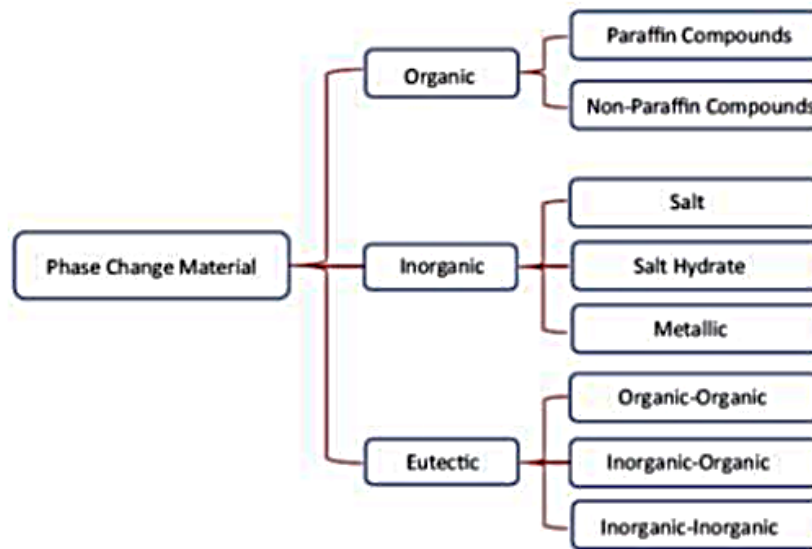


Fig 1.2 properties of PCM

Whereas these medium temperature PCMs have various applications, materials with a softening point in abundance of 300 °C are required for utilize at CSP plants. During the cementing prepare, the PCM includes a inclination to stay to the warm exchanger surface. As time advances, the strong layer increments in size, and due to the medium warm conductivity of the fabric it incorporates a restricting impact on the warm exchange rate, drawing out the cementing handle. In this way, broad inquire about into diverse strategies of moving forward the warm exchange inside PCM-based frameworks has been conducted. These upgrades can be broken down into either fabric or framework improvements. Fabric improvements are pointed at expanding the compelling warm conductivity of the base PCM by including a auxiliary profoundly conductive fabric ordinarily within the frame of nanoparticles. Framework upgrades on the other hand increment the surface region of the warm exchanger to extend the warm exchange rate either more often than not by actualizing blades or through epitome. Whereas framework enhancements may abdicate a more complex geometry, they don't encounter the misfortune of vitality capacity capacity that happens with material-based upgrades. Of specific intrigued is the utilize of typified stage alter fabric (EPCM) capsules.

1.2.1 Encapsulated Phase Change Materials

The embodiment of PCMs into person capsules moves forward the execution of the PCM since it comes about in a diminish within the charging/discharging time of the framework due to the increment within the region over which warm exchange can happen. All things considered, the embodiment of PCMs leads to its claim special challenges that ought to be overcome some time recently it can be utilized efficiently and taken a toll viably at CSP plants as portion of large-scale TES. Cautious consideration is required within the choice of a PCM and shell fabric match as the two materials ought to be chemically and metallurgically dormant to avoid a misfortune of capacity capacity from happening over rehashed warm cycling at hoisted temperatures. Also, the shell fabric must withstand not as it were its possess warm stresses but the increment in inside weight that comes about from the extension of the PCM amid dissolving. Given the tall temperatures experienced at CSP plants, metal epitome materials such as stainless steel, carbon steel, and nickel-based alloys are favored. To get the specified capsule characteristics, such as a tall PCM to shell proportion and solidness, there are two ways the PCMs can be typified: by coating of a PCM pellet or filling a pre-assembled shell with the specified PCM.

The drawback with the procedure of coating PCM pellets is the capacity to take off a adequate void space such that the capsules don't break upon dissolving without the utilize of a sacrificial layer. This can be not the same when pre-assembled shells are utilized. Inquire about into both strategies of embodiment with different PCMs and shell materials have been conducted Zheng et al. utilized ordinary calorimetry to assess the execution of both sodium nitrate (NaNO_3) and a sodium chloride and magnesium chloride eutectic (NaCl-MgCl_2 , 57 %mol NaCl) as PCMs that were typified in carbon or stainless steel.

They assessed the capacity of the EPCM capsules over both brief (~5 hours) and long term (~ 300 hours) cycling and the comes about shown that the combination of the PCM and embodiment fabric can be utilized for tall temperature TES as no misfortune of capacity happened. As an increment within the operational temperature of a Rankine cycle increments its productivity, a fabric that can store vitality at higher temperatures is alluring. Zhao et al. assessed the execution of MgCl_2 -stainless steel EPCM capsules. The capsules appeared no disintegration of capacity after 480 hours of tall temperature

introduction over 700 °C. Expanding the 1,000 hours of presentation at 850 °C no debasement of the storage fabric may well be identified. Whereas these comes about are promising, they were conducted on little (25.4 mm or 50.8 mm) laboratory-scale capsules. Zheng et al. tried a pilot scale inactive warm TES framework that comprised of 10 round and hollow EPCM capsules with measurements of 76.2 mm breadth and 254 mm long that were on a level plane put in a vertical test segment. Hot discuss was constrained over the capsules with a stream rate of 0.038 kg/s. They considered the utilize of NaNO_3 , a NaCl-MgCl_2 eutectic, and a cascaded framework of both NaCl-MgCl_2 and NaNO_3 .

The system put away 211 kJ/kg of vitality utilizing NaNO_3 as the PCM over the temperature extend of 250 to 386 °C and no diminishment in capacity was seen after 40 hours of operation. When compared to a framework that as it were had NaClMgCl_2 eutectic capsules, the cascaded framework put away more vitality after the primary 30 min of operation, emphasizing the advantage of utilizing different PCMs with shifting softening temperatures. The comes about displayed by Zheng illustrate the adaptability of EPCM-based inactive warm TES frameworks. The comes about over were all conducted on pre-assembled capsules that were filled with the required sum of PCM and after that fixed. While this process works for centimetre or larger capsules, it is difficult for sub-millimetre sized capsules. The advantage to smaller capsules is the reduction in discharging time as the characteristic length of the system is smaller, however these capsules tend to have smaller ratios of PCM to capsule shell which reduces the percentage of energy stored that is attributed to latent heat. These capsules are typically manufactured by coating PCM pellets first with a sacrificial polymer layer to accommodate PCM expansion, and then depositing a thin layer of metal onto the capsules to prevent leakage. Alam displayed a novel strategy of epitome that does not require this conciliatory layer by employing a profoundly flexible polymer with a nickel coating. Utilizing NaNO_3 as the PCM, these capsules were able to resist 2,200 warm cycles with no misfortune of capacity. Moreover, they tested a packed-bed system that held 770 capsules with a 2.7 cm diameter that survived 300 hours of testing without showing signs of mechanical or chemical deterioration.

While these results indicate that both nitrate- and chloride-based PCMs can be used for high temperature TES using EPCMs, they still have a low thermal conductivity in the solid phase that prolongs the solidification process. This led Zhao .21. and Solomon

.20. to evaluate the use of metal-based PCMs by using zinc and aluminium. However, due to intermetallic reactions a loss of storage capacity occurred for both PCMs when encapsulated within a stainless-steel shell. While this effect can be mitigated via the use of a protective paint, a non-metal-based shell should be used. Despite the promising research that has been conducted, further research into new novel materials is required to further improve the technology of EPCM-based high temperature latent heat TES.

Their results demonstrated the importance of the Prandtl number on the melting process at a fixed Rayleigh number and that natural convection in the molten PCM accelerates the melting process in comparison to pure diffusion models. Ismail characterized the solidification of various PCMs within cylindrical and spherical shells by examining the how different shell materials, capsule diameters, and surface temperatures affected the overall solidification process. Tan studied the effect of buoyancy-driven convection both experimentally and numerically by considering the constrained melting of n-octadecane inside a spherical glass shell. Pinelli and Piva incorporated the enthalpy-porosity method into Ansys FLUENT to investigate the use of n-octadecane in cylindrical capsules that were subject to a uniform exterior heat transfer coefficient. Assis et al. conducted a parametric investigation of the melting of a paraffin wax PCM encapsulated within 14 spherical shells. Using the enthalpy-porosity method within FLUENT they were able to model a 15% void fraction, volumetric expansion of the PCM upon melting, and convection within the fluid media by simultaneously solving the conservation equations for the air void, solid PCM, and liquid PCM. Their model included a vent at the top of the capsule that expelled the air void as the PCM expanded.

They validated their model using experimental results and were able to accurately capture the propagation of the solid-liquid interface. Assis et al. also conducted an analogous study on the solidification process within the same EPCM capsules. Recently, Archibold extended the results of Assis et al. to higher temperatures by employing NaNO_3 as the PCM. They obtained similar results and were able to capture the compression of the air void by considering a sealed capsule.

The effects of radiative heat transfer within EPCM capsules were studied by Archibold et al. by using NaCl as the PCM and their results indicate that radiative heat transfer increases the melting rate within the capsules. Bellan used an effective packed bed model

to study the heat transfer that occurs in a bed of centimetre-sized spherical EPCM capsules and the effect of heat transfer fluid (HTF) flow rate, Stefan number, shell thickness, and shell material. Zhao compared the comes about of utilizing both a front following and enthalpy-porosity strategy for the dissolving of NaNO_3 .

1.3 Numerical Modeling of Phase Change Materials

Various techniques have been employed to study heat transfer that involves a solid-liquid phase change. The progression of the solid-liquid interface can be tracked either directly or indirectly. The most popular method is the enthalpy-porosity method that was developed by Voller et al. which indirectly tracks the location of the 13 solid-liquid interfaces using a parameter called the liquid fraction. The enthalpy porosity strategy is additionally alluded to as the volume following strategy Brent and Voller. conducted a fixed-grid arrangement of the coupled force and vitality conditions without turning to variable changes, and by utilizing a two-dimensional energetic demonstrate they examined the impact of laminar normal convection on the dissolving prepare of gallium in rectangular cavities. Mackenzie and Robertson. illuminated the nonlinear enthalpy condition employing a semi-implicit moving work discretization at each time step. Kholdadadi and Zhang used an iterative finite volume method to study the effect of buoyancy-driven convection on the constrained melting of PCMs within spherical containers by using primitive-dependent variables and Darcy's law to govern convection in a porous medium horizontally and vertically orientated cylindrical EPCM capsules and concluded that both models are able to accurately capture the propagation of the solid-liquid interface for both the melting and solidification processes. While these numerical investigations lend insight into the complex heat transfer that occurs in latent heat-based TES systems, they tend to make 15 simplifications that limit their accuracy such as neglecting convection in the molten PCM and the inclusion of an internal void space. The development of a model that incorporates all aspects of an EPCM-based latent heat TES system is required to further understand how these systems operate under real world conditions and can aid in the optimization of these systems to allow for cost-competitive electricity generation at CSP plants.

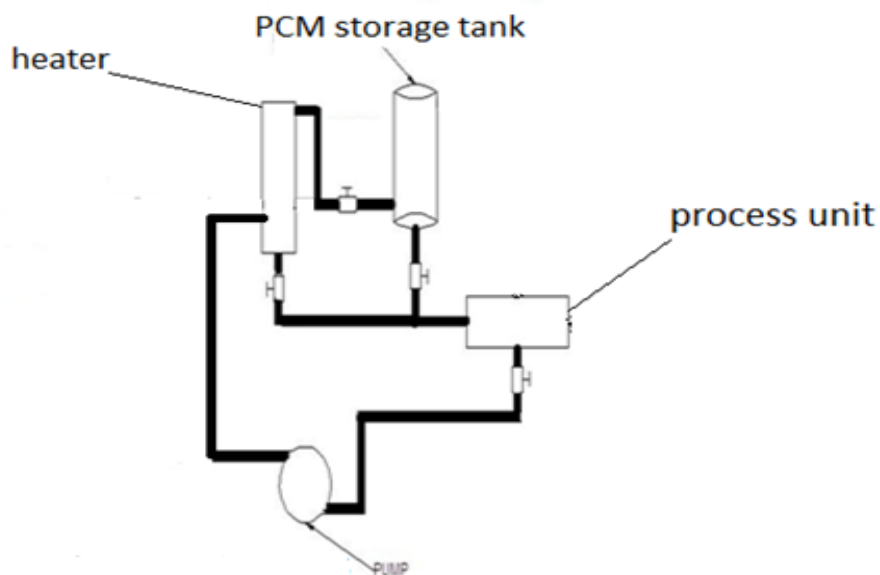


Fig 1.3 PCM Experimental setup

1.4 Materials and Method

In this paper two PCM's are used, which have been chosen according to their availability and effectiveness in maintaining a constant heat flux in the system.

They are:

1. Magnesium Chloride Hexahydrate
2. Magnesium Nitrate Hexahydrate

The heat transfer fluid used is Therminol-66.

This experimental study includes a thermal storage system; a circulating pump to circulate the constant volume of HTF throughout the set up to maintain a constant temperature, thermal storage tank encloses HTF and PCM. The PCM storage tank encloses the encapsulated PCM's within cylindrical encapsulation. The heater, to ensures the constant temperature of the HTF throughout the circuit and especially in PCM storage

tank. The experimental layout is shown in. The storage tank of diameter 0.25 m and the height of 0.33 m are made with MS plate. The PCM storage tanks are insulated with glass wool. The setup is completely insulated to prevent the heat escaping out from the storage tank. The PCM container acts as a storage device for PCM and is made of aluminium. The PCM container will be placed in the centre the HTF fluid will be made to flow around the PCM container so that heat transfer occurs between HTF and PCM container during charging and discharging phase. The PCM container consists of three shelf. In each shelf different PCM will be placed. Container has a slot for thermocouple in which thermocouple can be inserted. Bolt and nut type slot is made for thermocouple so that removal and insertion of PCM will be easy. The PCM container is made for the purpose of reusing. PCM container takes the shape of cylinder of 100 mm diameter and length which is greater than its diameter about 2 to 3 times. The PCM container is designed as per previous models based on multiple PCM.

There are two primary modes of operation:

Charging mode:

During the charging process, Heat Transfer fluid is made to circulate through the storage tanks by the use of regulating valves wherein the aluminium container filled with PCM's is placed inside the storage tank. Initially the heater is switched on which indeed heats the heat transfer fluid (Thermonole-66) which flows over it. The cyclic process is carried out in such a way that HTF fluid attains heat from the heater. This HTF is made to flow through the aluminium container. The PCM's filled inside the Aluminium container gradually picks up heat from the HTF fluid. Accordingly the temperature of PCM's increased. when the PCM's reach their respective melting temperatures, they start to make a transition i.e., it changes from solid to liquid. meanwhile when it absorbs heat it starts to melt. This charging mode is conducted for 3 hours and the reading is noted for every 10 minutes.

Discharging mode:

During the discharging process, the heater is switched off. Hence the temperature of HTF fluid is gradually decreased. The ambient temperature around the PCM falls and when this happen PCM's starts to release its stored latent heat to the thermal energy storage system moreover at this point PCM solidifies i.e., it changes liquid to solid. This

process maintains the temperature of the PCM constant or certain period of time. This discharging mode enables the solar thermal storage system to store heat energy which can be utilized during cut off time. This process is continued until Terminal temperature reaches room temperature the time taken was noted down for every 10 mins.

Tab 1.4 Properties of each PCM are given below:

Category	Magnesium Chloride Hexahydrate	Magnesium Nitrate Hexahydrate
Melting Temperature (°C)	120	90
Thermal Conductivity (W/mK)	0.704	0.554
Latent Heat of Fusion (KJ/kg)	168	162.8
Specific Heat Capacity (KJ/Kg)	2.25	0.611
Density (Kg/m³)	1636	1570

CHAPTER 2

LITERATURE SURVEY

In this chapter, a literature survey of recent studies associated with thermal energy storage, storage materials, heat transfer rate enhancement techniques, macro encapsulation, laboratory scale latent heat packed-bed storage system with encapsulated PCMs and melting/solidification inside a spherical capsule are discussed

2.1 THERMAL ENERGY STORAGE

TES can be utilized to minimize the difference between supply and demand of the periodic sources of generation. Three processes are involved in a TES system: charging, storing, and discharging/ retrieving. For instance, consider a TES system combined with a concentrated solar power plant. At daytime, the parabolic trough collects energy from the sun and transmits it through the HTF. During the charging stage, a fraction of the high temperature HTF is pushed through the heat exchanger of TES and heat is conveyed from the HTF to the storage media.

During the night the discharge mode starts, and a low temperature HTF is pumped through the TES in the reverse direction. As it passes through the TES, it absorbs the thermal energy from the system Zalbe et al. .18. and Fernandes et al .19. mentioned certain characteristics and requirements for design of an efficient TES in the literature. These are summarized as follows.

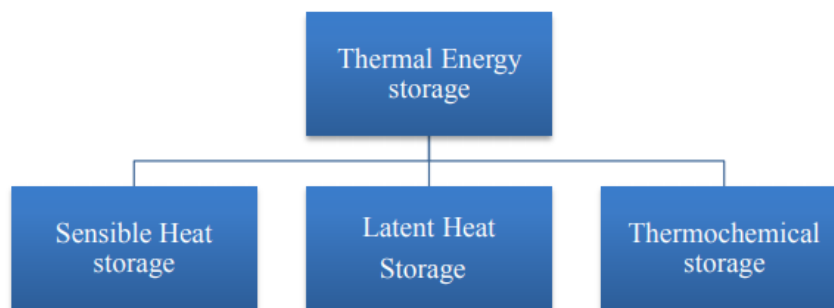


Figure 2-1: Category of thermal energy storage

2.2 CATEGORIES OF THERMAL ENERGY STORAGE

TES can be classified into three different categories. These are mentioned in figure 2-1 and discussed in the following sections.

2.3.1 SENSIBLE HEAT STORAGE

The energy storage capacity of the sensible warm capacity (SHS) depends on the temperature distinction of the gulf and outlet, particular warm capacity of the capacity fabric and the whole mass of the capacity media 20. This sort of storage is broadly examined and utilized commercially within the control plants .2, 3. It is expressed by the formula Thermal Energy storage Sensible Heat storage Latent Heat Storage

Thermochemical storage 6 $Q = \int mC_p dT = m (T_f - T_i)$ (1-1) Q = amount of heat (kJ), m = mass of storage material (kg) C_p = specific heat capacity (kJ/ kgoC) T_i = initial temperatures of SHS (°C) T_f = final temperatures of SHS (°C) Depending on the storage medium, the SHS is classified in solid or liquid base system (rock, concrete, metal, molten salt, synthetic oil and mineral oil).

2.3.2 LATENT HEAT STORAGE

LHS stores energy by absorbing or releasing the latent heat of fusion or vaporization of the storage material at the phase change temperature. LHS can store a large amount of energy compared to SHS in same volume for a smaller temperature range.20. It is expressed by the formula

$$Q = \int mC_p dT + mL + \int mC_p dT \quad T_f \quad T_m = .C_{sp}(T_m - T_i) + L + C_{lp}(T_f - T_m). \quad T_m \quad T_i \quad (1-2)$$

Q = amount of heat (kJ) m = mass of storage material (kg) C_{sp} = specific heat capacity in solid state (kJ/ kgoC) C_{lp} = specific heat capacity in liquid state (kJ/ kgoC) T_m = melting temperatures of storage material (°C) T_i = initial temperatures of LHS (°C) T_f = final temperatures of LHS (°C) L = latent heat of fusion (kJ/kg) 7 Due to the difficulty in handling high-pressure gases, and due to the high costs associated with the construction of storage systems for the liquid-vapor transition, most of the investigation and research has been conducted on solid- liquid transition of the material. According to Stekli et al. .1., LHS can be categorized into tank PCM TES and encapsulated PCM TES. Regin et al. .21. summarized three basic components to develop an effective LHS. These are presented as follows

a) Low-cost suitable storage material with higher latent heat of fusion for desired temperature range

- b) Durable storage material containment system
- c) Larger surface area to transfer the heat from the source to the storage material and from storage material to the heat sink efficiently.

2.3.3 THERMOCHEMICAL STORAGE

The core component of the thermochemical storage system is the reversible endothermic chemical reaction. To achieve the high efficiency, the reversibility of the chemical reaction needs to be ensured. As the heat from the heat source is brought to exothermize the endothermic chemical reaction, it will absorb the heat. If the reaction is reversible, the heat can be extracted. The energy density of this type of storage system is higher compared to other two storage systems. However, this technology is still at a very premature stage to go for commercialization

2.4 PHASE CHANGE MATERIAL FOR LHTES

Numerous researchers have conducted investigations on wide range of organic and inorganic PCMs. Lane et al. .20., Zalbe et al. .18., Abhat .22., Farid et al. .23. Regin .21., Sharma et al. .24. have summarized the characteristics of PCMs needed for efficient TES system design. These are presented as follows. a) High latent heat of fusion, high specific heat both in solid and liquid state, and high energy density to reduce the size of the storage system. It should also show insignificant volume of expansion and low vapor pressure during the phase change period. b) A desirable melting/solidification temperature corresponding with the operating temperature limit. c) High thermal conductivity to achieve required heat transfer between the HTF and the storage media and insubstantial supercooling during solidification. d) Congruent melting to avoid segregation of the component. e) Chemically stable, non-toxic, non-explosive and non-corrosive to protect the containment vessel. f) Abundantly available and cheap. Zalbe et al. .18. presented a comparison between organic and inorganic PCMs. Organic materials such as waxes or paraffin, terpenes, and low molecular weight alkanes have been studied by many researchers .25-29. for low temperature applications (below 100°C). The problem associated with the organic PCMs, compared to inorganic PCMs, is that they have lower latent heat of fusion, lower thermal conductivity, and higher flammability.18. In general, inorganic PCMs possess higher energy density than the organic PCMs and also have higher temperature utilization ranges .7. Salt hydrates can be used as a

potential PCM as they show higher latent heat of fusion .18, 24. The main problem associated with salt hydrates is their incongruent melting and subcooling of the PCM during freezing. To neutralize the subcooling effect, various nucleating agents need to be added which leads to a rise in the overall cost of the TES system .30. 9 Organic and hydrate PCMs have high chance of oxidation and formation of PCM solution that can reduce the storage density.

Encapsulating the PCM can solve this problem. In this research, inorganic PCMs and their eutectic, having temperature range of 100o C to 400o C, will be discussed as most of the Rankine cycle based solar plants (maximum temperature limit of synthetic oil is 400oC) and waste heat recovery systems use this range

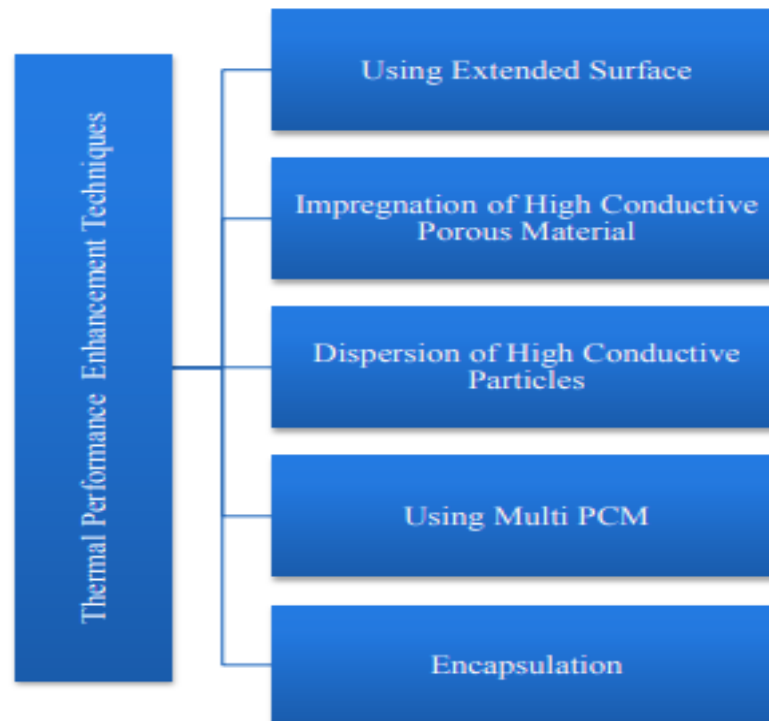


Fig 2.4 Thermal performance

To maximize the heat transfer area in the TES fins or extended surfaces are employed. If the conductivity of the PCM is lower than HTF, the fin will be placed in the PCM side or vice versa .38. Melting and solidification process dynamics has the influence of the configuration and orientation of the fin .36. Lacroix and Benmadda .39. conducted a research on the horizontal fin configuration in rectangular box and concluded that

instead of having a larger number of short fins, it is more effective to have fewer long fins in the system. Optimization of the number of fins depends on the wall temperature. Shatikian et al. .40. found that the performance of the enhancement depends upon optimization of both number of fins and thickness. Steinmann .41. tested aluminium fins in NaNO₃ PCM for 400 hours and found that aluminium fins are compatible with NaNO₃. Other materials like graphite foil, steel and copper can also be employed as the fin material. Porous matrices made of steel, stainless steel, aluminium, copper, and graphite can be impregnated in the PCM based LHTES to enhance the heat transfer rate. Mesalhy et al. .42. numerically investigated a horizontal cylindrical annulus structure and concluded that the performance of enhancement technique depends upon the pore size and the thermal conductivity of the material in the matrix. Recently, Fiedler et al. .43. compared aluminium and copper based porous matrices and found that the copper matrix had approximately 80% more effective thermal conductivity than the aluminium matrix. Even though melting and solidification time of the storage material reduces by employing the metal structures significantly, compatibility of the PCM and the porous structure has always been an issue. Multi-PCM-based LHTES refers to using a number of PCMs with various melting points in the storage system.

Employing multiple PCMs with decreasing melting points ensures a higher temperature difference between the HTF and the PCM in the flow direction, which will lead to 13 higher heat transfer performance of the system .36. Wang et al. .44. were the first group to introduce a novel technique to enhance the heat transfer rate. Michels and Pitz-Paal .34. conducted an experimental exploration on multiple PCMs in shell and tube configuration. Synthetic oil was used as the HTF and allowed it to go through the tube and three PCMs were placed in the shell side. It was found from the experiment that single PCM storage with a higher melting point has a lower storage/retrieval capacity compared with a multi-PCM storage with two PCMs

Charging and discharging experiments were demonstrated with three different melting point PCMs by Farid and Kanzawa .45. They observed an improvement of ten percent in the heat transfer rate. Cylindrical enclosures were used to load three different PCMs and air was used as HTF. In case of multi-PCM system, all the PCM started melting at the same time whereas for single capsules, it started at different time. Multi PCM

system is one of the more efficient ways to improve the performance of the system by enhancing the heat transfer rate. However, selection of right combination of PCMs is still a challenge .31.

Dispersing particles in the PCM is one of the most efficient and simplest ways to enhance the conductivity of the PCM .31. Hoover .46. is the pioneer of conducting research on particle impregnation technique to improve the thermal conductivity. Khodadadi et al. .47. conducted an extensive review on the enhancement of the heat transfer rate by dispersing particles in the PCM. Lots of materials have been employed as the particles such as metals (Ag, Cu, and Al), metal oxides (Al_2O_3 , MgO, CuO and TiO_2), carbon nano tubes, graphite, silver nanowires, and carbon-based nano particles (graphene flakes). 47. Mettawee and Assassa .48. conducted an experimental investigation to improve the thermal conductivity of PCM by dispersion of micro aluminium particles. It was found that there was a sixty percent reduction in the charging time as compared to pure PCM by adding the particle Zeng et al. .49. investigated the effect of silver 14 nanoparticles in 1-tetradecanol and found that silver nanoparticles did not show any strong reaction with 1-tetradecanol. Overall, the thermal conductivity of the PCM increased with the increase of silver nanoparticles. Xie et al..50., Hong et al..51., Weinstein et al. .52., Zeng et al. .53., and Kim and Drzal .54. employed alumina (Al_2O_3), MgO, graphite nanofibers, multiwalled carbon nanotubes, and exfoliated graphite nanoplatelets, respectively and all observed the enhancement of the heat transfer rate. Recently, researchers have shown great interest in graphene to improve the thermal conductivity of PCM .55-57.

Some important properties of graphene are presented As most of the works have been conducted with low temperature PCMs, this area has much open space for future work. Important properties of graphene for thermal conductivity improvement

Material	Thermal Conductivity ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)	Specific surface area ($\text{m}^2\cdot\text{g}^{-1}$)
Graphene	~5000	~5000
	~2630	.58.

.58. Khodadadi and Hosseini Zadeh .59. reported that overall latent heat of the PCM composite decreased with the increasing wt.% of the particles, though the thermal conductivity of the composite increased. Hence, optimization of the mass fraction of the particle and latent heat of the PCM is quite important.

2.5 ENCAPSULATION

Another strategy to upgrade the warm exchange rate is by utilizing smaller scale- (capsule estimate $\sim 1\text{--}1000\text{ }\mu\text{m}$) or macroencapsulated (capsule estimate over $1000\text{ }\mu\text{m}$) PCMs.⁶⁰ Impressive work has been carried out on microencapsulation of the moo softening point ($50\text{--}120^\circ\text{C}$) inorganic salt hydrates and natural materials such as waxes, terpenes, moo atomic weight polymers, etc. ^{61- 66}. Compared to macroencapsulation, the microencapsulation of PCMs gives speedier charging ¹⁵ and releasing rates since of the shorter remove for warm exchange. However, the lower PCM to-coating mass ratio ($\sim 1:1$) greatly reduces the energy storage density of the storage media and increases the storage capital cost.²⁰ Recently, Zhang et al. ^{.67}. encapsulated $\text{NaNO}_3/\text{KNO}_3$ PCM in AISI 321 tubular capsules. Zheng et al. ^{.68}. fabricated spherical capsules with copper as the PCM and chromium-nickel as the shell material. The fabricated capsules have been shown to with sand 1000 thermal cycles. Vincent and Silva ^{.69}. tried paraffin wax in rectangular steel shell in on a level plane empty brick for 8 days. Zhao ^{.70}. and Zheng et al. ^{.71}. have detailed an embodiment strategy that employments stainless steel/carbon steel as the shell fabric.

The method takes after a post-formed approach where round and hollow steel capsules are fabricated to begin with and after that filled with PCM taken after by welding a cap at the best. The major challenge in this approach is countering the erosion of the metal cans from the liquid salt at tall temperatures. Mathur et al. ^{.72}. have illustrated a ceramic-based macroencapsulation method for the sodium nitrate pellets (5-15 mm in distance across). The technique involves the deterioration of a conciliatory polymer layer to supply a void in between the coating and center PCM, which is required for pleasing extension of the PCM amid the stage move period. A few of the other techniques.

2.6 HEAT TRANSFER STUDY IN LATENT HEAT PACKED-BED STORAGE

A latent heat packed-bed storage system uses a single tank. The benefit of using this type of storage is the low cost of the system. As the PCM (filler material) needs to be non-reactive with the HTF in the packed-bed containment, it is better to encapsulate the PCM.

Numerous studies have been conducted to analyse the overall performance of this type of storage by many research groups .21,75-86. Saitoh .75. observed the effectiveness of spherical capsules over other geometries. Ozturk .76. used paraffin as PCM to experimentally investigate the thermal effect of the LHTES on greenhouse heating. Regin .21, 77. presented a review on utilizing organic PCM base capsules in a latent heat thermocline system and exhibited a numerical analysis of the system. Michel and Pitz-Paal .34. reported an experimental and numerical investigation of a shell and tube type cascaded LHTES system using alkali metal nitrates as PCMs. Recently, Esakkimuthu et al. 81. employed 75 mm circular holders containing a molten 17 temperature inorganic salt (softening point of 550°C) PCM in a packed-bed framework coordinates with a sun based disc radiator. Xiao and Zhang .82. performed tests with molten temperature natural PCMs in round and hollow capsules and examined the charging and releasing time, proficiency, and temperature profile of the PCM in a packed-bed environment. Zheng et al. .83. experimentally and numerically discussed the thermal energy storage using sodium nitrate (NaNO_3) PCM contained in cylindrical steel containers ($25.4 \text{ cm} \times 3.81 \text{ cm}$ ($h \times r$)). Bellan .84. worked on the numerical investigation of the encapsulated NaNO_3 LHTES system and optimized the main parameters of the storage tank. Peng .85. also carried out a numerical analysis of a LHTES system containing sodium nitrite as the PCM, examined the temperature distribution inside the bed, and established the relationship of charging and discharging efficiency with the HTF flow rate and capsule size. Nithyanandam et al. .86. investigated the dynamic response of a thermocline energy storage system and provided guidelines for constructing an encapsulated PCM-based packed bed storage for CSP plant operation.

2.7 MELTING AND SOLIDIFICATION IN SPHERICAL CAPSULES

Melting and solidification within the spherical containers can be classified into constrained and unconstrained categories. In the presence of a thermocouple, the solid PCM clasps itself to the thermocouple and restrain it from sinking or rising inside the capsule due to density difference of two phases of the PCM. This is called fixed or constrained melting. On the other hand, in the absence of a thermocouple, direct contact melting next to the capsule wall is observed as the solid PCM sinks or rises up inside the capsule due to density difference of two phases of the PCM. This is called unconstrained or unfixed melting.⁸⁷ Saitoh ^{.75}. explored a thermal storage system with various geometrically shaped capsules filled with organic PCM and concluded that spherical capsules exhibited the best 18 storage performance. Moore and Bayazitoglu ^{.88}. conducted a numerical and experimental investigation with low temperature PCM in a spherical glass enclosure considering unconstrained melting.

The numerical result had shown good agreement with the experimentally investigated data. Roy and Sengupta ^{.89}. conducted further study on melting in spherical geometry. This analysis was assumed to have constant wall temperature and high solid density and the analytical modeling was adopted from Bareiss and Beer's ^{.90}. model for cylindrical geometries. Fomin and Saitoh ^{.94}. considered the wall temperature of a spherical capsule as a sinusoidal function and developed a numerical model for the unconstrained melting process. The gotten comes about were in great assention with a inconsistency not more than $\pm 15\%$. Cho and Choi ^{.95}. detailed an test examination of paraffin and paraffin-water blend as the PCM in a round capsule for watching the dissolving and cementing and warm exchange co-efficient. It was found that the warm exchange coefficient of immaculate fabric was 40% more than the blend. Caldwell and Chan ^{.96}. compared two diverse numerical strategies, the enthalpy strategy and the warm adjust necessarily strategy for hardening within the circular control; they found that both strategies appeared great assention for higher Stefan numbers. Ismail and Henriquez ^{.97}. also reported a numerical solidification-based model 19 of a spherical vessel with PCM. The model was validated with available experimental results and found good agreement. Khodadadi and Zhang ^{.98}. developed a buoyancy driven convection show for obliged softening of PCM in a circular capsule. Eames and Adref ^{.99}. conducted a hardening explore with water in circular capsules and created an observational connection to

foresee the strong division interior the capsule. Barba and Spiga .100. compared three diverse geometries and illustrated that cementing took the most limited time in little circular capsules. Afterward, Ismail and Henriquez .101. conducted a parametric consider on ice arrangement interior a circular capsule to discover the impacts of capsule measure, gulf temperature on hardening. Wei et al. .102. performed an test and numerical examination with PCM to watch the cementing wonders of different geometries. Round geometry appears the finest execution with the numerical and test information concurring to inside 10%. Chan and Tan .103. conducted a hardening try in round capsules where n-hexadecane was utilized as PCM. The perception was made for steady temperature of the surface and concluded that at first the cementing rate is tall and consistently concentric. With time, the solidification rate decreases and forms a void inside the sphere. Tan .104. reported the visual observation of fixed and unfixed melting inside a the predicted results of the numerical solution were compared with the experimental data presented by Moore and Boastingly .88. and showed good agreement. Bahrami and Wang .91. also employed the same model .90. of unconstrained melting in the spherical geometry with a modified assumption. Roy et al. .92. later proposed a gravity-assisted model for melting PCM in a sphere with an isothermal boundary condition, in which they considered the natural convection effect during unconstrained melting. Saitoh et al. .93. presented a numerical and experimental investigation of spherical capsule using n-octadecane and water considering inner wall temperature distribution. spherical capsule using organic PCM for different wall temperatures. Later, Tan et al. .105. compared the experimental findings with numerical simulation for fixed melting of PCM inside a sphere. It was watched that the dissolving time in exploratory finding was speedier than in numerical considers, which was due to warm stratification of the walled in area shower water. Rizan et al. .106. conducted an test examination of dissolving in a round holder. They too utilized natural PCM, and uniform warm flux condition was kept up on the divider boundary. The highlight of the ponder was the impact of Stefan number on the dissolve division rate. As of late, Archibold et al. .107. numerically 20 examined the warm exchange rate amid the dissolving of NaNO_3 PCM interior a round capsule. They validated their numerical model with Tan's .104. experimental model and found good agreement. Also, calculated the liquid mass fraction of NaNO_3 and finally proposed a correlation for the liquid mass fraction, which will be helpful for designing warm vitality

capacity frameworks. Afterward, the same bunch proposed another numerical demonstrate for solidifying in a circular shell with NaNO_3 as PCM; this time they included the impact of concurrent conduction, convection and warm radiation amid solidification.¹⁰⁸

2.8 SCOPE OF RESEARCH IN THIS STUDY,

Molten alkali metal nitrate-based salts and their eutectics are selected as the PCM. The challenge is to fabricate encapsulated PCMs that can withstand the highly corrosive environment and the volumetric expansion of the PCMs on melting. The present work is concerned with the stability of the encapsulation material and thermophysical properties of the PCM before and after thermal cycling in various environments like air, thermal oil and molten salt. As is clear from the writing study, most of the LHTES ponders have either been carried out for moo temperature typified PCMs (300oC) typified in expansive metallic cylindrical containers.⁸³ There are many reports on the numerical investigation of high temperature LHTES based on large scale or microencapsulated circular PCMs capsules.⁸⁴⁻⁸⁶; be that as it may, there's no report on the test show of the packed-bed LHTES framework that contains tall temperature typified circular PCM capsules (m.p. >300oC). As a result, this investigation focuses on constructing a packed-bed LHTES system with fabricated spherical capsules, and also, on evaluating the thermal performance of the system by measuring the temperature profile for different flow rates. 21 Lack of reports on melting and solidification of different-sized spherical capsules filled with high temperature PCM, points of the need for the study in this direction. In this investigation, different-sized complete capsules will be tested to observe the temperature profile and their charging discharging time.

CHAPTER 3

Design Model

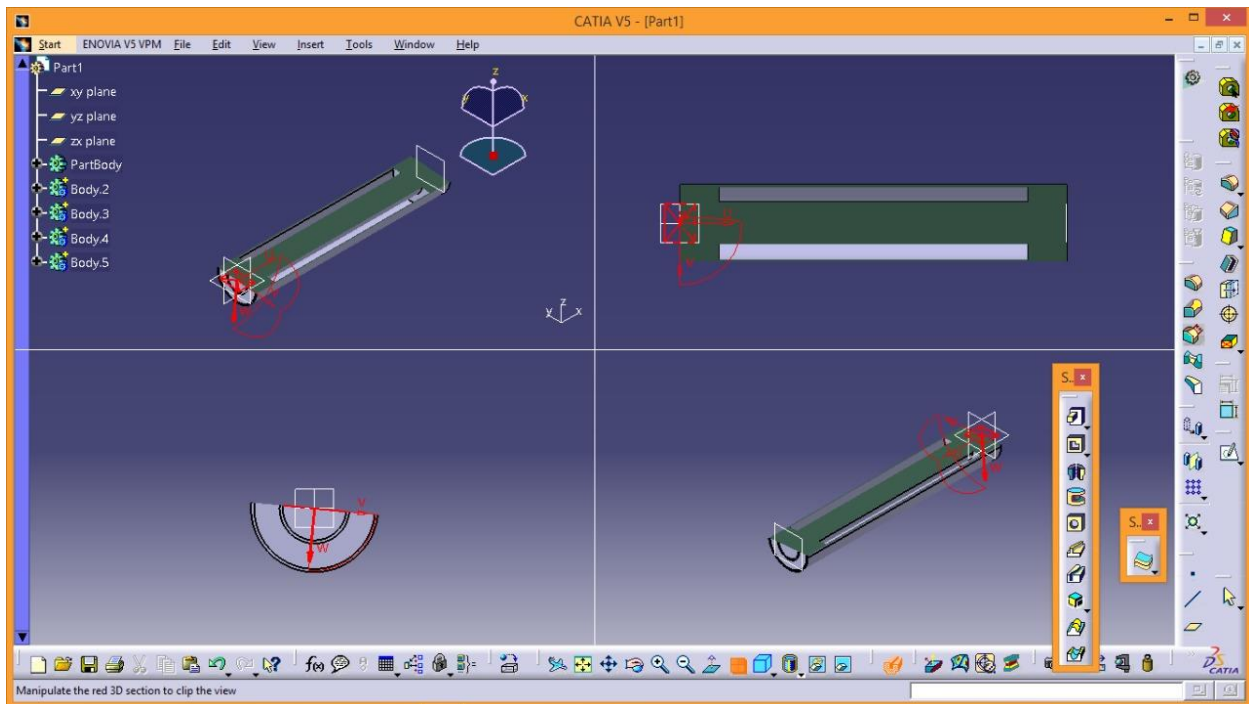
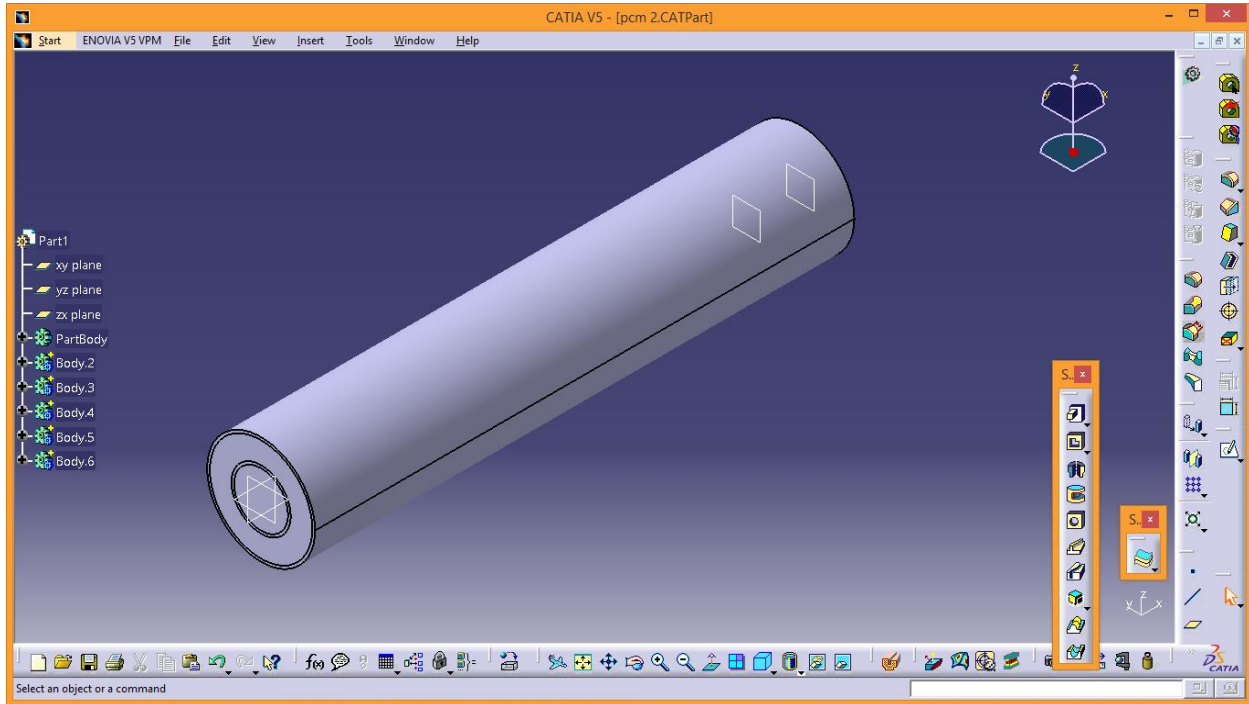


Fig 3.1 Geometrical Design

MESHING

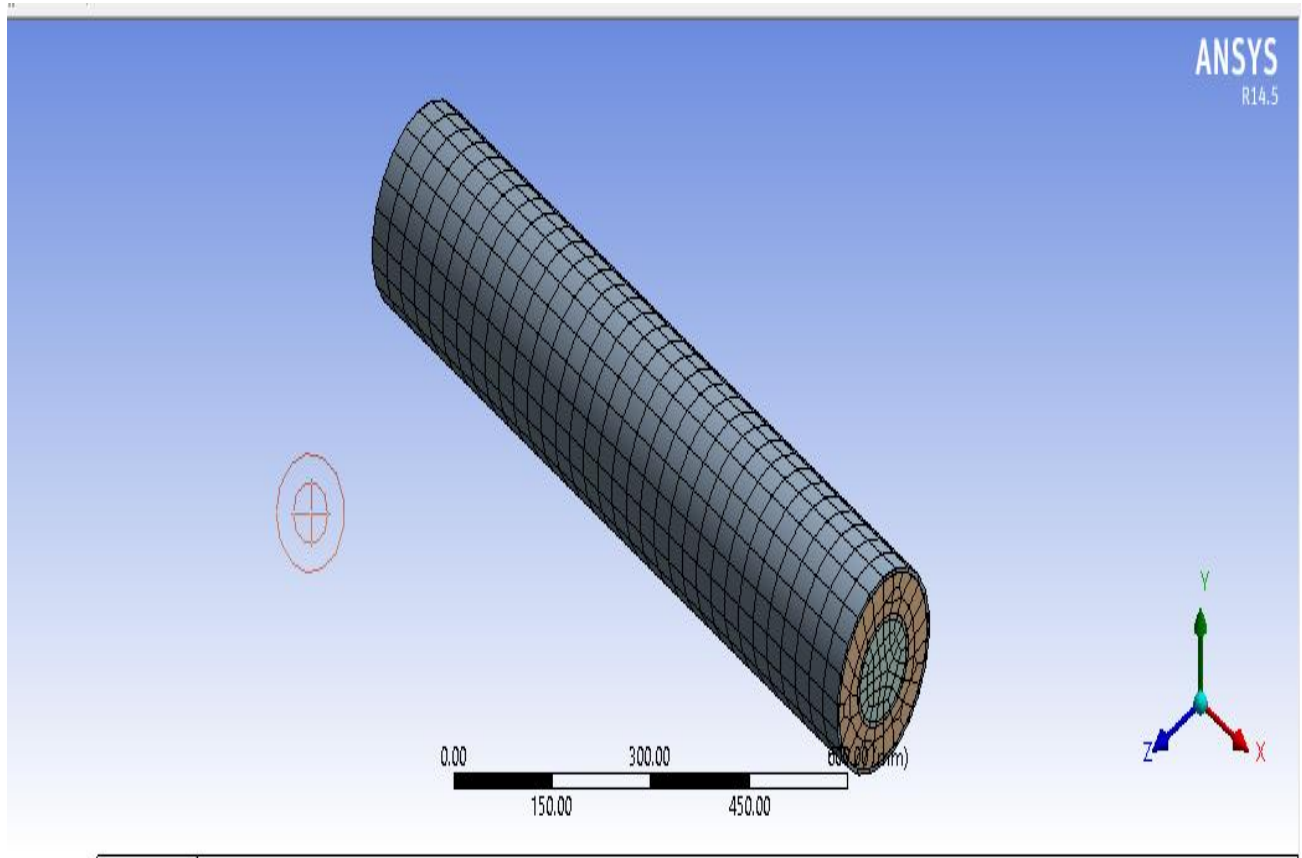


Fig 3.2 Meshing design

CHAPTER 4

EXPERIMENTAL AND METHODS

4.0 Thermal Analysis

Magnesium chloride, magnesium nitrate has been thermally analysed in cylindrical aluminium encapsulation and a study has been made.

There are two important modes involved in the functioning of the PCM,

1. Charging Mode
2. Discharging Mode

4.1 Graphical Analysis in Charging Mode

Here, different PCM's have been used to study the performances of the LHTES. The PCM's have been selected according to the increasing order of their melting point i.e., 120°C, 90°C. The figure shows that greater the melting temperature difference between multiple PCM's quicker the PCM with the lowest melting point melts.

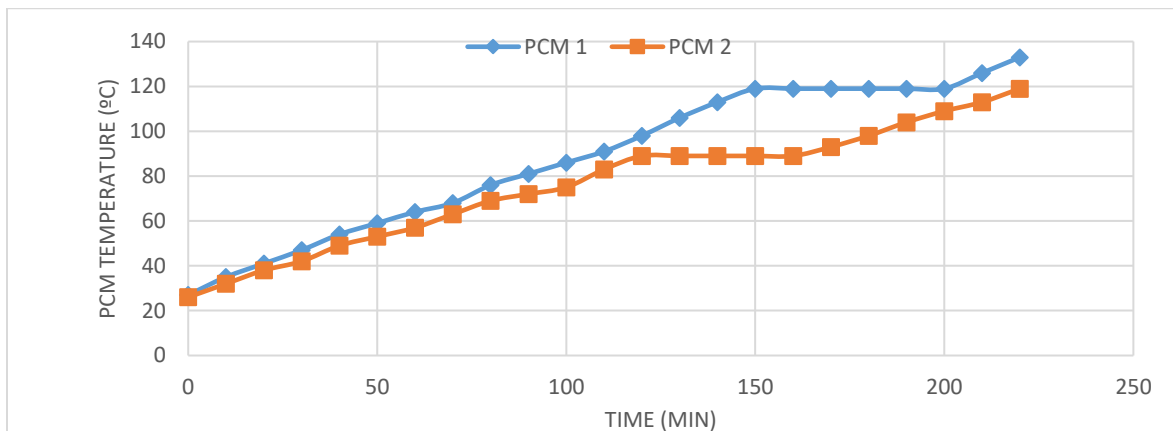


Fig: 4.1: Charging of HTF and PCM in aluminium encapsulation

The figure shows the varying rate at which the employed multiple PCM's are melting. This is because of the fact that greater the melting temperature difference between multiple PCM's quicker the PCM with the lowest melting point melts. After magnesium nitrate hexahydrate having a melting point of 90°C starts melting. At last magnesium chloride hexahydrate with 120°C melts. Here charging is done for about 220

minutes. During charging PCM reaches the phase transition point and changes from solid to liquid uniformly at constant temperature and stores the energy in them.

4.1.2 Graphical Analysis of Discharging Mode

The following figure shows the variations in the heat transfer for the different PCM's that has been used and temperature vs time graph has been plotted. From the graph it is clear that magnesium nitrate hexahydrate, which has the lowest melting point of 90°C converted into solid first followed with the solidification of magnesium chloride hexahydrate.

After certain interval of time the line of discharge becomes constant as soon as the PCM's reaches its melting point and stays in the constant temperature region. During this time the energy that was stored in the respective PCM's, was released to the HTF.

4.2 HEAT TRANSFER IN PCM DURING CHARGING

In order to find out the heat transfer involved in the PCM's. A graph is plotted between the temperature and the heat flux.

Heat transfer In PCM1

Here, magnesium chloride hexahydrate is taken as PCM1. As mentioned earlier the plotted graph between the temperature and the heat flux as shown in figure. It shows that the magnesium chloride hexahydrate starts melting at 145mins and the total time required is almost 200 mins. It is clear from the study that heat transfer rate and melting time of PCM1 is directly proportional to each other. Heat starts to get stored when clocked at 145mins and continues up to 200mins and the transition of phase occurs.

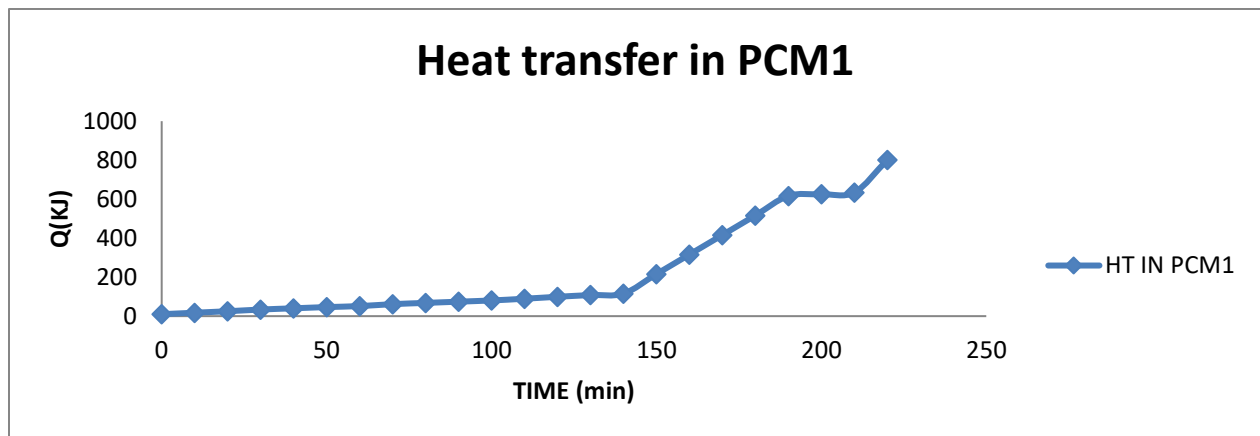


Fig:4.2.1: Heat transfer in PCM1

Heat transfer in PCM 2

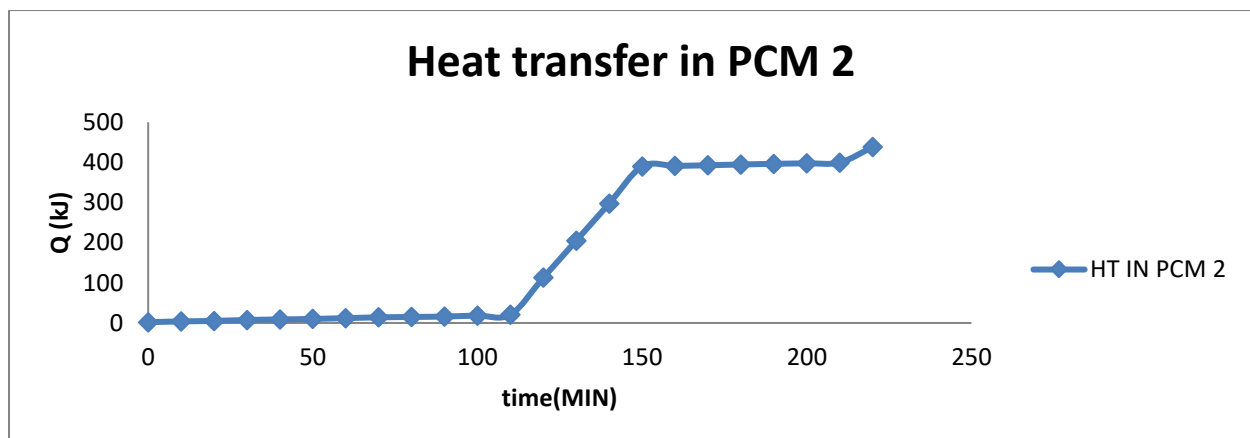


Fig: 4.2.2: Heat transfer in PCM2

From the graph it is evident that PCM2 Magnesium nitrate hexahydrate starts melting at 115mins and continues up to 170mins. Heat starts to get stored when clocked at 115mins and continues up to 170mins and the transition of phase occurs.

4.2.3 Heat transfer in multiple PCM during charging

It is clear from the graph that presence of PCM in low temperature slows down the heat transfer rate of PCM. After that PCM will tend to undergo transition of phase. Magnesium nitrate hexahydrate transits its phase in about 120mins and in a period of 50mins heat transfer rate occurs from zero to 400kw as rate of heat transfer is higher

during the period of phase transition. Due to the higher latent heat of fusion magnesium chloride hexahydrate will have higher rate of heat transfer.

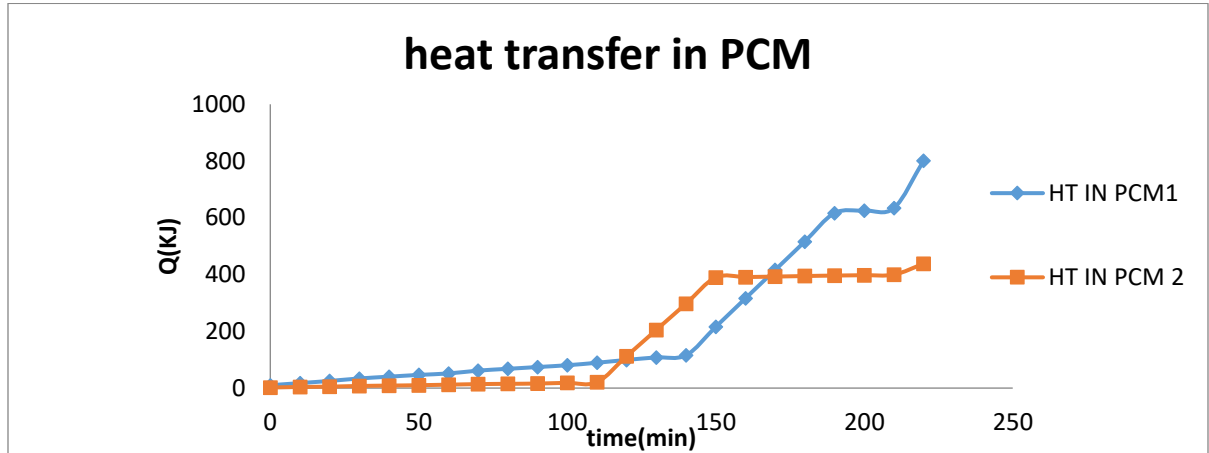


Fig. 4.2.3: heat transfer in PCM during charging

4.3 HEAT TRANSFER IN PCM DURING DISCHARGING

With the help of the plotted graph between the temperature and the heat flux the transferred heat involved in the PCM's is obtained.

4.3.1 Heat transfer from PCM 1

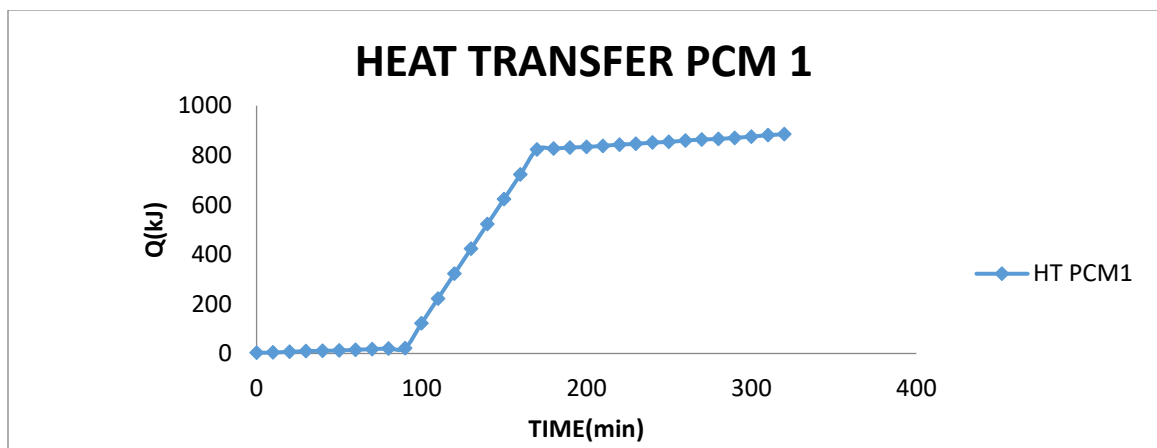


Fig. 4.3.1: Heat transfer in PCM1 during discharging

From the graph it is evident that the solidification of the PCM 1 i.e., magnesium chloride hexahydrate will start at 90mins and continues up to 185 mins for complete solidification. It is clear from the study that heat transfer rate and solidification time of PCM is directly proportional to each other during discharging. Above figure shows that the rate of heat transfer from PCM to the HTF increases with respect to time and in a

period of 90mins heat is being stored drastically till 185 mins. Due to storing of heat change of phase occurs.

4.3.2 Heat transfer in PCM2

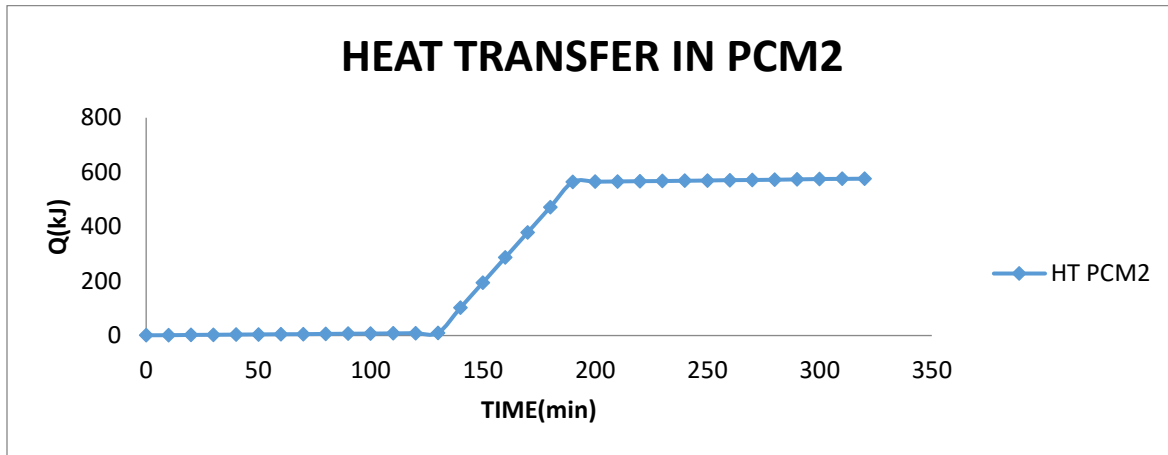


Fig: 4.3.2: Heat transfer in PCM2 during discharging

4.3.3 Heat transfer in multiple PCM during discharging

Heat transfer mainly depends on the temperature difference between the HTF and PCM. A time vs. heat transfer graph is drawn to determine the heat transfer rate of all the two PCM's -HT PCM1, HT PCM2, denoting magnesium chloride hexahydrate and magnesium nitrate hexahydrate respectively. During the change of phase from liquid to solid the heat transfer rate will be maximum and the heat flux will be abruptly high. At first Magnesium nitrate under goes phase transition within 140mins due to low specific heat capacity. Due to higher latent heat of fusion magnesium chloride has higher phase transition period. In case of magnesium chloride hexahydrate, heat transfer rate increases rapidly within 100mins to 180mins. Phase transition of different material occurs at different time so the heat supply to the HTF will be constant.

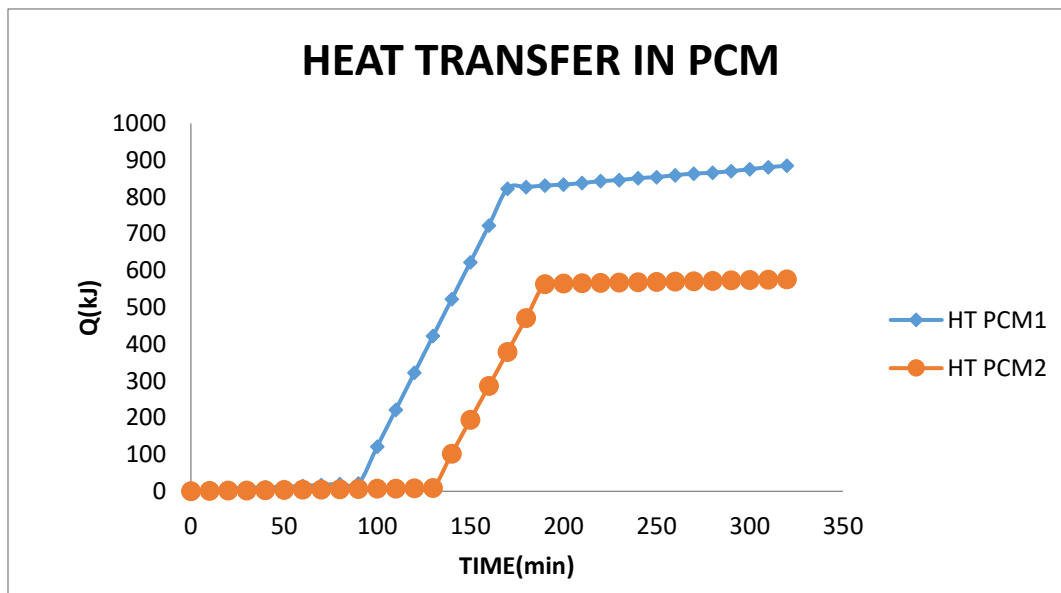


Fig: 4.3.3: Heat transfer in PCM during discharging

Therefore, to increase the heat transfer rate within the HTF multiple PCM has been employed

Nomenclature:

Q - Energy absorbed

m - Mass of the material

dT - Temperature difference

C_p - Specific heat capacity

T_f - Final temperature

T_i - Initial temperature

Q_{stored} = Heat stored in the PCM

M_{PCM} = Mass of PCM used

C_{PCM} = Specific heat capacity of PCM

T_m = Melting temperature of PCM

T_a = Ambient temperature of PCM

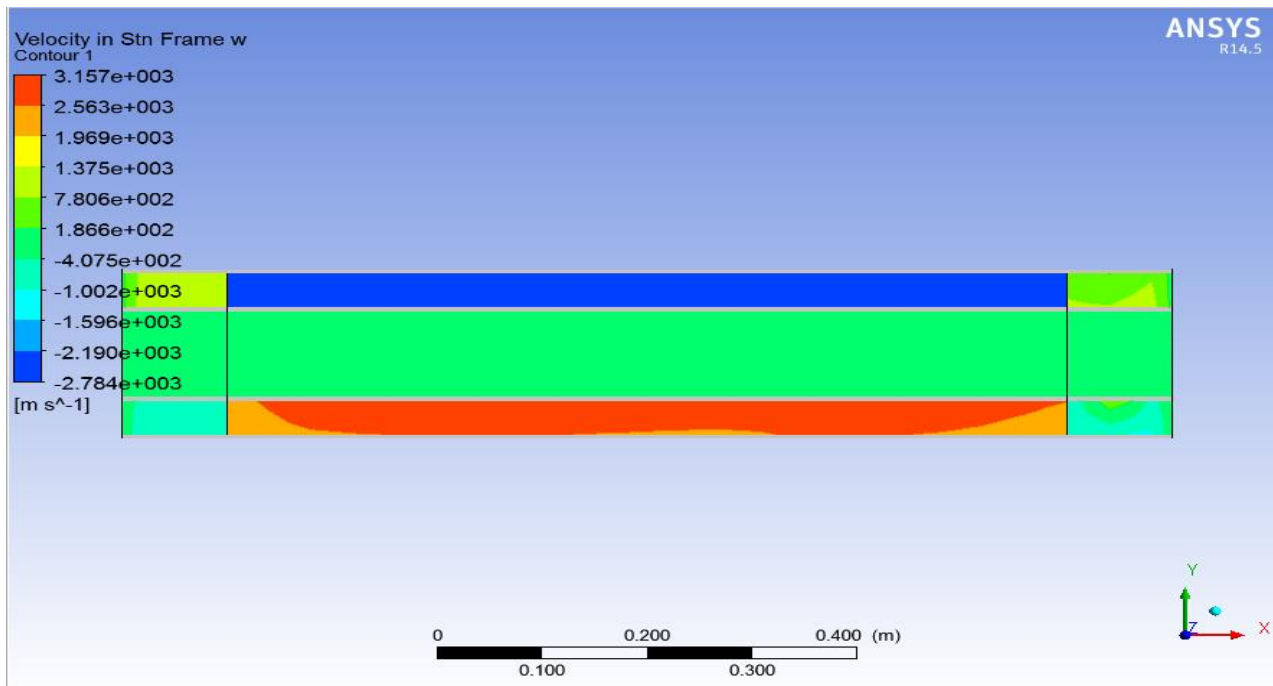
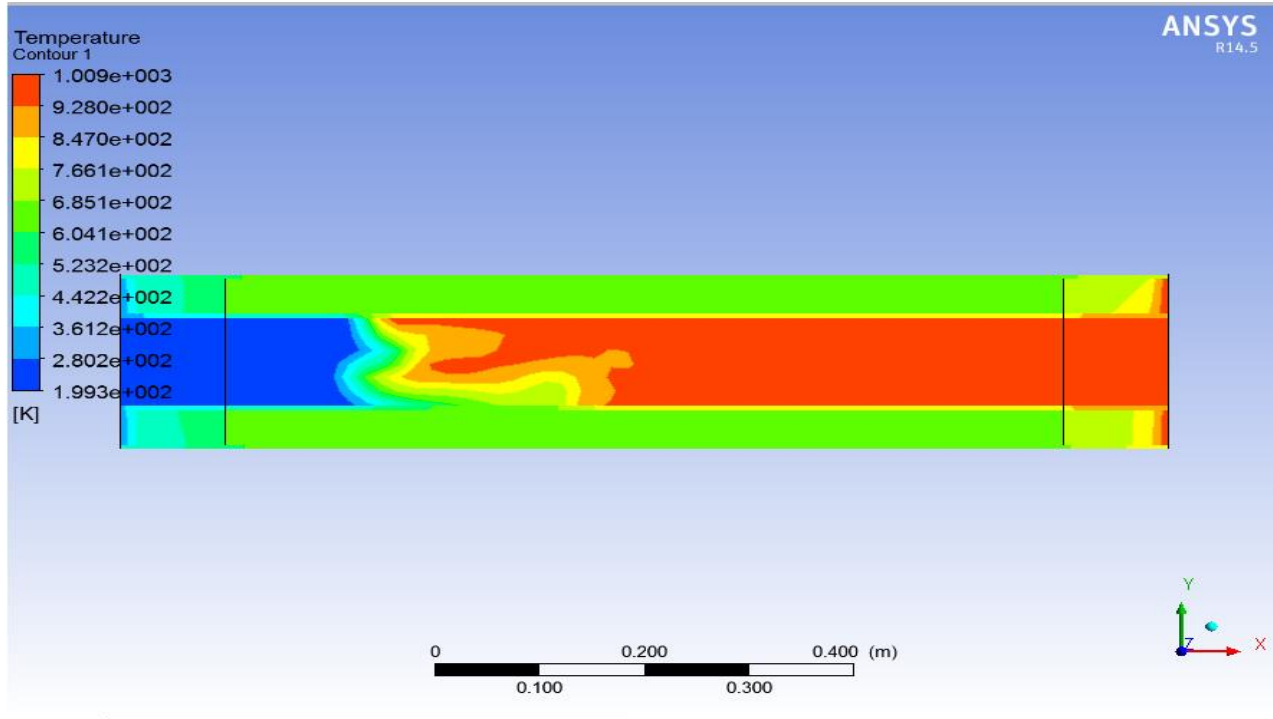
$T_{\text{PCM max.}}$ = Maximum temperature of PCM

L_f = Latent Heat of Fusion

CHAPTER 5

RESULTS

5.1 Heat transfer in multiple PCM during charging



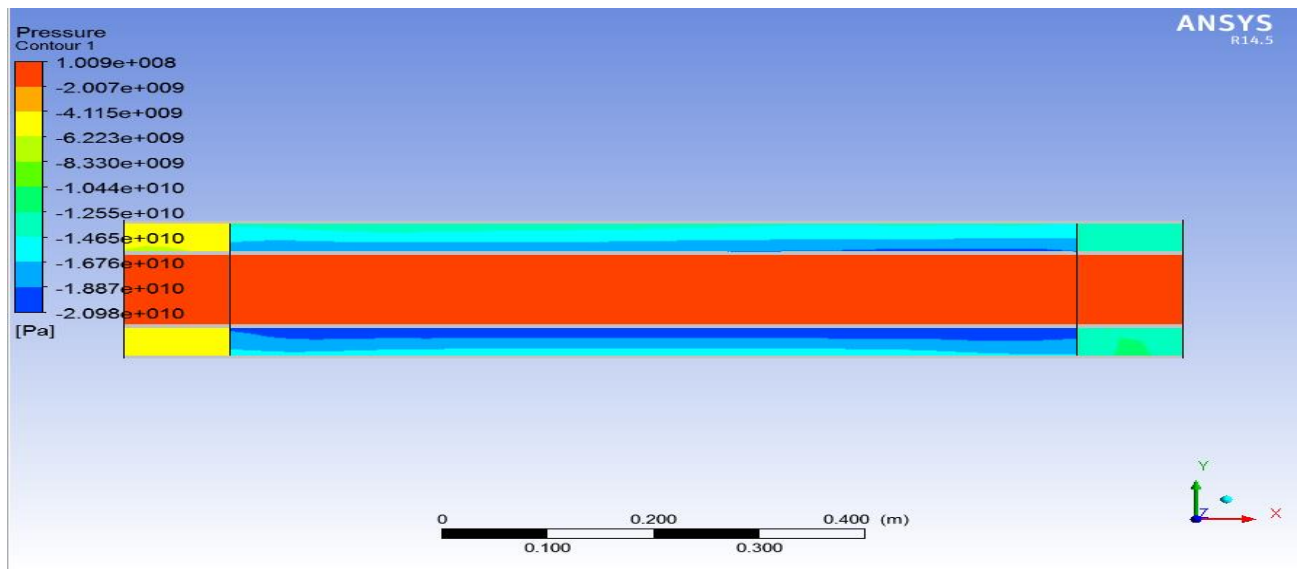
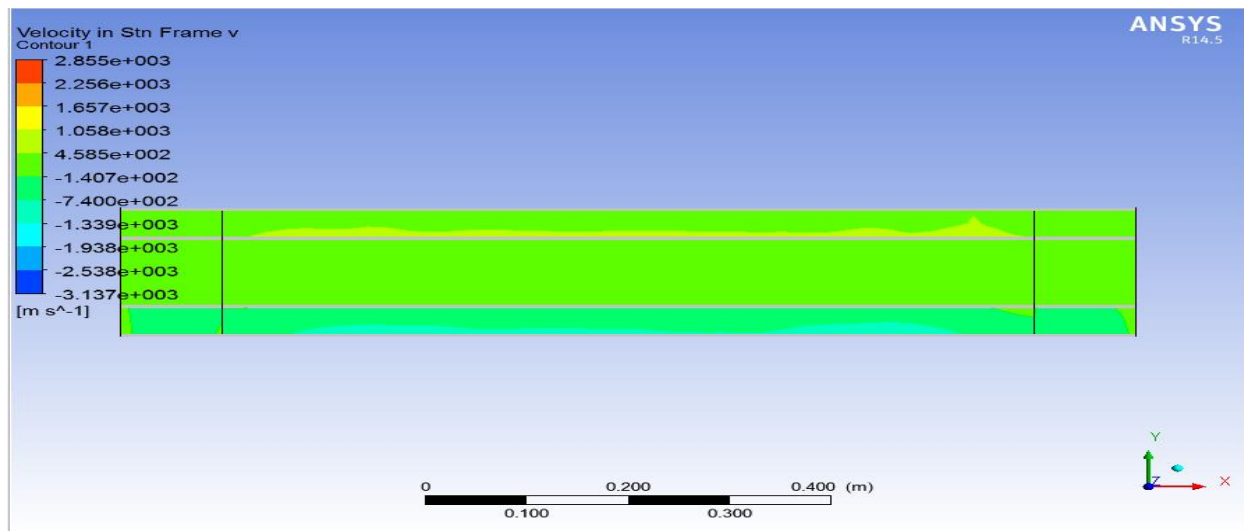
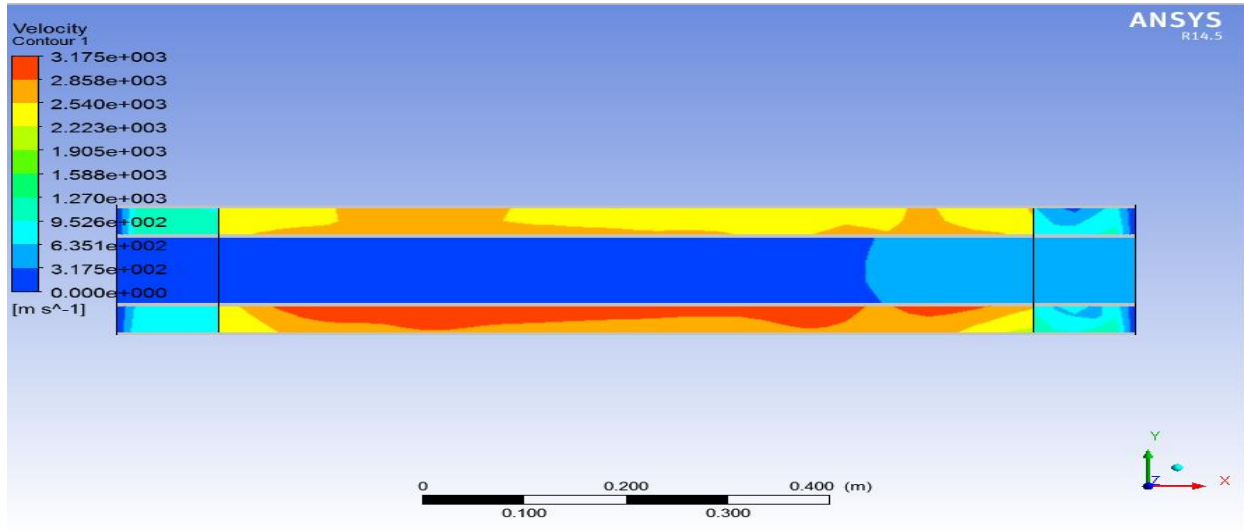


Fig 5.1 Heat transfer in multiple PCM during charging mode

The above figures are contained with containers, PCM materials when the heat flows through the pipe, the PCM placed in the container melt its phase change to liquid phase

5.2 Heat transfer in multiple PCM during discharging



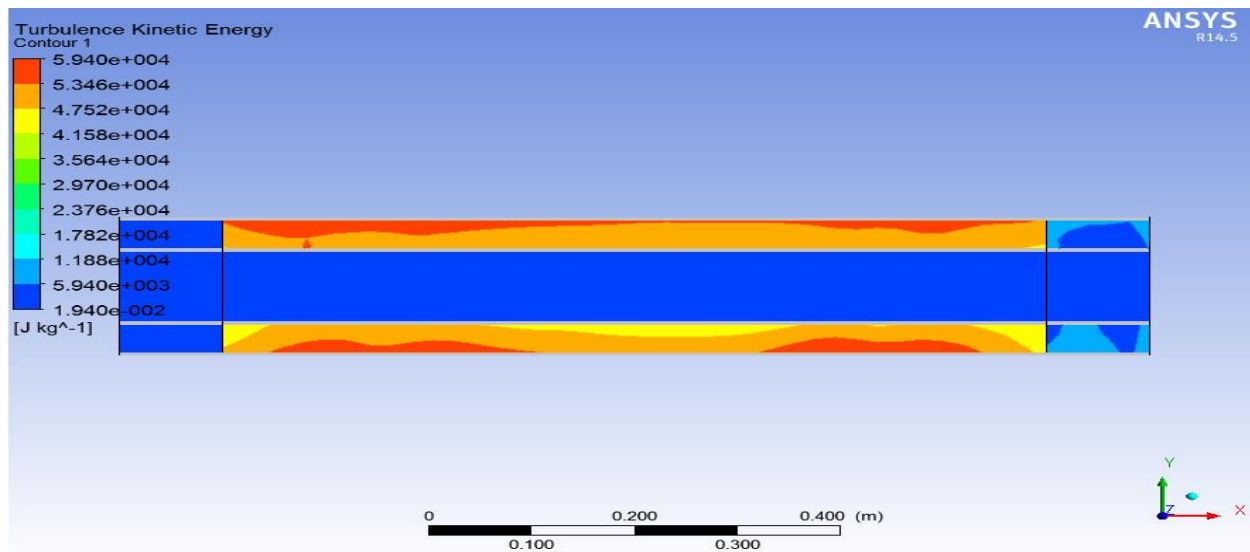


Fig 5.2 1 Heat transfer in multiple PCM during discharging mode

The above figures are contained with containers, PCM materials when the cold flows through the pipe, the PCM placed in the container melt its phase change to solid phase

CHAPTER 6

CONCLUSIONS

The present work has been carried out on the preparation and evaluation of Thermal Energy Storage System by using multiple PCM's in an aluminium container. Based on the availability and better efficiency, the phase change materials chosen were magnesium chloride hexahydrate(120°C) and magnesium nitrate hexahydrate(90°C). The variation of heat flux should be maintained constant so that supply of heat to HTF will be constant and it is also maintained. Being completed the design and fabrication of the set. By studying the charging and discharging characteristics of multiple PCM, the results obtained are:

- During Charging Process by using Therminol-66 Heat transfer from HTF to multiple PCM units is found out to be 657.764kJ.
- During Discharging process by using Therminol-66 it was observed that Heat Transfer from multiple PCM to HTF unit is found to be 655.3kJ.
- The use of multiple PCM's especially (magnesium chloride hexahydrate and magnesium nitrate hexahydrate) in LHTES systems increases the charging and discharging rates of the unit.
- Variation of heat flux between layers is maintained at a constant difference of 40%.

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