Thermal Energy Storage Training System

LHS Based

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Contents

List of Tables

1 Introduction

Thermal energy storage systems are temporary storage of thermal energy at high or low temperatures. These systems reduce the mismatch between energy supply and demand. They also play very important role in energy conservation. These systems areused in the sectors like air conditioning, concentrated solar power plant, cogeneration, waste heat recovery, district heating & cooling, food and textiles industries.

1.1 Types of Thermal Energy Storage

1.1.1 Sensible Heat Storage

In sensible heat storage systems, energy is stored or extracted by heating or cooling a liquid or solid material. A variety of materials are used in this type of storage systems. The most familiar materials include water, different kinds of heat transfer oils and certain inorganic salts, rocks, pebbles and refractory. With its highest specific heat and inexpensive, water is the most commonly use substance in a sensible heat storage systems. The choice of substances for sensible heat storage material depends largely upon the temperature limit of applications. Sensible heat storage systems are simple in design. However they suffer from disadvantage of being bigger in size. A second disadvantage associated with sensible heat storage systems is that they cannot store or deliver energy at constant temperature.

1.1.2 Latent heat Storage

The principle behind latent heat energy storage system is that when heat is supplied/extracted to certain kinds of material the phase of the material changes from one state to other. If it is a solid to liquid phase transition then the heat is stored as latent heat of fusion while in a liquid to vapor phase transition the heat is stored as latent heat of vaporization. When the stored heat is extracted by load, the material regains its initial state. Solid to vapor and liquid to vapor transitions involves large amounts of heat of transformation, but large changes in volume make the system complex. The solid to liquid transition relatively, stores small amount of latent heat but due to small changes in volume it is easy to design practical systems with these types of phase changing materials. Large numbers of solid to liquid phase changing latent heat storage materials are available in nature and commercial market.

1.1.3 Thermo-chemical energy storage

Thermo-chemical system works on the principle of absorption and release of energy due to breaking and reforming molecular bonds in a completely reversible chemical reaction. In this case, the amount of heat stored depends on storage material quantity, endothermic heat of reaction and the extent of conversion.

1.2 Selection criteria of thermal energy storage type

Broadly following points are need to be consider in selecting the type of thermal energy storage

- The temperature range needed over which the storage will operate.

- Duration of storage
- The rate of charging and discharging
- Cost of the storage unit: This includes the initial cost of the storage medium, the containers and insulation, and the operating cost.

1.3 Properties of a good PCM

Thermal, Physical and Chemical properties

- Phase change temperature falls under the operating range
- High latent heat per unit mass
- High specific heat
- High thermal conductivity in both solid and liquid phases
- High density
- Low density variation during phase change
- Chemical stability
- No chemical decomposition
- Compatibility with container materials
- Non-poisonous, nonflammable and non-explosive

Economic factors

- Easily available, Low cost

2 Theory

The TES system that we have designed is a LHS based. In general the LHS are most expansive among the TES system. But they are most promising future option if problem associate with phase changes stages are resolved. The LHS based system has lot of advantages over the other system. Some basic advantages of LHS systems are mentioned below

- They storethermal energy as latent heat which allows higher thermal energy storage capacity per unit weight or material without any change in temperature
- This technology would lead to sizing HVAC equipment for average load rather than peak load
- Other advantages with LHS systems are the space and amount of heat storing medium requirement

The space and amount of storing material requirement in a LHS is much smaller than a SHS system. For example the space requirement to store 1000 kJ energy in a sensible heat storage system is 30 m^3 while the same energy can be store in 2.7 m^3 by using the latent heat storage technology. Similarly, in a rock pebbles bed energy storage system we would require 300 to 500 kg rocks per square meter of a flat plate solar collector.

Other advantages in using the LHS are the possibility of storing and extraction of large amounts of heat with only small temperature changes.

2.1 Types of PCM

A large number of phase change materials are available in any required temperature range. However, except melting point, majority of phase change materials does not satisfy the required criteria of a proper storage system. As no single material can have all the required properties for an ideal thermal-storage medium, one has to use the available materials and try to make up for the poor physical property by an adequate system design.

2.1.1 Organic PCM

Organic PCMs have a number of characteristics which render them useful for latent heat storage. They are highly chemically stable, they melt congruently and super-cooling does not pose as a significant problem. Moreover, they have been found to be compatible with various kinds of materials.

2.1.2 Inorganic PCM

Inorganic PCMs have higher energy storage capacity. These PCMs have also some other attractive properties. They are not flammable and their high water content means that they are inexpensive and readily available.

However, the inorganic PCMs have many difficulties in using for energy storage system. These include corrosiveness, instability; improper re-solidification and tendency to super cool. As they require containment, they have been deemed unsuitable for impregnation into porous building materials.

2.1.3 Salt hydrates

Salt hydrates may be regarded as alloys of inorganic salts and water forming a typical crystalline solid of general formula AB_nH2O. The solid–liquid transition of salt hydrates is actually a dehydration of the salt. The most attractive properties of salt hydrates are high latent heat of fusion per unit volume, relatively high thermal conductivity (almost double of the paraffin's), small volume changes on melting.

2.1.4 Eutectics PCM

A eutectic is a minimum-melting composition of two or more components, each of which melts and freeze congruently forming a mixture of the component crystals during crystallization. Eutectic nearly always melts and freezes without segregation.

2.1.5 Stages of thermal energy storage in a solid to liquid phase transition material

A solid to liquid PCM stores heat in three stages. At the beginning of the heating process the material is in a solid state. Before it reaches the melting point the heat absorbed is sensible heat. Starting at the melting point, the material undergoes a change of state from a solid to liquid. During this process, the heat absorbs by the material is known as enthalpy of melting.

The temperature remains constant during this process. If the material is heated up further heat get absorbed as sensible heat into the material.

3 System description

The system has been designed to perform TES related experiment by using phase changing materials (PCM). As there are several types of PCMs, the system has been design to perform experiment with at least two PCMs separately. Provision has also been kept to examine the combine (known as cascading) effect of two PCMs in thermal energy storage.

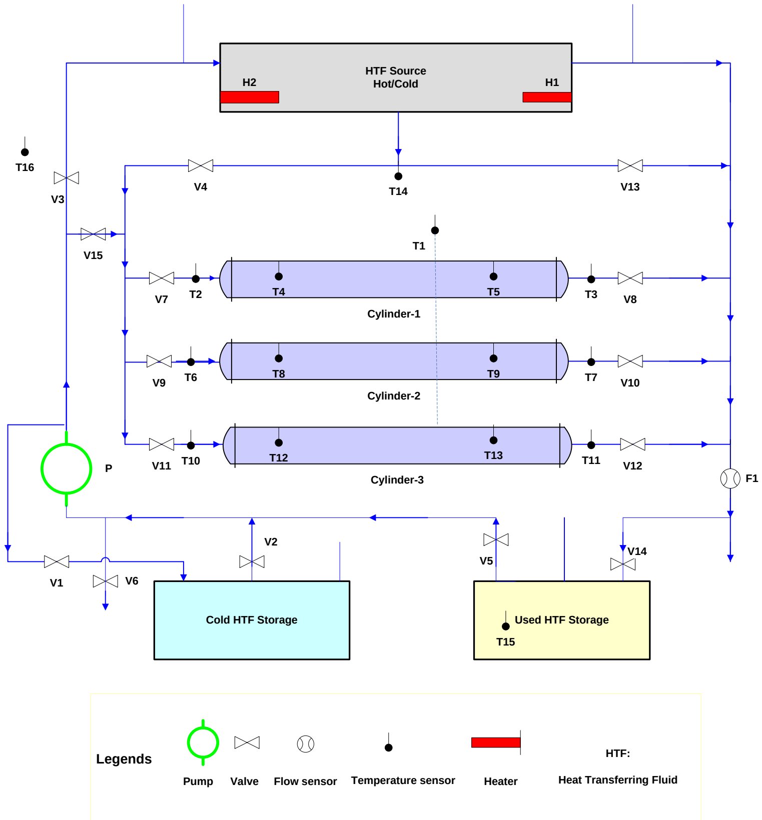
Stainless steel cylinders are there to contain the PCMs. To charge and discharge (store and extraction of heat) the PCMs, spiral type heat exchangers made of copper of appropriate dimensions are installed in the containers. The PCMs and heat exchangers are meticulously arranged inside the S.S cylinders. In order to block heat loss from the PCM, all the cylinders are insulated by polyurethane (PUF) foam insulation.

To visualize the phase changing process another set of arrangement is there in the system. In this set the heat exchanger-PCM duo are there inside a transparent container made of acrylic and nylon. No insulation is there in this set of arrangement.

Water is the heat transferring fluid (HTF) in the system. While hot water gives heat to the PCM during charging, the cold water absorbed heat from the same PCM during discharging. To supply water for different purposes, three tanks are there in the system. For source of energy, special arrangement has been made within the system. Besides the integrated arrangement, the system can also be connected with flat plate solar collector or parabolic trough solar collector for the source of energy.

Different parts of the systems are connected with G.I pipes of ½ inch size. To direct the heat transferring fluid as per requirement several gate valves are there in the appropriate locations. To measure different variables such as temperature, flow rate, etc., respective sensors are placed at the targeted points. There is a control unit in the system where all meters and control buttons are strategically arranged to display the reading from the respective sensors.

4 Schematic diagram of the system



5 Working of the system

The working of the system starts with filling of water in the cold HTF storage tank. Once this tank is full the water is uplifted to the HTF hot/cold source tank by switching the pump on. When water overflows the pump is switched off and heat is supplied to the water by switching on the electric heaters. Once water at required temperature is available in the HTF hot/cold source tank the appropriate vales are open and allow the hot water to flows through the heat exchanger of the targeted PCM cylinder(s). The hot water gives heat to the PCM by the process of convection and conduction on its way of flow from one end to other of the heat exchangers. This stage in which the PCMs accrued energy is known as charging stage. After giving heat to PCM the water get accumulated into the used HTF storage tank. Hot water keeps flowing continuously through the heat exchanger till the PCM charged fully. Once the PCM stored energy up to the maximum level the hot water is stopped by closing the appropriate valve (s). With the stop of flow of hot water the charging stage of the system gets completed. After completing the charging stage the remaining hot water in the HTF hot/cold source tank drains out to the used HTF storage tank by unlocking the drain valve. To cool the HTF hot/cold source tank some cold water can also be pass through it from the cold HTF tank by using the pump.

The 2nd step of the experiment is extraction of heat from the PCM. This step is also known as discharging of PCM. To discharge the PCM cold water is sent through the heat exchanger of the targeted PCM cylinder from the same HTF hot/cold source tank. The cold water can also be sent from the cold HTF tank directly by using the pump. The direct option is use only when high flow rate of water is required. The cold water, while flows from one end to the other of the heat exchangers absorbed heat from the PCM. After absorbing heat the water get accumulated in the used HTF storage tank.

There is a control unit in the system. All required meters and control knots are fitted in this unit. From this unit the user can take the values of different parameters such as water flow rate, temperature at different condition of the system.

Table 1: Overall Specification of different components in the systems

Sl. No.	Components	Specification	Purpose	Remark
1	HTF source tank	Capacity : 50L Material: S.S.	To supply hot HTF during charging the PCM and cold HTF during discharging the PCM.	Two electrical heater of 3000 W capacity are there to heat the HTF
2	Heat exchangers	Type of Heat exchanger: shell and tube 3 heat exchangers: Heat exchanger tube material: Copper Shell material: Stainless Steel PCM carrying capacity of shell : 5 kg	To deliver and extract heat to and from the PCM without mixing the HTF and the PCM	Heat exchangers are the heart of the TES system. The 1st Heat exchanger contains paraffin based PCM (PCM-1). The 2nd heat exchanger contains fatty acid based PCM (PCM-2). The 3rd heat

				exchanger contains both the PCMs.
3	Used HTF storage tank	HTF holding capacity : 120 L Tank material: FRP	To accumulated the HTF after charging and discharging the PCM	The tanks are as per the space available in the main structure
4	Cold HTF storage tank	HTF holding capacity : 120 L Tank material: FRP	To supply cold HTF for charging and discharging the PCM	
5	PCM-1	Paraffin based PCM, Melting temperature: 55^{0}C Heat of fusion: 173 kJ/kg	To store/extract the required amount of heat	It is organic PCM having a medium melting temperature
6	PCM-2	Fatty acid based PCM Melting temperature is 67 ^{0}CHeat of fusion: 210 kJ/kg		It is a also a medium melting temperature PCM comes under the sub-category of organic PCM
7	Pump	Power: 0.12 HP Maximum head:6m Maximum flow rate :33 LPM	To send HTF to HTF source tank and heat exchangers at some regulated speed	It is Hot water pump can sustain up to 90^{0}C
8	Flow measuring instrument	Number of flow sensor and meter: 1 Flow range: 0.5 to 25 LPM	To measure the flow rate of HTF during charging and discharging of the PCM	Flow sensor is turbine wheel based

9	Temperature measuring instrument	Sensor: Class A sensor Range: -200 to 650 ^{0}C Accuracy : ± 0.15 +0.002*(t) Where t is absolute value of temperature in ^{0}C Display: 4 digit display Range: -100 to 200^{0}C Supply Voltage: 230AC	To measure the temperature at different locations such as inlet, outlet, HTF temperature PCM temperature etc.	Platinum based RTD temperature probe with S.S sheath
10	Valves	Number of valves: 17 Size: All are ½ inch	To divert the HTF as per required. Control the flow rate	Manually driving valves
11	Control unit	Dimension: 760*400*180 mm Material: M.S , Acrylic	To read different reading and control the pump etc	All meters and switches are fitted in this unit

Table 2: Heat exchanger dimension

Sl. No.	Parameters	Value	Unit
1	Heat exchanger shell inner diameter	150	Mm
2	Heat exchanger shell thickness	2	Mm
3	Heat exchanger shell length	400	Mm
4	Heat exchanger tube (copper pipe) inner diameter	11.5	Mm
5	Heat exchanger tube (copper pipe) outer diameter	12.7	Mm
6	Heat exchanger tube (copper pipe) thickness	0.6	Mm

7	Length of Heat exchanger tube (copper pipe)	6000	Mm
8	Conductivity of Heat exchanger tube (copper pipe)	390	$\frac{W}{mK}$

<u>Properties of PCM used in the system</u>

Table-C: PCM-1

Type of PCM	organic	
Name of PCM	Organic fatty acid	
Density in solid state	860	kg/m3
Density in liquid state	833	kg/m3
Specific Heat capacity in solid state	0.73	kJ/kg K
Specific Heat capacity in liquid state	NA	kJ/kg K
Heat of fusion	210	kJ/kg
Melting temperature	66-68	^{0}C

Table-D: PCM-2

Type of PCM	organic	
Name of PCM	Paraffin wax	
Density in solid state	916	kg/m3
Density in liquid state	790	kg/m3
Specific Heat capacity in solid state	2.9	kJ/kg K
Specific Heat capacity in liquid state	2.14	kJ/kg K
Heat of fusion	173	kJ/kg
Melting temperature	53-54	^{0}C

5.1 Analysis of sub system process

5.1.1 Charging Period

In this stage the hot HTF flows through the heat exchanger and give energy to PCM

The charging period efficiency (η_{ch}) can be expressed as follows

$$\eta_{ch} = \frac{\text{Energy accumulated during charging}}{\text{Energy input during charging}}$$

Here, energy input during charging,

$$E_{in,j-1} = \dot{m}_{HTF,ch,j}\, C_{HTF}\,(T_{i,HTF,ch,j} - T_a) \times t \quad \text{Joule} \ldots\ldots (12)$$

Energy accumulated during charging,

$$E_{1,j} = E_{in,j-1} - E_{loss,1,j} - E_{loss,wa,j} \ldots\ldots (13)$$

Where,

$\dot{m}_{HTF,ch}$: Hot HTF flow rate during charging (water, $\frac{kg}{sec}$)

C_{HTF} : Specific heat capacity of HTF (water, $\frac{kJ}{kgK}$)

$T_{i,HTF,ch}$: Inlet temperature of hot HTF during charging (^{0}C)

$T_{o,HTF,ch}$: Outlet temperature of hot HTF during charging (^{0}C)

$E_{loss,1}$: Amount of Energy loss during the charging period through the cylinder (J)

$E_{loss,wa,j}$: Amount of energy loss without absorption (J)

$$E_{loss,1,j} = \dot{q}_{1,j} \times L_4 \times t \quad (J) \ldots\ldots (14)$$

$$E_{loss,wa,j} = \dot{m}_{HTF,ch,j}\, C_{HTF}\,(T_{o,HTF,ch,j} - T_a) \times t \quad (J) \ldots\ldots (14a)$$

Therefore,

$$\eta_{ch,j} = \frac{E_{1,j}}{E_{in,j-1}} \ldots\ldots (15)$$

5.1.2 Storing period

In this period, the energy stays ideally inside the PCM. Due to losses to the environment the amount of available energy reduces with time.

The storing period efficiency (η_{st}) can be expressed as follows

$$\eta_{st} = \frac{\text{Energy stored in TES at the end of the storing}}{\text{Energy stored in TES at the begining of storing}}$$

Energy stored in TES at the begining of storing,

$E_{1,total,j-1}$=$E_{in,total}$-$E_{loss,1,total} - E_{loss,wa,total} - E_{loss,2,j}$ .... (16)

Energy stored in TES at the end of the storing,

$E_{2,j}$=$E_{1,total,j-1}$-$E_{loss,2,j}$ .... (17)

Here,

$E_{loss,2}$: Loss of energy during storing period

$E_{loss,2,j}$= $\dot{q}_{2,j} \times L_4 \times t$ (J)... (18)

$$\dot{q}_{2,j} = \frac{T_{pcm,j} - T_a}{R_2}$$

$$R_2 = \frac{\ln\left(\frac{r_4}{r_3}\right)}{2\pi k_3 L_3} + \frac{\ln\left(\frac{r_5}{r_4}\right)}{2\pi k_4 L_4} + \frac{\ln\left(\frac{r_6}{r_5}\right)}{2\pi k_5 L_5}$$

$T_{pcm,st,j}$: Temperature of stored PCM (^{0}C)

j-1: represent a observation step ahead of the jth step. For j=0 the above logic is not valid.

Therefore,

$\eta_{st,j} = \frac{E_{2,j}}{E_{1,total,j-1}}$... (19)

5.1.3 Discharging period

In this stage the energy stored in the PCM is extracted to use in the load.

The efficiency for the discharging period can be expressed as follows

$$\eta_{dis} = \frac{\text{Energy recovered from TES during discharging}}{\text{Amount of energy available to discharge}}$$

Theenergy recovered from TES during discharging,

$E_{dis,j}$=$\dot{m}_{HTF,dis,j} \times C_{p,HTF}(T_{HTF,O,dis,j} - T_{HTF,i,dis,j})$×t (kJ)... (20)

Amount of energy available to discharge ,

$E_{3,j}$=Energy available at the end of the storing period - ($E_{dis,j-1} + E_{loss,3,j-1}$)... (21)

Where,

$E_{loss,3,j}$= $\dot{q}_{3,j} \times L_4 \times t$ (J) .... (22)

$$\dot{q}_{3,j} = \frac{T_{pcm,j} - T_a}{R_3}$$

$$R_3 = \frac{\ln\left(\frac{r_4}{r_3}\right)}{2\pi k_3 L_3} + \frac{\ln\left(\frac{r_5}{r_4}\right)}{2\pi k_4 L_4} + \frac{\ln\left(\frac{r_6}{r_5}\right)}{2\pi k_5 L_5}$$

$T_{pcm,st,j}$: Temperature of stored PCM (^{0}C)

$\dot{m}_{HTF,dis}$: Cold HTF flow rate during discharging ($\frac{kg}{sec}$)

$T_{HTF,O,dis}$: Outlet temperature of the HTF during discharging (^{0}C)

$T_{HTF,i,dis}$: Inlet temperature of the HTF during discharging (^{0}C)

$$\eta_{dis} = \frac{E_{dis,j}}{E_{3,j-1}} \qquad (23)$$

5.1.4 Overall system efficiency

Overall system efficiency of thermal energy storage systems can be defined as the ratio of the energy extracted from the TES to energy input. The overall system efficiency is also the first law efficiency of the TES system.

The overall system efficiency can be expressed as follows

$$\eta_{overall} = \frac{\text{Energy recovered from TES during dischargin g}}{\text{Energy input during charging}}$$

Therefore

$$\eta_{overall} = \frac{E_{dis,total}}{E_{in,total}} \qquad (24)$$

5.1.5 Figure of merit (FOM)

To know the solidification response of a give PCM quantitatively we can define a figure of merits as follows. A higher value of FOM represents the higher quality of a PCM

$$FOM = \frac{T_{sol} \times t_{total}}{T_{max} \times t_{cool}} \qquad (25)$$

Where,

T_{sol} : The temperature at which the PCM starts to solidify, which is a material property and is the beginning of the solidification range(K) (54 ^{0}C paraffin wax).
T_{max} : The maximum measured temperature of the PCM during the test (K)
The calculation is done with all temperatures in Kelvin.
t_{total} , (The total test time in sec): time elapsed from the initiation of the charging stage at the beginning of the test to the point at which PCM temperatures drop below the solidification temperature at the conclusion of the cool down/re-solidification
t_{cool} (Total time of cooling in sec): time elapsed from the finish of charging stage to the point at which all PCM is solidified at the conclusion of the cool down/re-solidification

Assumptions:

A number of assumptions have been considered to use the above equations

- The heat exchanger tube is a straight tube of equivalent diameter running through the PCM
- The thickness to PCM is uniform around the heat exchanger tube
- Average value of PCM conductivity is maintain throughout the calculation
- The flow rate and temperature of the water is constant during charging the PCM so that the heat supply remain constant

6 List of experiments

Experiments no.-1:

Experiment on PCM-1 (organic fatty acid)

6.1 Charging period analysis of system containing PCM-1

In this stage the hot HTF (water) give energy to the PCM.

Methodology

- Open valves 6 and fill the cold HTF storage tank fully
- Open valves 2 and 3 and fill the HTF hot/cold source tank by switching on the pump
- When water overflows the HTF hot/cold source tank and water start come back to the used HTF storage tank switch off the pump and closed all valves
- Switch on the electric heaters
- Observed the water temperature continuously on temperature meter T_{14}
- When water in the HTF hot/cold source tank reached the required temperature switch off the heaters
- Note all readings corresponding to temperature sensors T_1, T_2,T_3,T_4,T_5, and T_{16}
- Open valves 4,7,8 and 14 to flow hot water through the heat exchanger
- Collect water in the measuring beaker through the tap
- Set flow rate by adjusting the valve number 8. Keep adjusting at regular interval
- Note the temperature reading corresponding to temperature sensors T_1, T_2,T_3,T_4,T_5, and T_{16} in a step of twenty minute
- Continue the above process till the average temperature of reached the melting temperature of PCM
- Once the above condition is achieved stop the charging stage by closing valve number's 4,7,8 and 14
- On completing the charging process open valve number 13&14and empty the HTF hot/cold source tank completely
- To bring the HTF hot/cold source tank to normal temperature wash it internally by cold water with the help of the pump

<u>Observation during charging period of PCM-1</u>

Table-1: Observed values during charging period of PCM-1

Sl. No.	Time (t) mi	Water temperature of HTF hot/cold	Ambient temperature	Cylinder's surface temperature	Inlet temperature of HTF during charging	Outlet temperature of HTF during charging	PCM-1 front end temperature	PCM-1 rear end temperature (T_5)	Water flow rate $\dot{m}$ $(\frac{kg}{sec})$

	n	source tank (T_{14}) ^{0}C	(T_a= T_{16}) ^{0}C	($T_{s,cy}=T_1$) ^{0}C	($T_{i,HTF,ch}$ = T_2)^{0}C	($T_{0,HTF,ch}$ = T_3) ^{0}C	(T_4) ^{0}C	^{0}C	
1	0								

Calculations

On completing the charging stage the user can calculate/ observe the following aspects

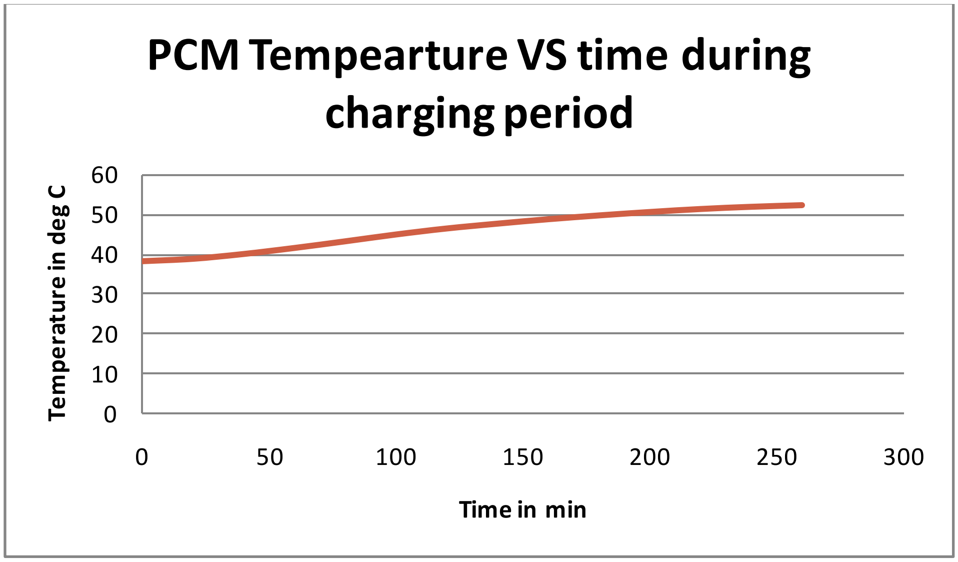
- Calculate rate of heat loss from the HTF by using equation (1) through (11)
- Calculate energy input to the TES system during charging period by using equation (12)
- Calculate energy accumulated in the TES system during charging period by using equation (13)
- Evaluate the system thermal efficiency during charging period by using equation (15)

Table-2: Calculated values during charging period of PCM-1

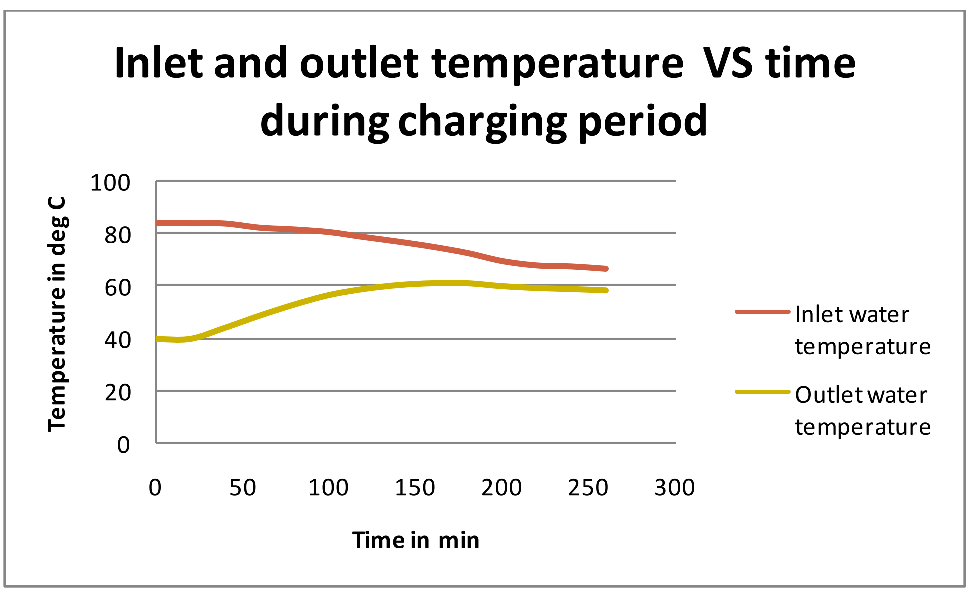
SL NO.	Time in (min)	Average temperature of PCM during charging period $T_{pcm,ch}$ $(=\frac{T_4+T_5}{2})$ ^{0}C	Energy loss from the system (J)	Energy input to the system during charging period E_{in} (J)	Energy accumulated in the system during charging period (J)	system thermal efficiency during charging period η_{ch}
1	0					
6	60					

Result:

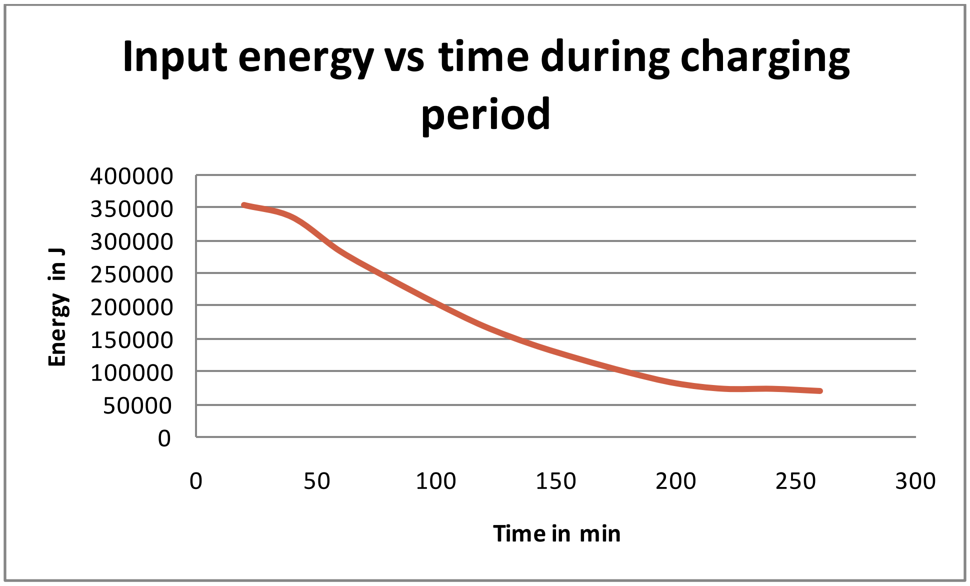
- Change in PCM-1 temperature during the charging period



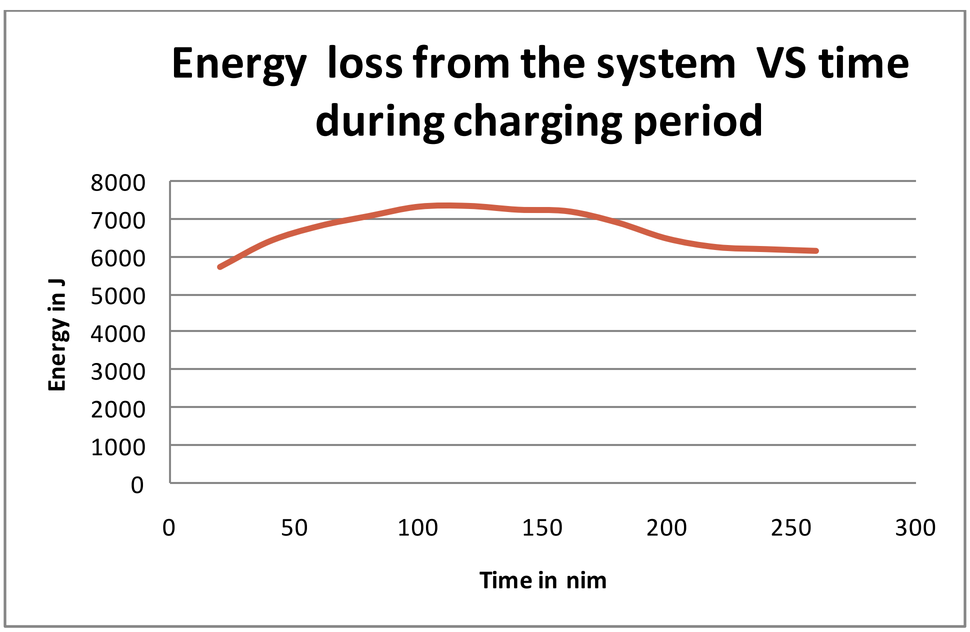
- Change in inlet and outlet HTF temperature during charging period of PCM-1



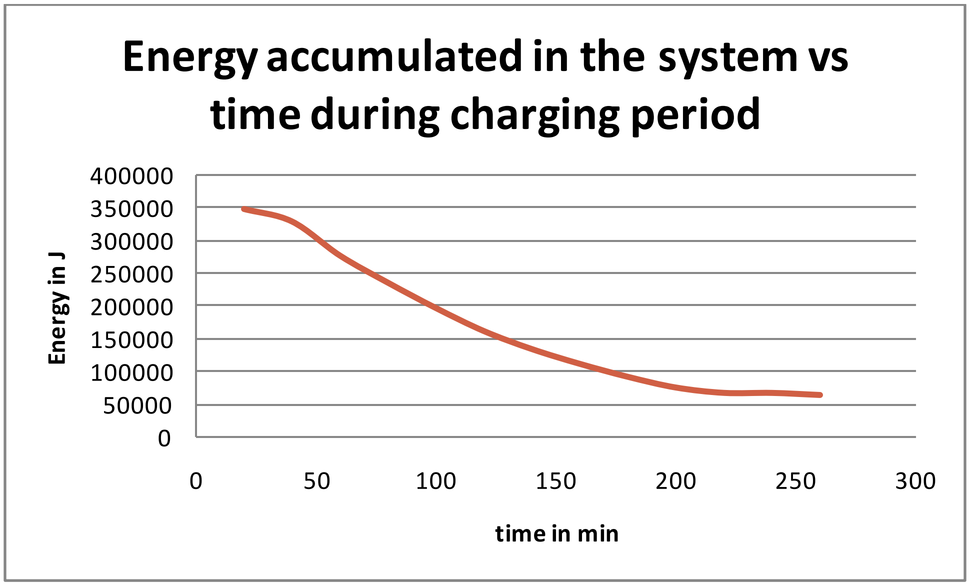
- Change in energy input to the system during charging period of PCM-1 (E_{in})



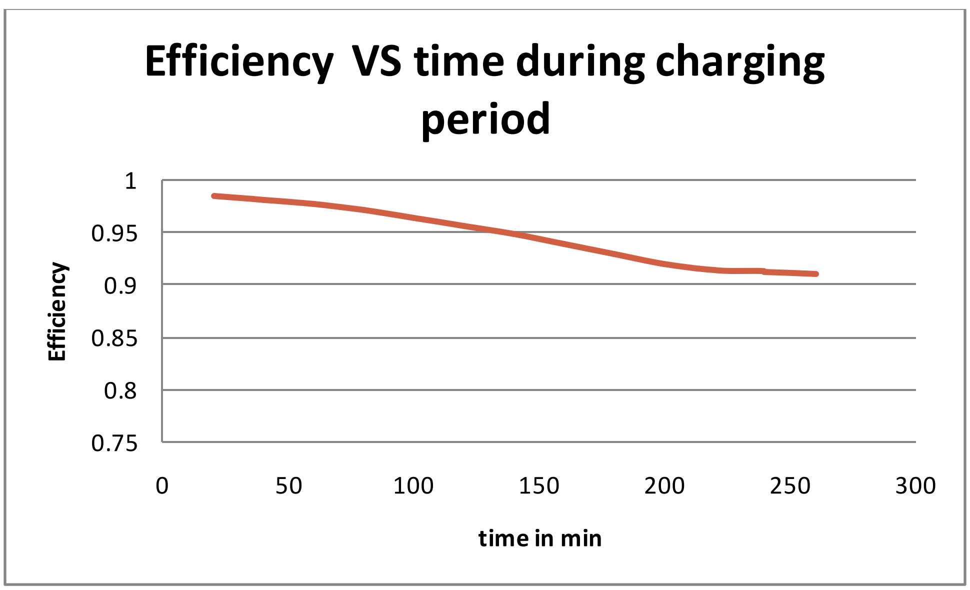
- Change in amount of energy from the PCM cylinder during charging period of PCM-1



- Change in energy accumulation in the system during charging period of PCM-1



- System thermal efficiency during charging period of PCM-1 (η_{ch})



- **Storing period analysis**

The period between the charging and discharging is the storing stage. In this stage the user need only to observed and calculate different parameters of the system.

Table-3: Observed values during energy storing period

SL NO.	Time in (min)	Ambient temperature $(T_{16})\,^0$C	PCM-1 front end temperature $(T_4)\,^0$C	PCM-1 rear end temperature $(T_5)\,^0$C
1	0			
6	60			

Calculation

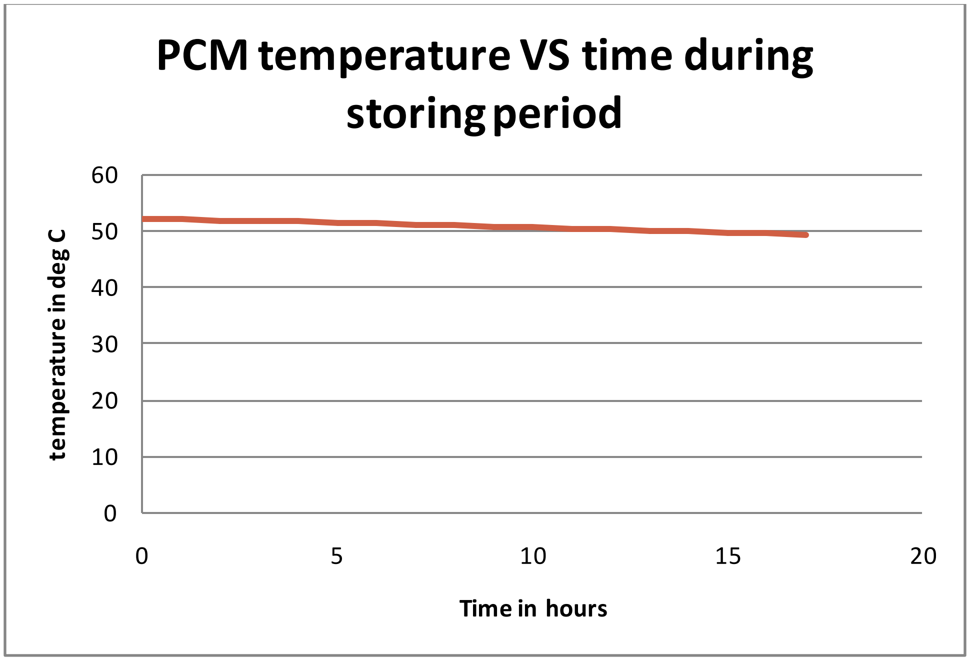
- Calculate Energy accumulation/loss in TES during storing by using equation (17)
- Calculate energy loss during storing period by using equation (18)
- Calculate storing period efficiency by using equation (19)

Table-4: Calculated values for PCM-1 during storing period

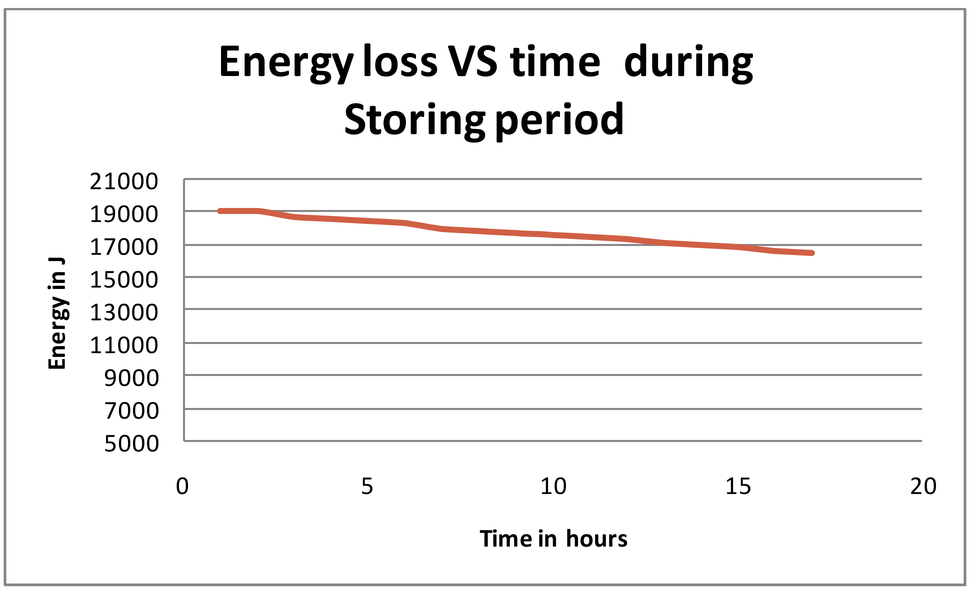
SL NO.	Time in (min)	Energy stored in the system during storing period (J)	Energy loss from the system during storing period (J)	System thermal efficiency during storing period η_{st}
1	0			
6	60			

Result:

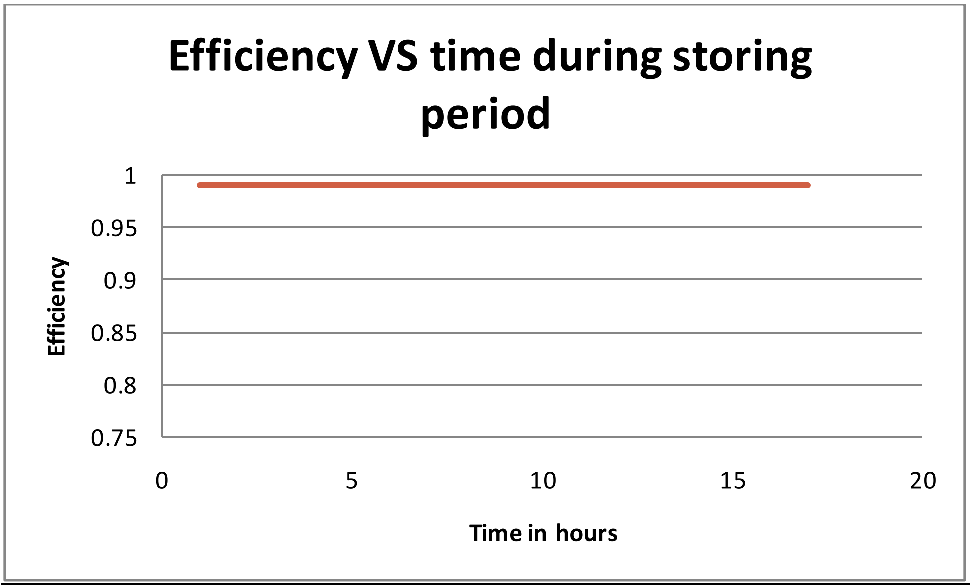
- Change in PCM-1 temperature during storing period ($T_{pcm,st}$)



- Change in energy loss from the system during energy storing period



- Change in System thermal efficiency during energy storing period (η_{st})



6.2 Discharging period Analysis of the system containing PCM-1

In this stage the energy stored in the PCM is extracted from the system to use in the load

Methodology

- Pre set the duration between charging and discharging
- To start the discharging process, open valve numbers 2 and 3 and fill the HTF hot/cold source tank fully with the help of the pump
- When water overflows the HTF hot/cold source tank switch off the pump and close all valves
- In empting the used HTF storage tank the user has two options either throw the water In choosing one of the above two options the user will have to decide the frequency experiments
- Note all readings corresponding to temperature sensors $T_{1,}$ T_2,T_3, T_4 , T_5 and T_{16}
- Open valve numbers 4,7&8 and allow the cold water to flow through cylinder containing PCM-1
- Adjust the flow rate by adjusting valve number 8. Keep adjusting at regular interval
- Note the temperature reading continuously corresponding to temperature sensors $T_{1,}$$T_2$,$T_3$, T_4, T_5 and T_{16} in a step of five minute
- Continue the above process till the PCM's temperaturebecome equal to the inlet water temperature (almost)
- To finish the discharging stage close valve numbers 4, 7 and 8.

- On completing the discharging process open valve number 13 and 14 empty the HTF hot/cold source tank completely

Observation during discharging period of PCM-1

Table-5: Observed values during discharging period of PCM-1

Sl No.	Time (t) min	Water temperature of HTF hot/cold source tank (T_{14}) ^{0}C	Ambient temperature (T_a= T_{16}) ^{0}C	Cylinder's surface temperature ($T_{s,cy}$=T_1) ^{0}C	Inlet temperature of water during discharging ($T_{i,HTF,dis}$ = $T2$)^{0}C	Outlet temperature of water during discharging ($T_{0,HTF,dis}$ = T_3) ^{0}C	PCM-1 front end temperature (T_4) ^{0}C	PCM-1 rear end temperature (T_5) ^{0}C	Water flow rate $\dot{m}$ ($\frac{kg}{sec}$)
1	0								
6	60								

Calculations

On completing the discharging stage the user can calculate/ observe the following aspects

- Calculate the Energy recovered from TES during discharging period by using equation (20)
- Calculate amount of energy available to discharge by using equation (21)
- Evaluate the system thermal efficiency during discharging of the system by using equation (23)
- Calculate the overall system efficiency (24)
- Calculate the value of FOM by using equation (25)

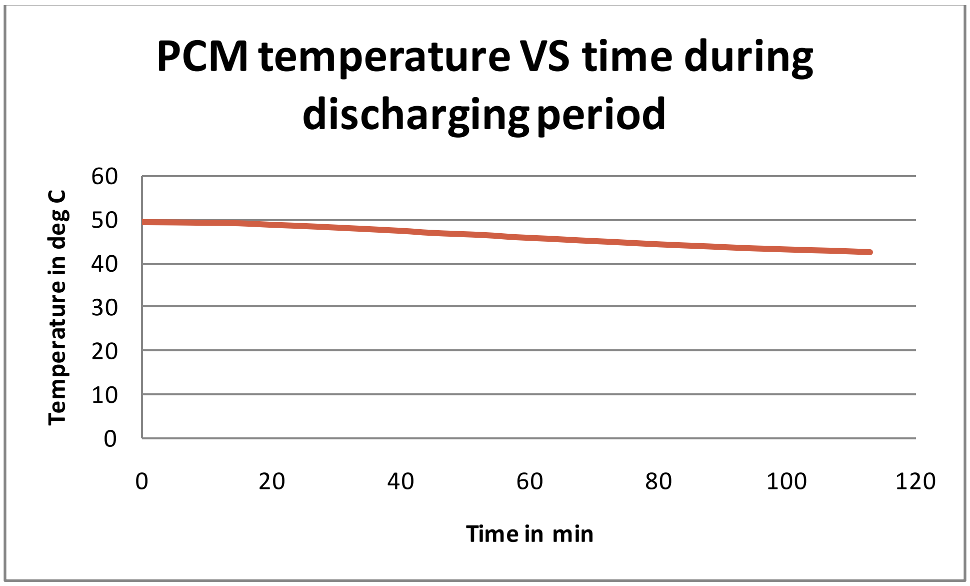
Table-6: Calculated values during discharging of PCM-1

SL NO.	Time in (min)	Energy loss from the system (J)	Energy available to discharge from the system (J)	Energy recovered from TES during discharging period E_{dis} (J)	system thermal efficiency during discharging period η_{dis}

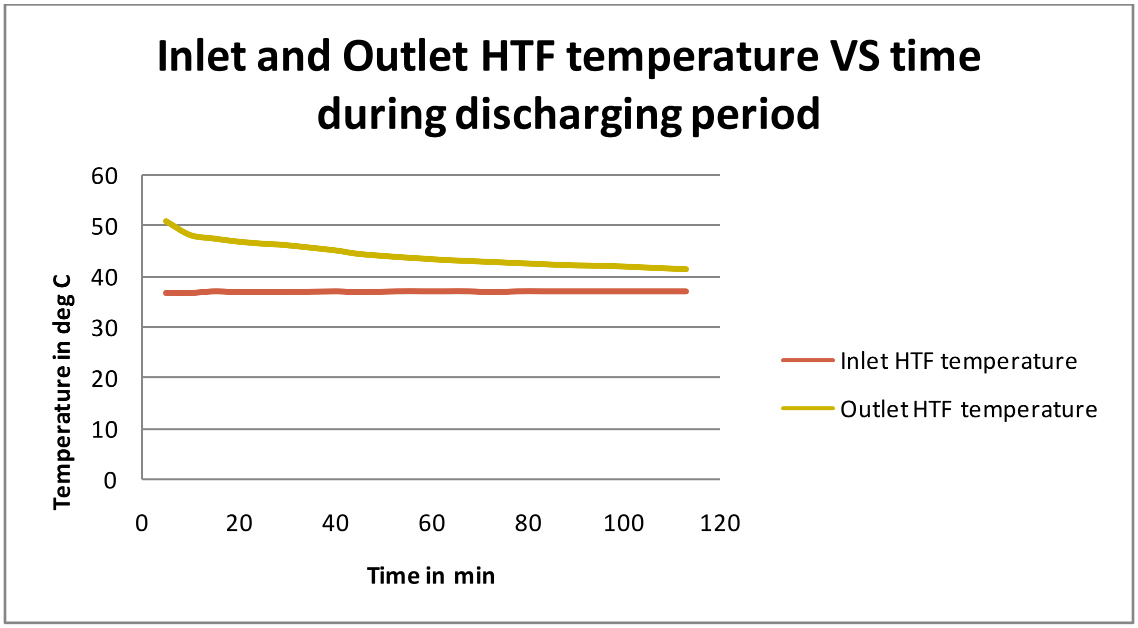
1	0				
6	60				

Result:

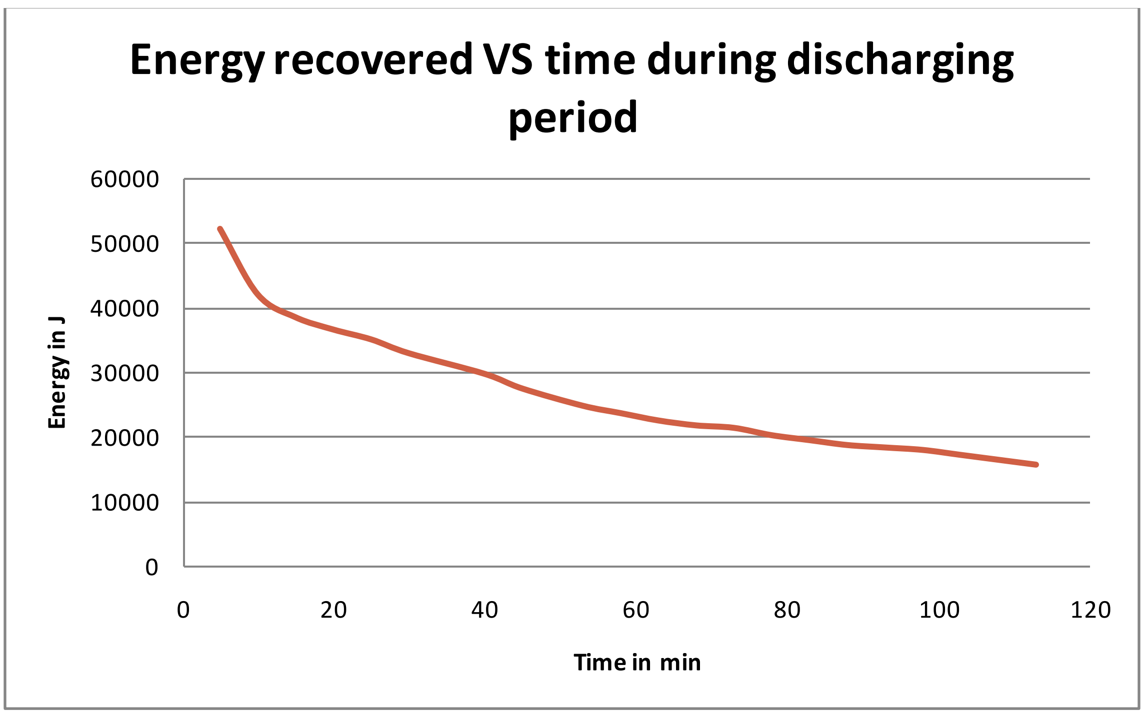
- Change in PCM-1 temperature ($T_{pcm,dis}$) during the discharging period



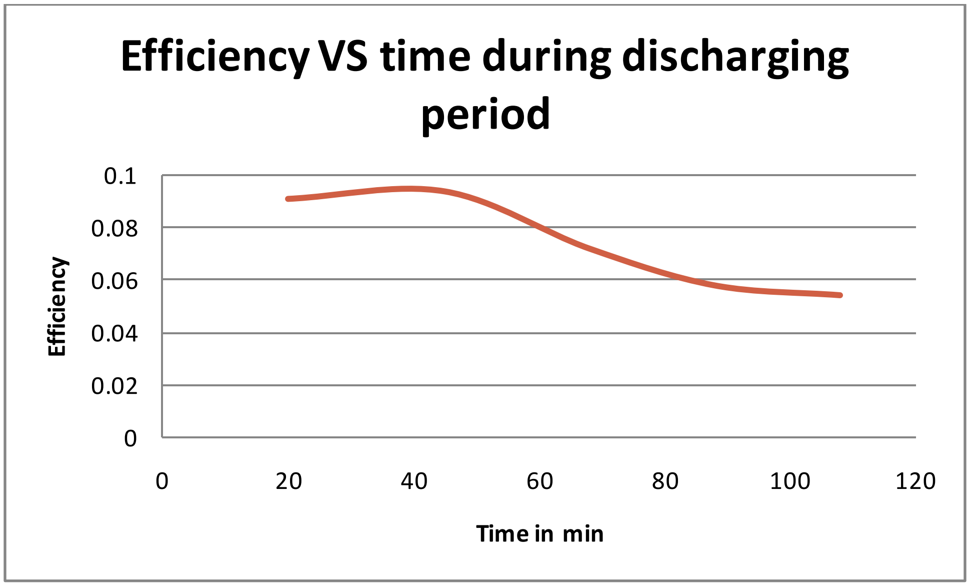
- Change in inlet and outlet water temperature during discharging ($T_{i,HTF,dis}$, $T_{o,HTF,dis}$) period of PCM-1



- Change in heat recovered with time during discharging period of PCM-1



- Change in system thermal efficiency with during discharging period of PCM-1


Efficiency VS time during discharging period
Efficiency
0.1
0.08
0.06
0.04
0.02
0
0
20
40
60
80
100
120
Time in min

Experiments number-2:

Experiment on PCM-2 (Paraffin wax)

6.3 Charging period analysis of the system containing PCM-2

Methodology

- Open valves 6 and fill the cold HTF storage tank fully
- Open valves 2 and 3 and fill the HTF hot/cold source tank by switching on the pump
- When water overflows the HTF hot/cold source tank and water start come back to the used HTF storage tank switch off the pump and closed all valves
- Switch on the electric heaters
- Observed the water temperature continuously on temperature meter
- When water in the HTF hot/cold source tank reached the required temperature switch off the heaters
- Note all reading corresponding to temperature sensors.
- Open valves 4,9 and 10 to flow the hot water through the heat exchanger
- Adjust the flow rate by adjusting the valve number 10. Keep adjusting at regular interval. (Maintain it at equal to experiment number 1)
- Note the temperature reading corresponding to temperature sensors
- Continue the above process till the average temperature of PCM reached melting temperature of PCM
- Once the above condition is achieved stop the charging stage by closing valve number's 4, 9 and 10.
- On completing the charging process open valve number 13, 14 and empty the HTF hot/cold source tank completely
- To bring the HTF hot/cold source tank to normal temperature wash it internally by cold water with the help of the pump

<u>Observation during charging period of PCM-2</u>

Table-7: Observed values during charging period of PCM-2

Sl No.	Time (t) mi	Water temperature of HTF hot/cold	Ambient temperature	Cylinder's surface temperature ($T_{s,cy}$ =T_1	Inlet temperature of HTF during charging	Outlet temperature of HTF during charging	PCM-2 front end temperature	PCM-2 rear end temperature (T_9)	Water flow rate $\dot{m}$ ($\frac{kg}{sec}$)

	n	source tank (T_{14}) ^{0}C	(T_a= T_{16}) ^{0}C	) ^{0}C	($T_{i,HTF,ch}$ = T_6)^{0}C	($T_{0,HTF,ch}$ = T_7) ^{0}C	(T_8) ^{0}C	^{0}C	
1	0								
6	60								

Calculations

On completing the charging stage the user can calculate/ observe the following aspects

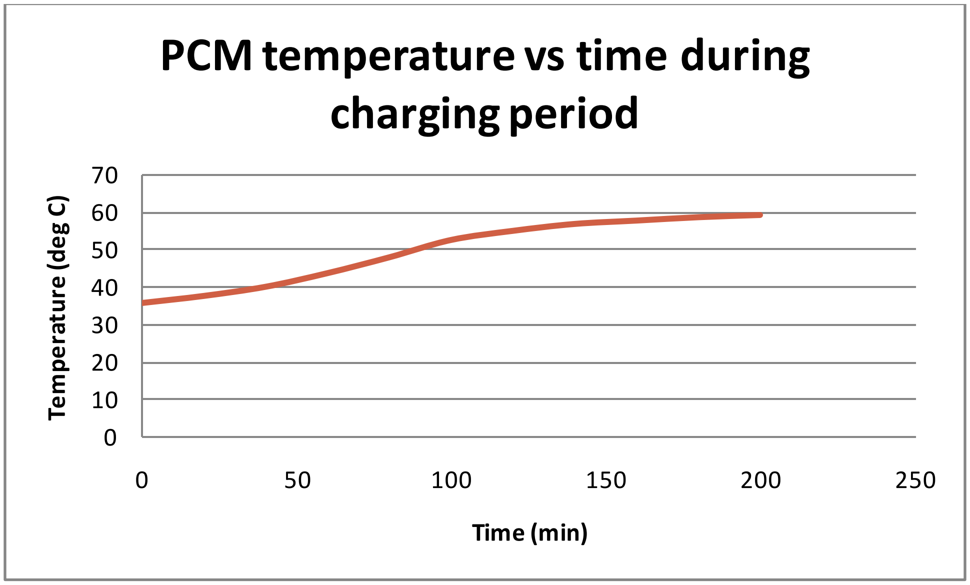
- Calculate rate of heat transfer from the cylinder by using equation (1) through (11)
- Calculate energy input to the TES system during charging period by using equation (12)
- Calculate energy accumulated in the TES system during charging period by using equation (13)
- Evaluate the system thermal efficiency during charging period by using equation (16)

Table-8: Calculated values during charging period of PCM-2

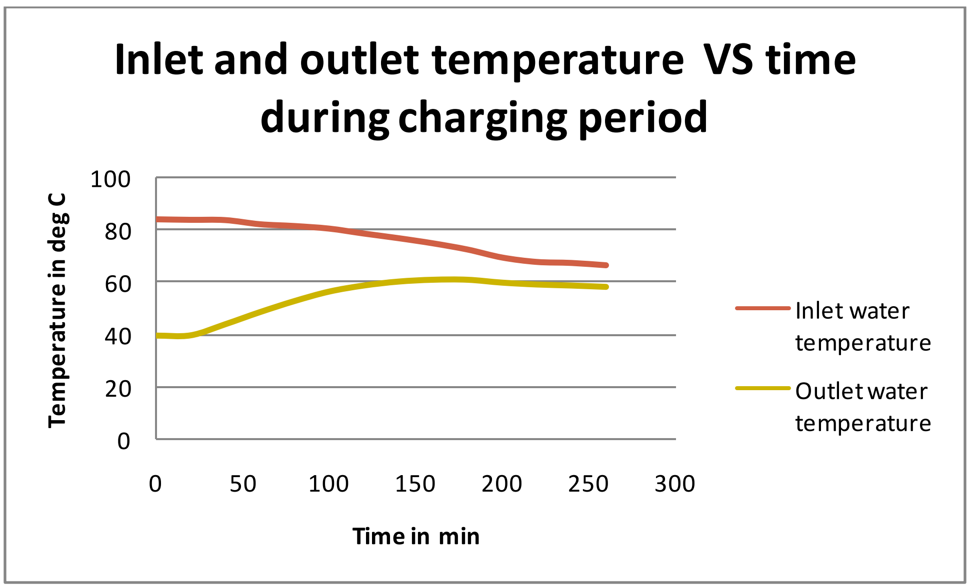
Sl No.	Time in (min)	Average temperature of PCM during charging period $T_{pcm,ch}$ (= $\frac{T_8+T_9}{2}$) ^{0}C	Energy loss from the system (J)	Energy input to the system during charging period E_{in} (kJ)	Energy accumulated in the system during charging period ΔE_1(kJ)	System thermal efficiency during charging period η_{ch}
1	0					
6	60					

Result:

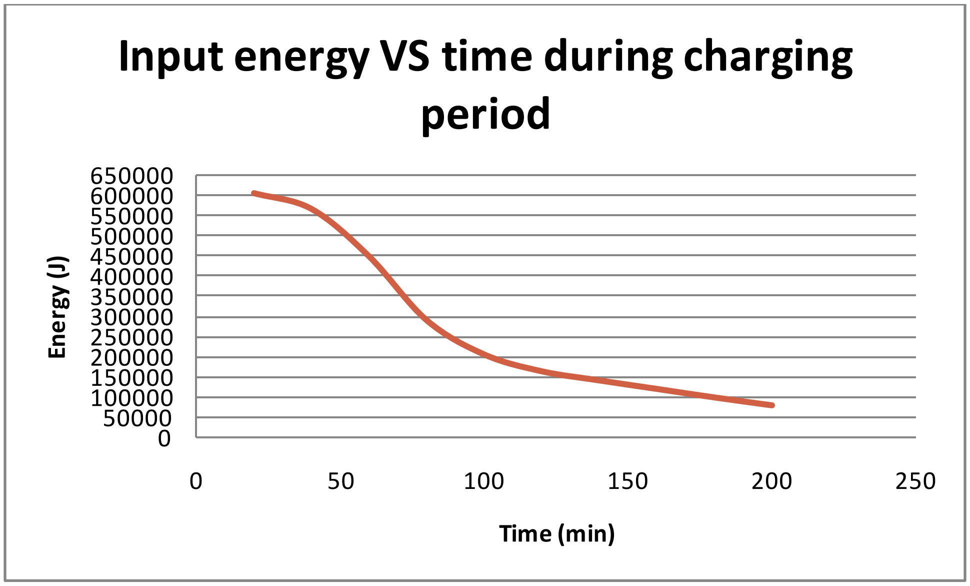
Change in PCM-2 temperature during the charging period ($T_{pcm,ch}$)



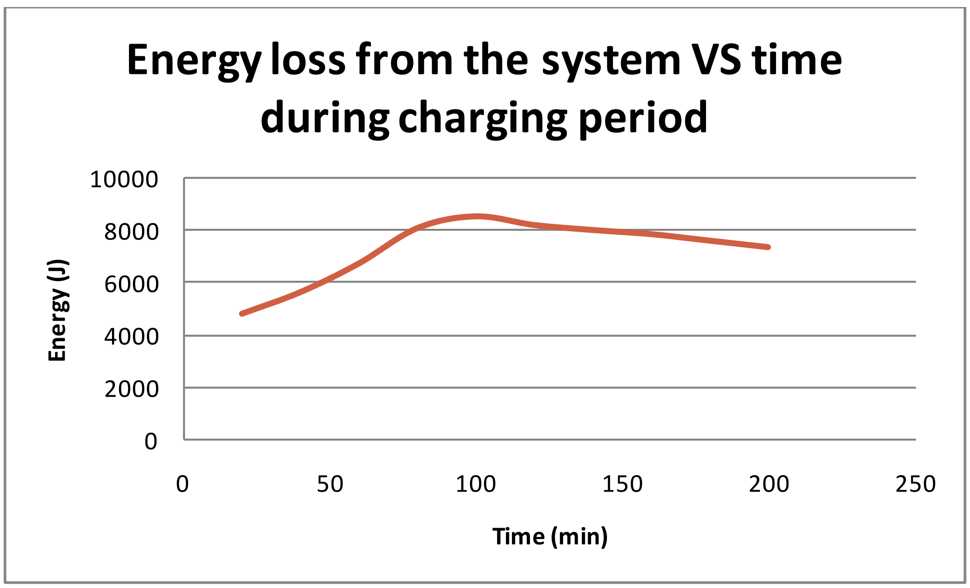
- Change in inlet and outlet HTF temperature during charging period of PCM-2



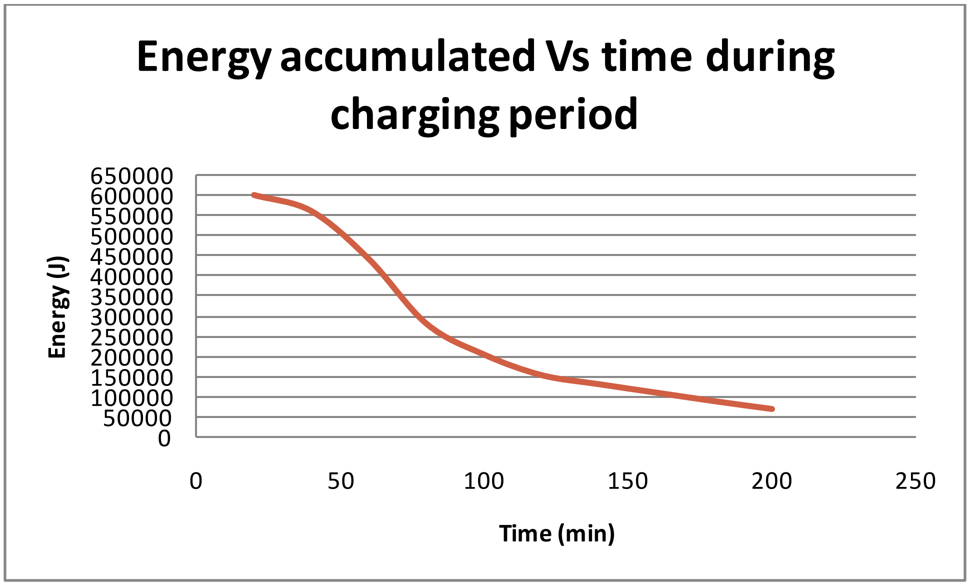
- Change in energy input to the system during charging period of PCM-2 (E_{in})



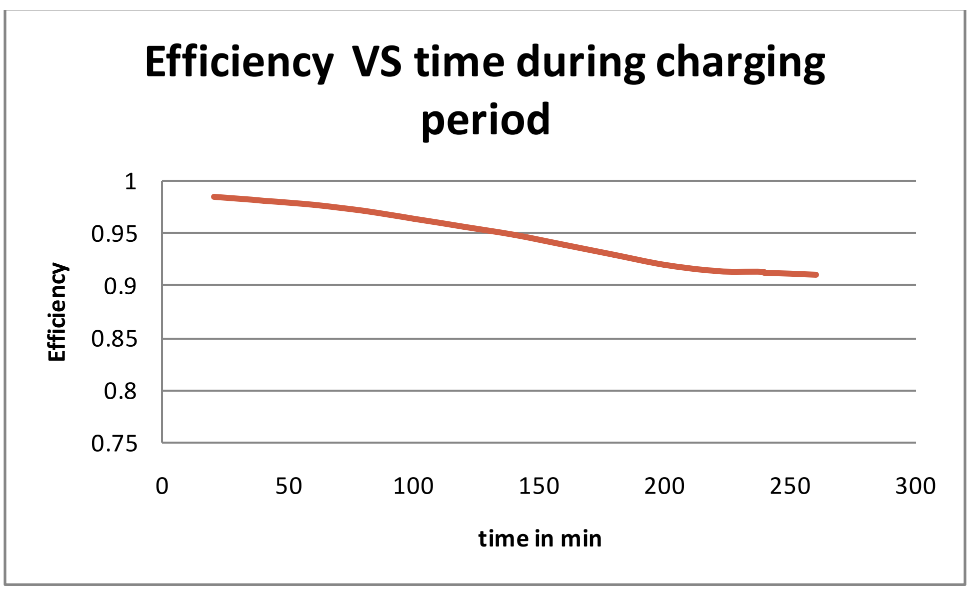
- Change in energy loss from the cylinder during charging period of PCM-2



- Change in energy accumulation in the system during charging period of PCM-2 (ΔE_1)



- System thermal efficiency during charging period of PCM-2 (η_{ch})



- **Storing period analysis**

Table-9: Observed values during energy storing period

SL NO.	Time in (min)	Ambient temperature $(T_{16})\,^0$C	PCM-2 front end temperature $(T_8)\,^0$C	PCM-2 rear end temperature (T_9) ^{0}C
1	0			
6	60			

Calculation

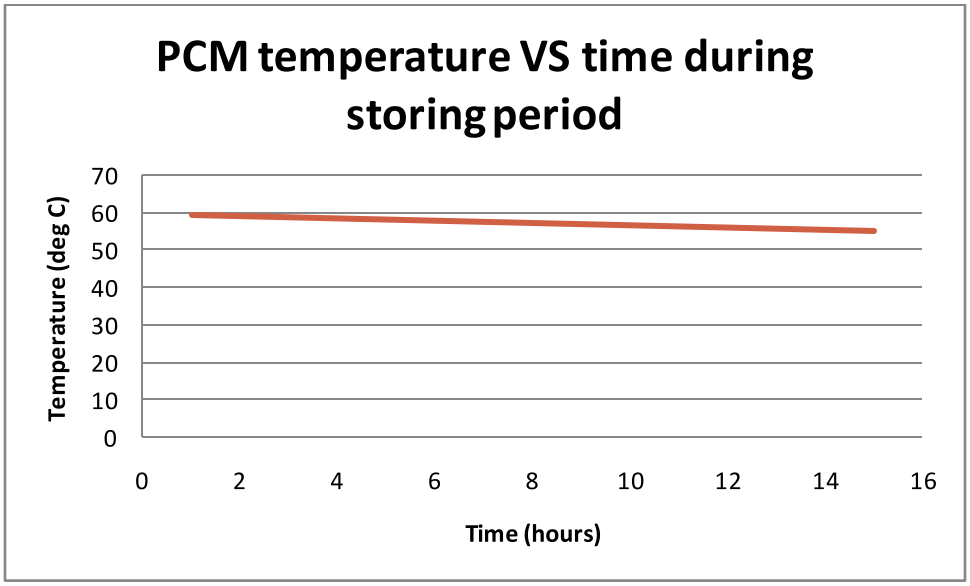
- Calculatein TES during storing by using equation (17)
- Calculate storing period efficiency by using equation (19)

Table-10: Calculated values for PCM-2 during energy storing period

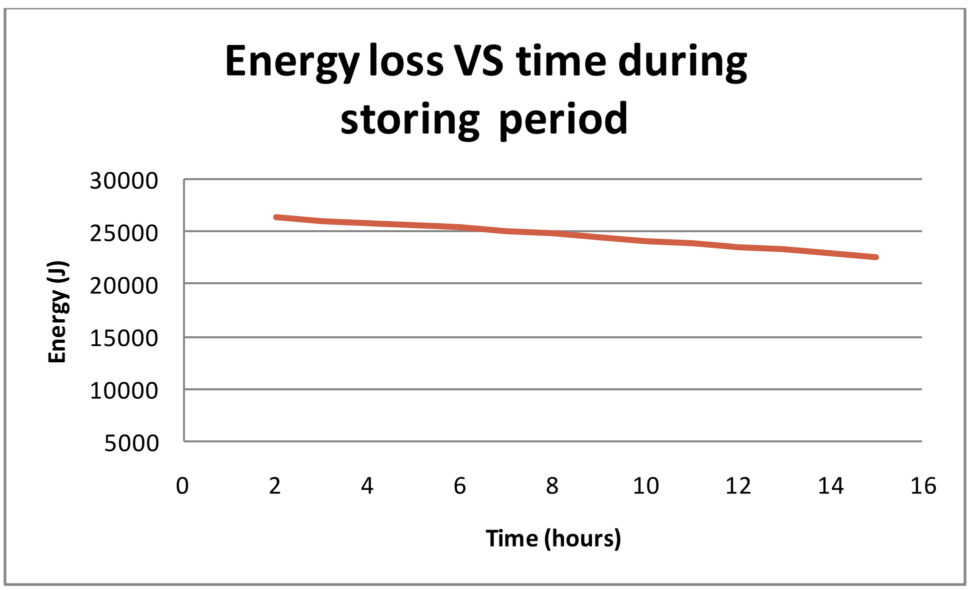
SL NO.	Time (min)	Energy loss from the system during storing period (J)	Energy stored in the system during storing period (J)	System thermal efficiency during storing period (η_{st})
1	0			
6	60			

Result:

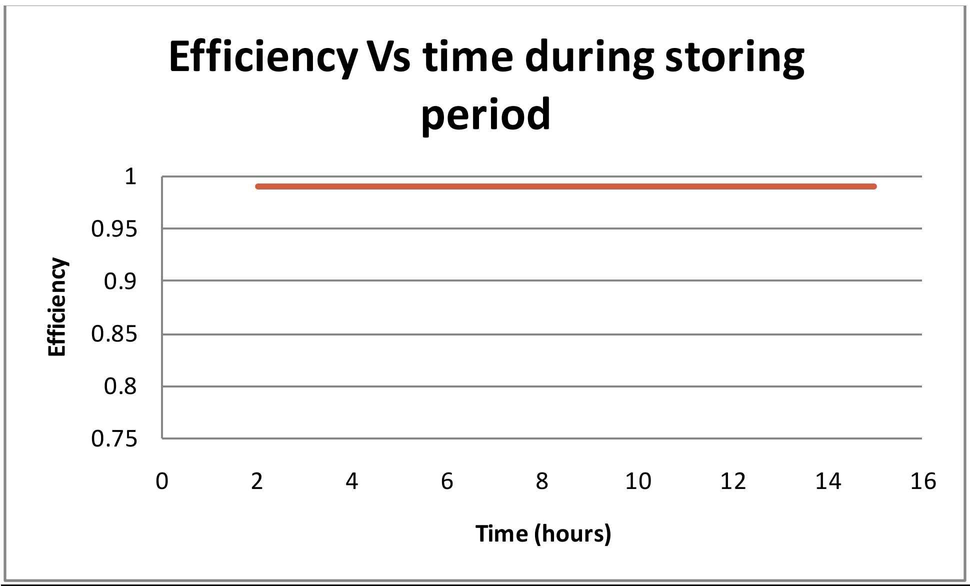
- Change in PCM-2 temperature during storing period ($T_{pcm,st}$)



- Change in energy loss from the system during energy storing period



- Change in System thermal efficiency during energy storing period (η_{st})



6.4 Discharging period Analysis

Methodology

- Preset the duration between charging and discharging
- To start the discharging process, open valve numbers 2 and 3 and fill the HTF hot/cold source tank fully with the help of the pump
- When water overflows the HTF hot/cold source tank switch off the pump and close all valves
- Open valve numbers 5, 1 and 6; empty the used HTF storage tank by switching the pump on.
- In choosing one of the above two options the user will have to decide the frequency experiments
- Note all readings corresponding to temperature sensors.
- Open valve numbers 4, 9&10 to flow through cylinder containing PCM-2
- Adjust the flow rate by adjusting valve number 12
- Note the temperature reading continuously corresponding to temperature sensors
- Continue the above process till the PCM's temperaturebecome equal to the inlet water temperature (almost)
- To finish the discharging stage close valve numbers 4, 9 and 10

- On completing the discharging process open valve number 13,14 and empty the HTF hot/cold source tank completely

Observation during discharging period of PCM-2

Table-11: Observed values during discharging period of PCM-2

Sl No.	Time (t) min	Water temperature of HTF hot/cold source tank (T_{14}) ^{0}C	Ambient temperature (T_a= T_{16}) ^{0}C	Cylinder's surface temperature ($T_{s,cy}$ =T_1) ^{0}C	Inlet temperature of water during discharging ($T_{i,HTF,dis}$ = $T6$)^{0}C	Outlet temperature of water during discharging ($T_{0,HTF,dis}$ = T_7) ^{0}C	PCM-2 front end temperature (T_8) ^{0}C	PCM-2 rear end temperature (T_9) ^{0}C	Water flow rate $\dot{m}$ ($\frac{kg}{sec}$)
1	0								
6	60								

Calculations

On completing the discharging stage the user can calculate/ observe the following aspects

- Calculate the Energy recovered from TES during discharging period by using equation (20)
- Calculate amount of energy available to discharge by using equation (21)
- Evaluate the system thermal efficiency during discharging of the system by using equation (23)
- Calculate the overall system efficiency (24)
- Calculate the value of FOM by using equation (25)

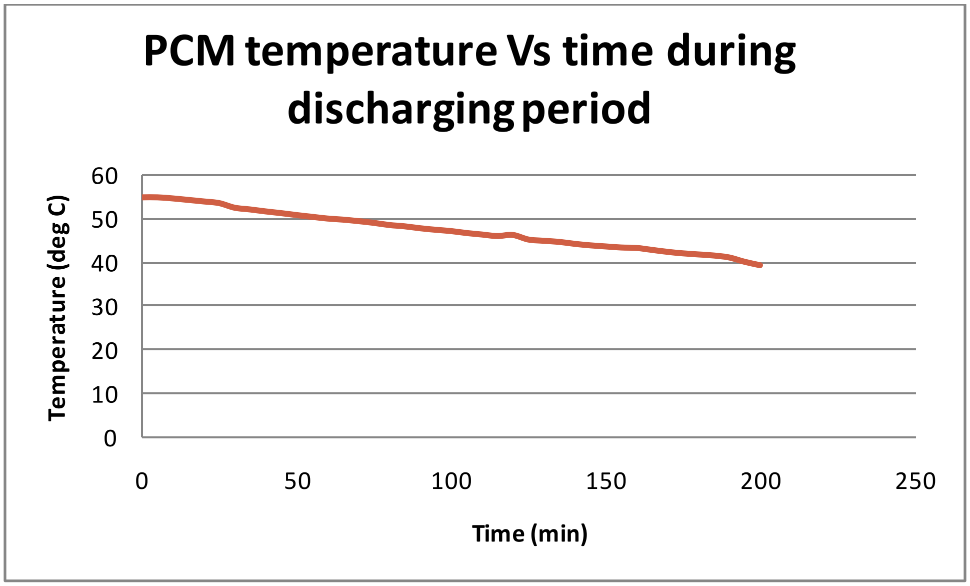
Table-12: Calculated values during discharging of PCM-2

SL NO.	Time in (min)	Energy loss from the system	Energy available to recover from the	Energy recovered from TES during discharging period E_{dis} (kJ)	system thermal efficiency during discharging period η_{dis}

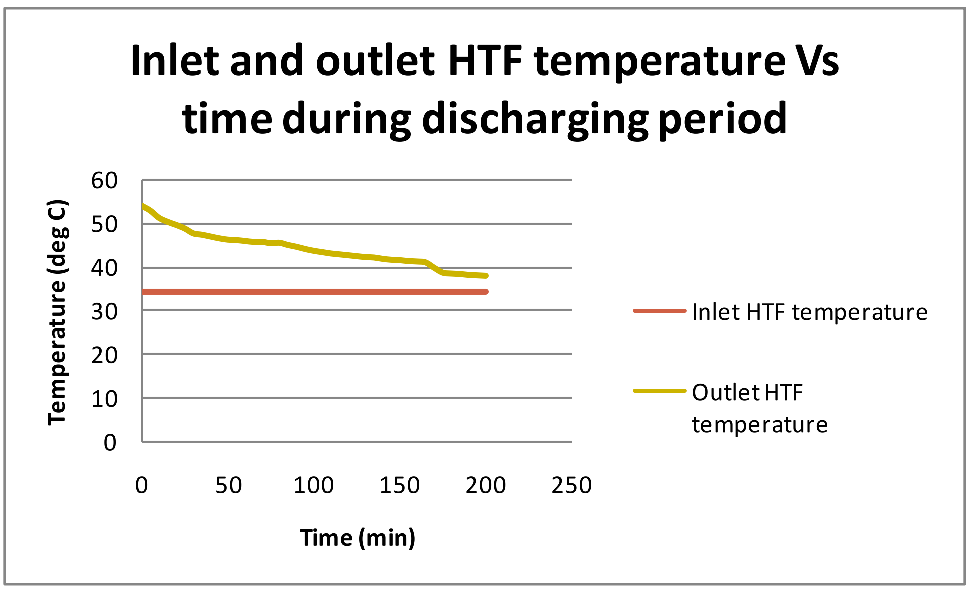
		(J)	system (J)		
1	0				
6	60				

Result:

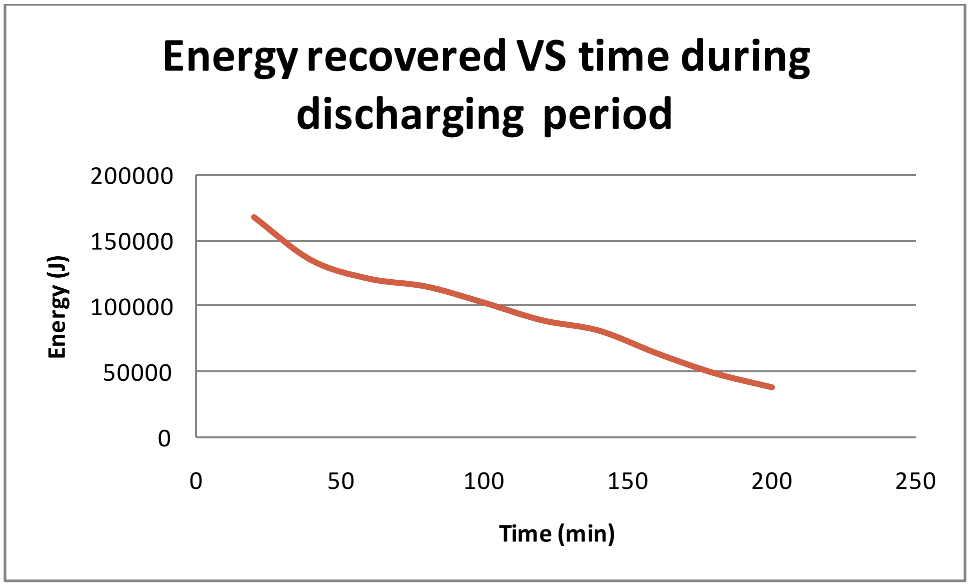
- Change in PCM-2 temperature ($T_{pcm\ ,dis}$) during the discharging period



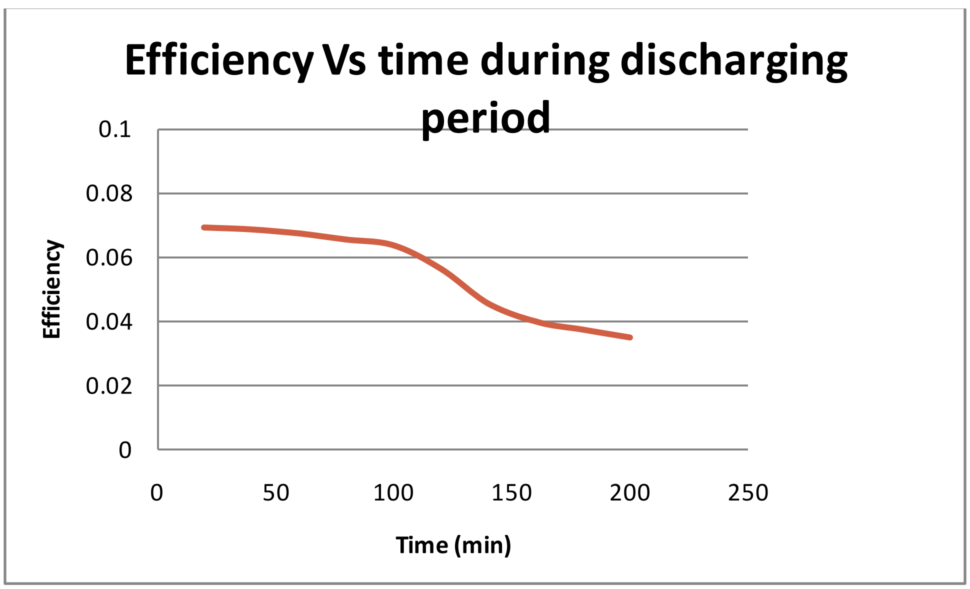
- Change in inlet and outlet water temperature during discharging $(T_{i,HTF,dis}, T_{o,HTF,dis})$ period of PCM-2



- Change in heat recovered with time during discharging period of PCM-2



- Change in system thermal efficiency with during discharging period of PCM-2



Experiments no.-3:

Experiment on PCM-1 & 2 in cascading (paraffin plus Fatty acid, unmixed)

6.5 Charging period analysis of the system containing PCM-1&2 in cascading

Methodology

- Open valve 6 and fill the cold HTF storage tank fully
- Open valves 2 and 3 and fill the HTF hot/cold source tank by switching on the pump
- When water overflows the HTF hot/cold source tank and water start come back to the used HTF storage tank switch off the pump and closed all valves
- Switch on the electric heaters
- Observed the water temperature continuously on temperature meter (keep equal to experiments number 1 and 2 for comparison)
- When water in the HTF hot/cold source tank reached the required temperature switch off the heaters
- Note all readings corresponding to temperature sensors
- Open valves 4,11 and 12 to flow hot water through the heat exchanger
- Set the flow rate by adjusting the valve number 12 (keep equal to experiments number 1 and 2 for comparison)
- Note the temperature reading corresponding to temperature in a step of twenty minute
- Continue the above process till the temperature of PCM reached above the melting temperature of the respective PCM's
- Once the above condition is achieved stop the charging stage by closing valve number's 4,11 and 12
- On completing the charging process open valve number 13,14 and empty the HTF hot/cold source tank completely
- To bring the HTF hot/cold source tank to normal temperature wash it internally by cold water with the help of the pump

<u>Observation during charging period of the system containing PCM-1&2 in cascading</u>

Table-13: Observed values during charging period of PCM-1&2 in cascading

Sl. No.	Time (t) min	Water temperature of HTF hot/cold source tank (T_{14})	Ambient temperature (T_a=	Cylinder's surface temperature ($T_{s,cy}=T_1$	Inlet temperature of HTF during charging ($T_{i,HTF,ch}$ =	Outlet temperature of HTF during charging ($T_{0,HTF,ch}$ =	PCM-1 temperature (T_{12})^0	PCM-1 temperature (T_{13})	Water flow rate $\dot{m}$ ($\frac{kg}{sec}$)

		^{0}C	T_{16}) ^{0}C	) ^{0}C	T_{10})^{0}C	T_{11}) ^{0}C	C	^{0}C	
1	0								
6	60								

Calculations

On completing the charging stage the user can calculate/ observe the following aspects

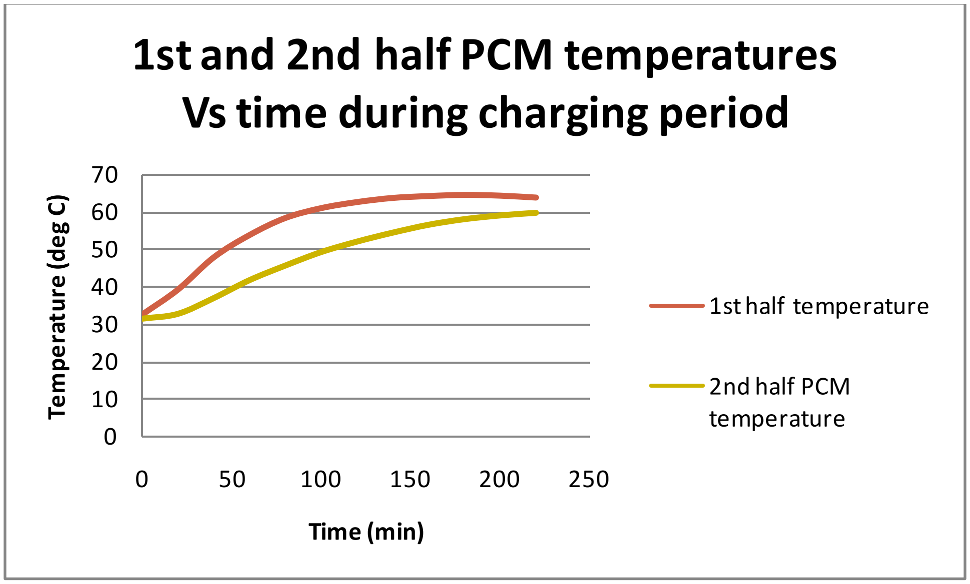
- Calculate rate of heat transfer from the cylinder by using equation (1) through (11). Take average value of the two PCM's wherever required
- Calculate energy input to the TES system during charging period by using equation (12)
- Calculate energy accumulated in the TES system during charging period by using equation (13). Calculate it for both the PCM's separately. Use overall value in calculating the thermal efficiency
- Evaluate the system thermal efficiency during charging period by using equation (16)

Table-14: Calculated values during charging period of PCM-1&2 in cascading

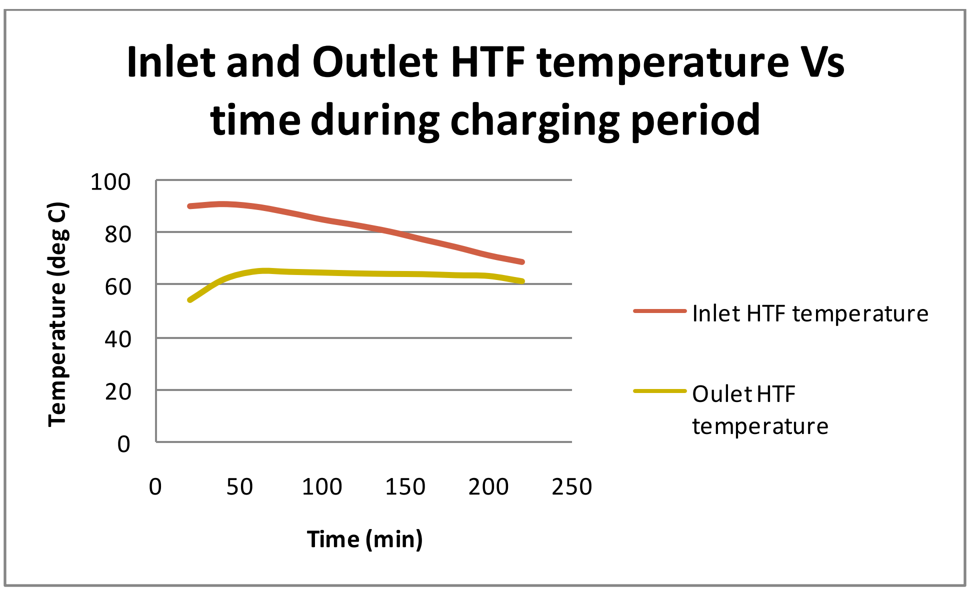
SL NO.	Time in (min)	Energy input to the system (J)	Total Energy loss from the system (J)	Total energy accumulated in the system (J)	system thermal efficiency during charging period (η_{ch})
1	0				
6	60				

Result:

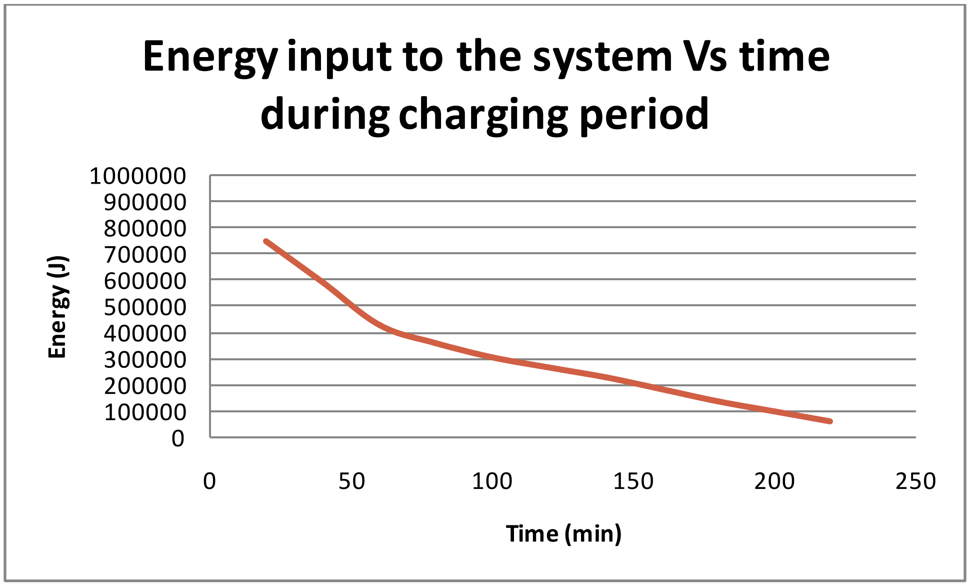
- Change in temperature of the 1st half and 2nd half PCM during the charging period



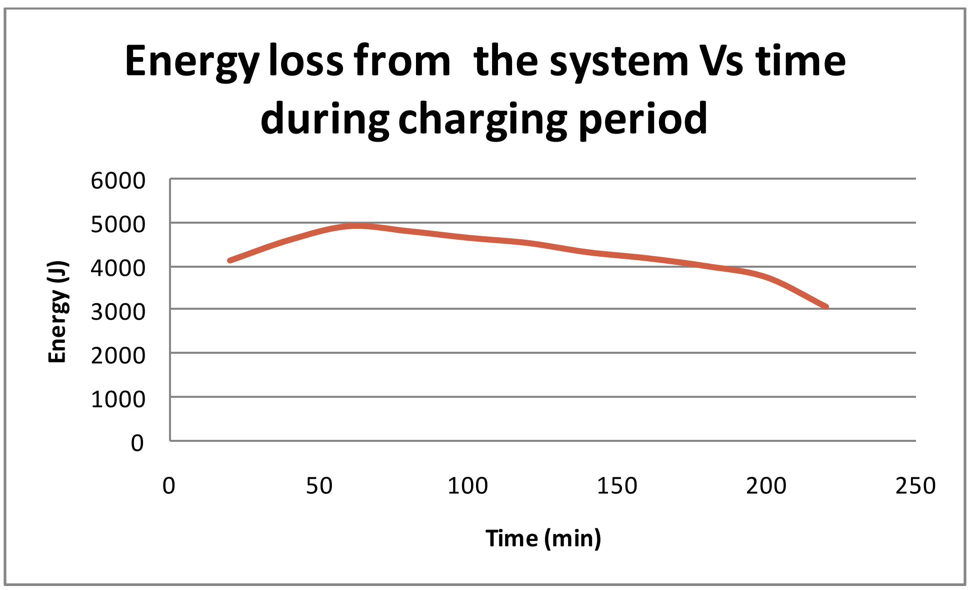
- Change in inlet and outlet HTF temperature during charging period of PCM-1&2 in cascading



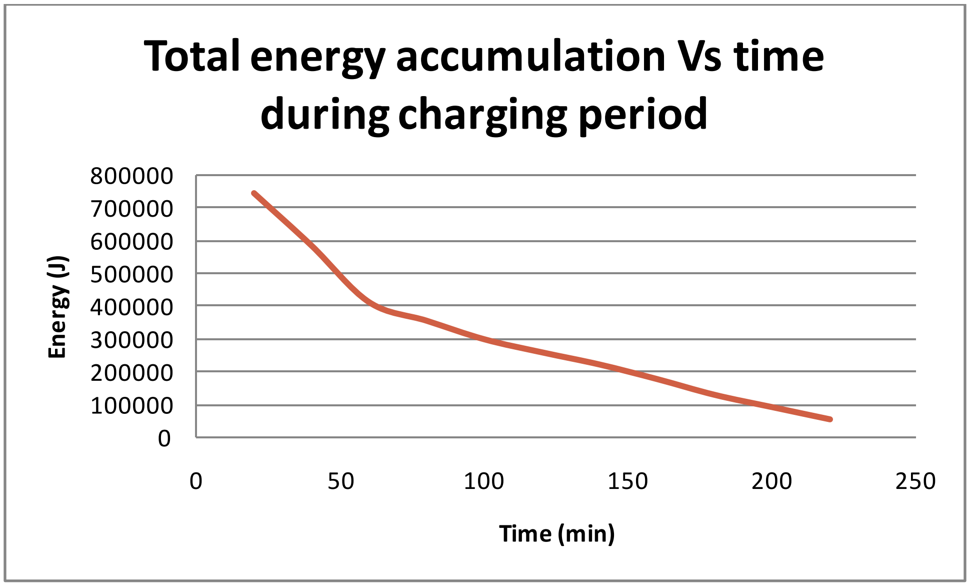
- Change energy input to the system during charging period of PCM-1&2 in cascading



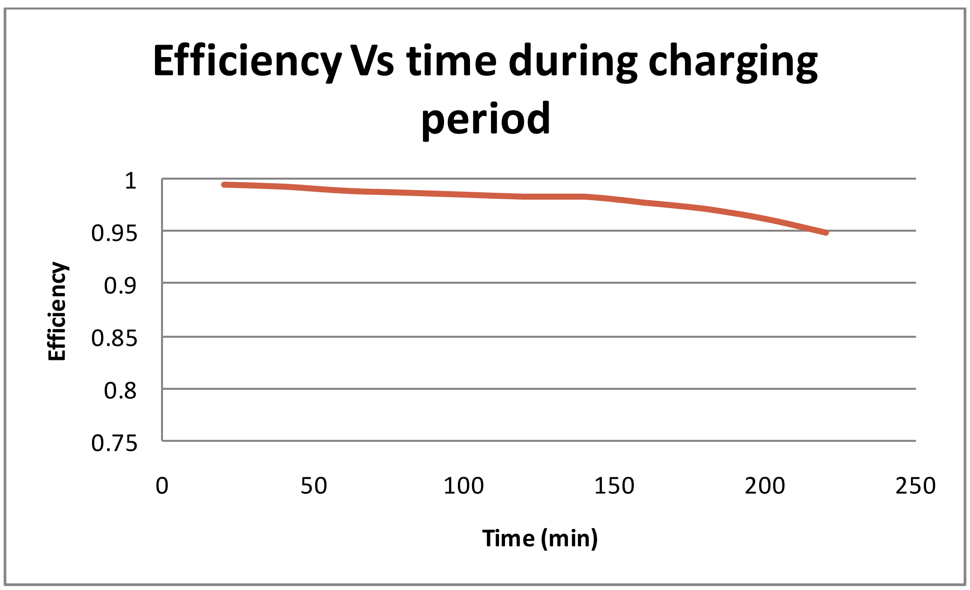
- Change in energy loss from the system during charging period of PCM-1&2 in cascading



- Change in total energy accumulation in the system during charging period of PCM-1&2 in cascading



- System thermal efficiency during charging period of PCM-1&2 in cascading (η_{ch})



- **Storing period analysis**

Table-15: Observed values during energy storing period

SL NO.	Time (hours)	Ambient temperature (T_{16}) ^{0}C	1st half PCM temperature (T_{12}) ^{0}C	2nd half PCM temperature (T_{13}) ^{0}C
1	0			
6	60			

Calculation

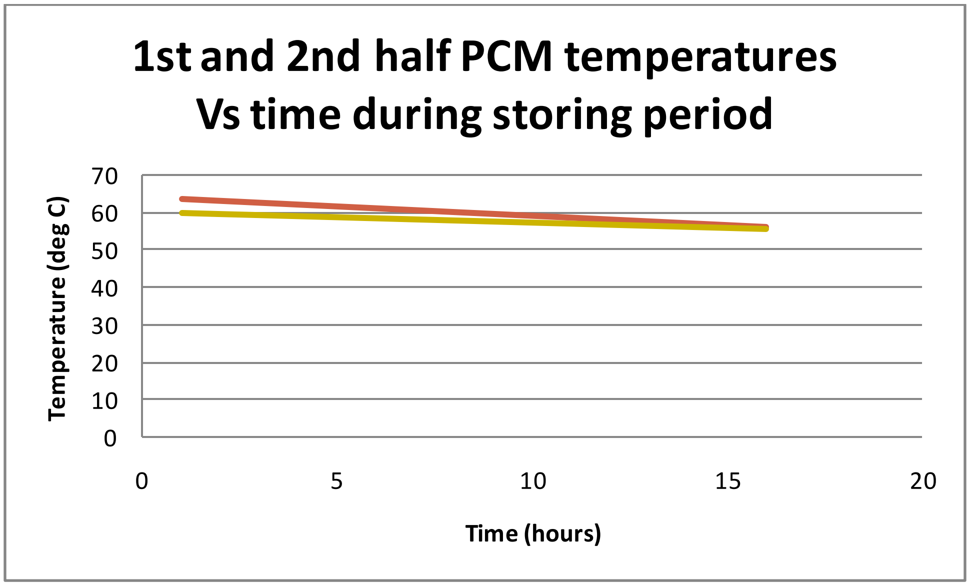
- Calculate Energy accumulation/loss in TES during storing by using equation (17). Take average values wherever required
- Calculate storing period efficiency by using equation (19)

Table-16: Calculated values for PCM-1&2 in cascading during storing period

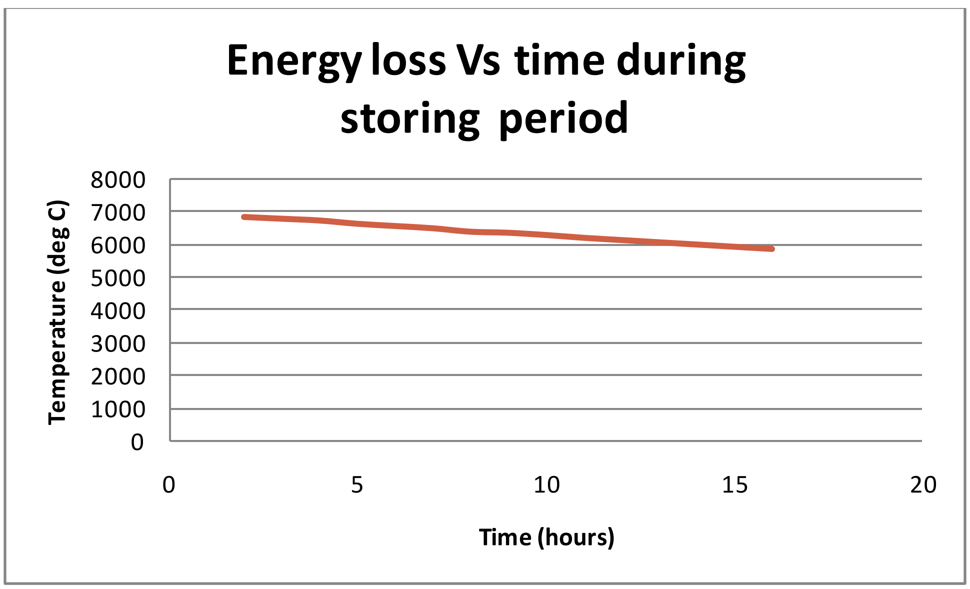
SL NO.	Time (hours)	Total Energy loss from the system during storing period (J)	Total energy stored in the system (J)	System thermal efficiency during storing period (η_{st})
1	0			
6	60			

Result:

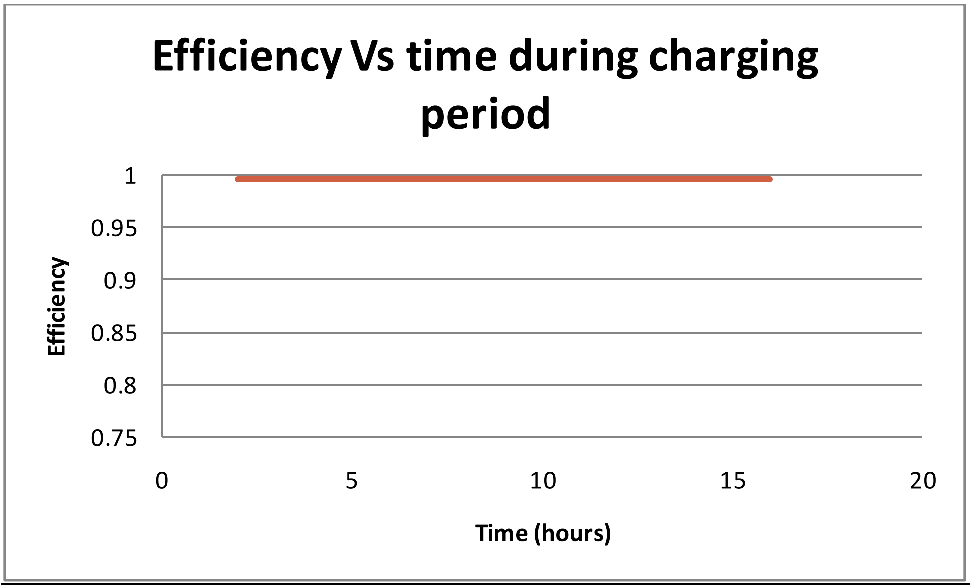
- Change in 1st and 2nd half PCM temperatures during storing period



- Change in energy loss from the system during energy storing period



- Change in System thermal efficiency during energy storing period (η_{st})



6.6 Discharging period Analysis of the system having PCM-1&2 in cascading

Methodology

- Preset the duration between charging and discharging
- To start the discharging process, open valve numbers 2 and 3 and fill the HTF hot/cold source tank fully with the help of the pump
- When water overflows the HTF hot/cold source tank switch off the pump and close all valves
- In empting the used HTF storage tank the user has two options either throw the water to environment by opening the valve 5 or sent to the cold HTF storage tank by opening the valve 6
- In choosing one of the above two options the user will have to decide the frequency experiments
- Note all readings corresponding to temperature sensors
- Open valve numbers 4, 11 & 12 and allow the cold water to flow through cylinder containing PCM-1&2 in cascading
- Adjust the flow rate by adjusting valve number 12 (keep this value equal to the above experiments for comparison)
- Note the temperature reading continuously corresponding to temperature sensors in a step of twenty minute
- Continue the above process till the PCM's temperaturebecome equal to the inlet water temperature (almost)

- To finish the discharging stage close valve numbers 4, 13 and 14
- On completing the discharging process open valve number 15 and empty the HTF hot/cold source tank completely

<u>Observation during discharging period of the system having PCM-1&2 in cascading</u>

Table-17: Observed values during discharging period of PCM-1&2 in cascading

Sl No.	Time (t) min	Water temperature of HTF hot/cold source tank (T_{14}) ^{0}C	Ambient temperature (T_a= T_{16}) ^{0}C	Cylinder's surface temperature ($T_{s,cy}$ =T_1) ^{0}C	Inlet temperature of water during discharging ($T_{i,HTF,dis}$ = $T2$)^{0}C	Outlet temperature of water during discharging ($T_{0,HTF,dis}$ = T_3) ^{0}C	1st half PCM temperature (T_{12}) ^{0}C	2nd half PCM temperature (T_{13}) ^{0}C	Water flow rate $\dot{m}$ ($\frac{kg}{sec}$)
1	0								
6	60								

<u>Calculations</u>

On completing the discharging stage the user can calculate/ observe the following aspects

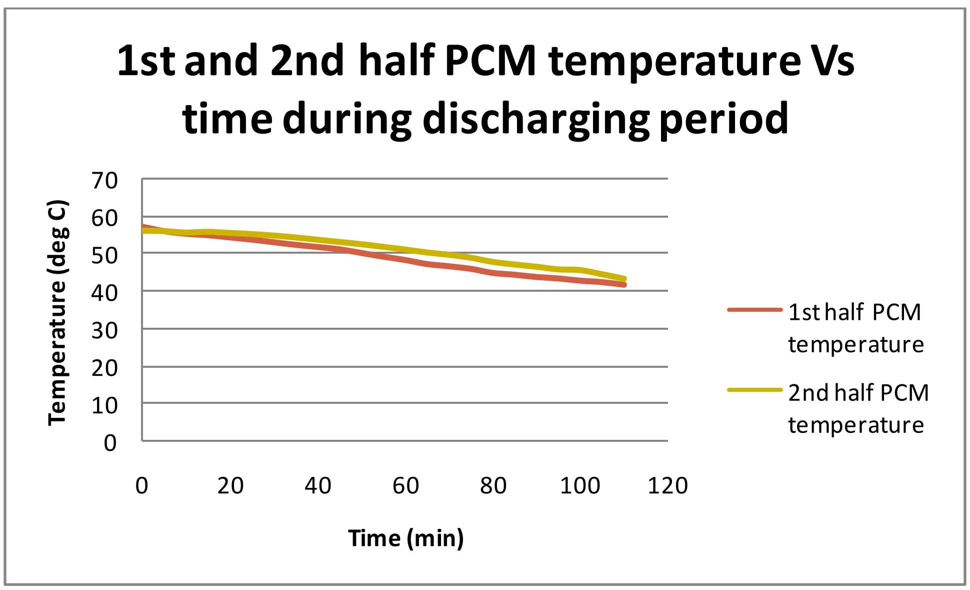
- Calculate the Energy recovered from TES during discharging period by using equation (20)
- Calculate amount of energy available to discharge by using equation (21)
- Evaluate the system thermal efficiency during discharging of the system by using equation (23)
- Calculate the overall system efficiency (24)
- Calculate the value of FOM by using equation (25)

Table-18: Calculated values during discharging of PCM-1&2 in cascading

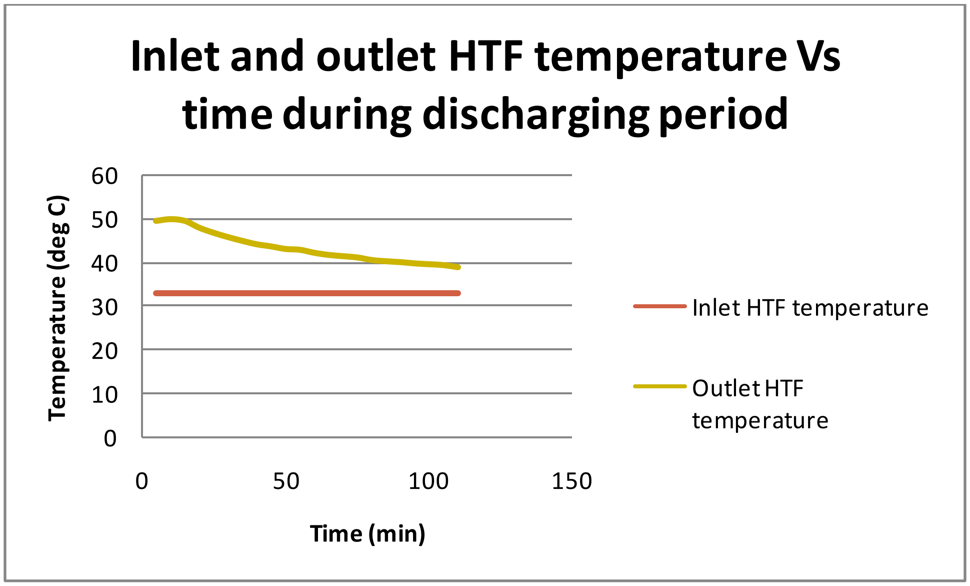
SL NO.	Time in (min)	Average temperature of PCM during discharging period $T_{pcm,dis}$ $(=\frac{T_{12}+T_{13}}{2})$ ^{0}C	Energy loss from the system (J)	Energy available to recover from the system (J)	Energy recovered from TES during discharging period E_{dis} (J)	system thermal efficiency during discharging period (η_{dis})
1	0					
6	60					

Result:

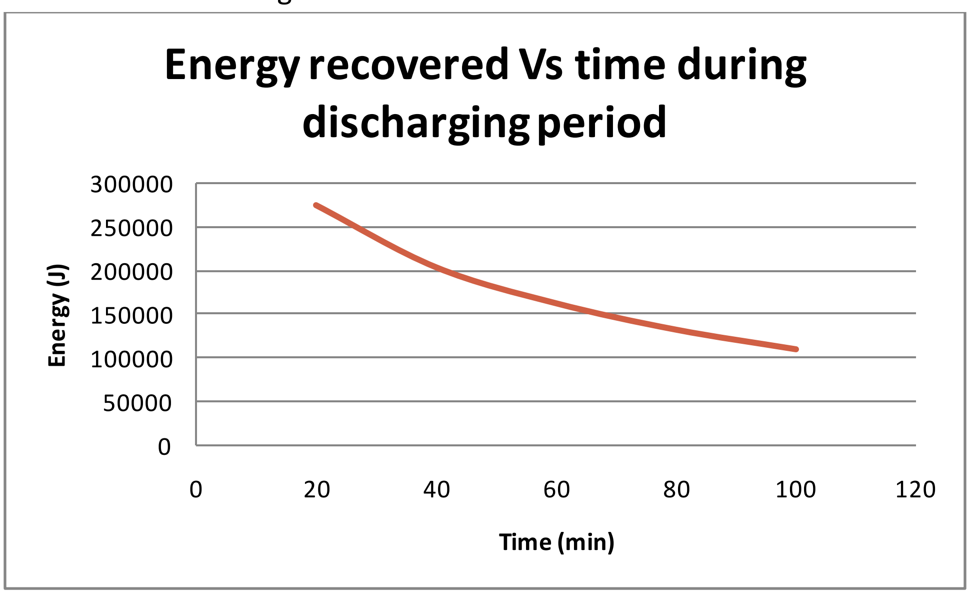
- Change in 1stand 2ndhalf PCM temperature during the discharging period of the system containing PCM-1 &2 in cascading



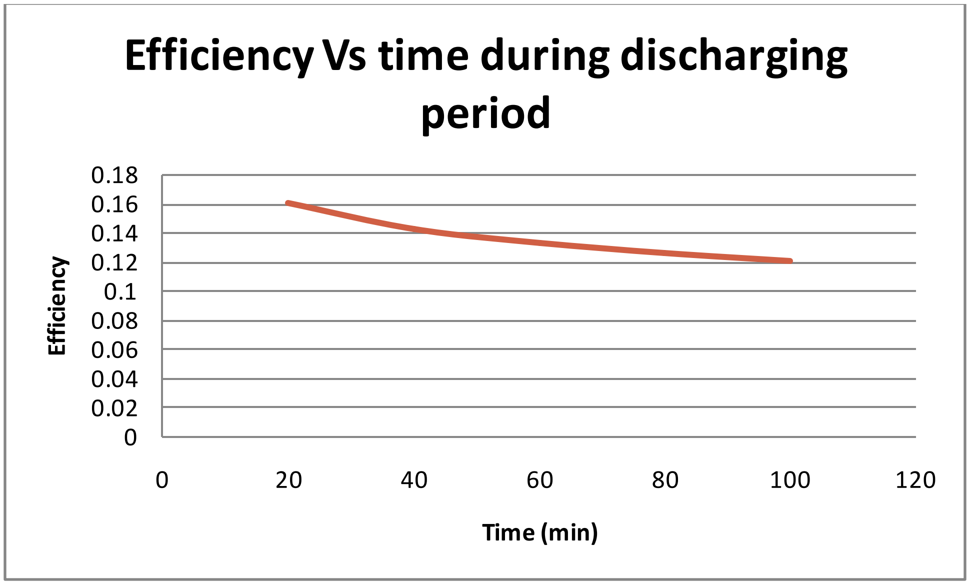
- Change in inlet and outlet water temperature ($T_{i,HTF,dis}$, $T_{o,HTF,dis}$) during discharging period of the system containing PCM-1&2 in cascading



- Change in heat recovered with time during discharging period of the system containing PCM-1&2 in cascading



- Change in system thermal efficiency with during discharging period of the system containing PCM-1&2 in cascading



Experiments no.-4:

6.7 Experiment on PCM-1 (paraffin based) with different HTF flow rate during charging and discharging

In this experiment the user will have to perform all the sub-processes with at least three flow rates of the HTF

- 1st flow rate (10 LPH)

- **<u>Charging period analysis of the system containing PCM-1</u>**

Methodology

- Same as charging stage of experiment number-1 except setting the flow rate at 10 LPHby adjusting the valve number 8.
- Adjust the valve number at regular interval to maintain the flow rate at the required value

<u>Observation during charging period of the system containing PCM-1 with HTF flow rate (10 LPH)</u>

Table-19: Observed values during charging period of the system containing PCM-1 corresponding to flow rate (10 LPH)

Sl No.	Time (t) min	Water temperature of HTF hot/cold source tank (T_{14}) ^{0}C	Ambient temperature (T_a= T_{16}) ^{0}C	Cylinder's surface temperature ($T_{s,cy}$ = T_1) ^{0}C	Inlet temperature of HTF during charging ($T_{i,HTF,ch}$ = $T2$)^{0}C	Outlet temperature of HTF during charging ($T_{0,HTF,ch}$ = T_3) ^{0}C	PCM-1 front end temperature (T_4) ^{0}C	PCM-1 rear end temperature (T_5) ^{0}C	Water flow rate $\dot{m}$ ($\frac{kg}{sec}$)
1	0								
6	60								

Calculations

On completing the charging stage the user can calculate/ observe the following aspects

- Calculate rate of heat transfer from the cylinder by using equation (1) through (11)
- Calculate energy input to the TES system during charging period by using equation (12)
- Calculate energy accumulated in the TES system during charging period by using equation (13)
- Evaluate the system thermal efficiency during charging period by using equation (16)

Table-20: Calculated values during charging period of the system containing PCM-1 with HTF flow rate (10 LPH)

SL NO.	Time in (min)	Average temperature of PCM during charging period $T_{pcm,ch}$ $(=\frac{T_4+T_5}{2})$ ^{0}C	Energy loss from the system (J)	Energy input to the system during charging period E_{in} (kJ)	Energy accumulated in the system during charging period	system thermal efficiency during charging period η_{ch}
1	0					
6	60					

- **<u>Storing period analysis of the system containing PCM-1 with HTF flow rate (10 LPH) during charging period</u>**

Table-21: Observed values during energy storing period of the system containing PCM-1 with HTF flow rate (10 LPH) during charging period

SL NO.	Time (hours)	Ambient temperature (T_{16}) ^{0}C	PCM-1 front end temperature (T_4) ^{0}C	PCM-1 rear end temperature (T_5) ^{0}C

1	0			
6	60			

Calculation

- Calculate Energy accumulation/loss in TES during storing by using equation (17)
- Calculate storing period efficiency by using equation (19)

Table-22: Calculated values for storing period of the system containing PCM-1 with HTF flow rate (10 LPH) during charging period

SL NO.	Time in (min)	Average temperature of PCM during storing period $T_{pcm,st}$ $(=\frac{T_4+T_5}{2})$ ^{0}C	Energy loss from the system during storing period (J)	Energy stored in the system (J)	System thermal efficiency during storing period (η_{st})
1	0				
6	60				

6.8 Discharging period Analysis of the system containing PCM-1 with HTF flow rate (10 LPH)

Methodology

- Same as discharging stage of experiment number-1 except adjusting the valve number 8 for a flow rate 10 LMP
- Adjust valve number 10 at regular interval to maintain the required flow rate

<u>Observation during discharging period of the system containing PCM-1 corresponding to flow rate (10 LPH)</u>

Table-23: Observed values during discharging period of the system containing PCM-1 corresponding to flow rate (10 LPH)

Sl No.	Time (t) min	Water temperature of HTF hot/cold source tank (T_{14}) ^{0}C	Ambient temperature (T_a= T_{16}) ^{0}C	Cylinder's surface temperature ($T_{s,cy}=T_1$) ^{0}C	Inlet temperature of water during discharging ($T_{i,HTF,dis}$ = $T2$)^{0}C	Outlet temperature of water during discharging ($T_{0,HTF,dis}$ = T_3) ^{0}C	PCM-1 front end temperature (T_4) ^{0}C	PCM-1 rear end temperature (T_5) ^{0}C	Water flow rate $\dot{m}$ ($\frac{kg}{sec}$)
1	0								
6	60								

Calculations

On completing the discharging stage the user can calculate/ observe the following aspects

- Calculate the Energy recovered from TES during discharging period by using equation (20)
- Calculate amount of energy available to discharge by using equation (21)
- Evaluate the system thermal efficiency during discharging of the system by using equation (23)
- Calculate the overall system efficiency (24)
- Calculate the value of FOM by using equation (25)

Table-24: Calculated values during discharging of the system containing PCM-1 corresponding to flow rate (10 LPH)

SL NO.	Time in (min)	Average temperature of PCM-1 during discharging period $T_{pcm,dis}$ $(=\frac{T_4+T_5}{2})$ ^{0}C	Energy loss from the system (J)	Energy available to recovered from the system (J)	Energy recovered from TES during discharging period E_{dis} (J)	system thermal efficiency during discharging period η_{dis}
1	0					

6	60					

- **2^{nd} flow rate (15 LPH)**

  Perform all the above steps in similar ways with a HTF flow rate 15 LPM for charging and discharging the PCM-1. Observed and calculate all the required parameters. Use above tables.
  All steps in this experiment are same except setting the flow rate at 15 LPH by adjusting the valve number 8 at regular interval

- **3^{rd} flow rate (20 LPH)**
  Similar to the above experiments except setting the flow rate at 20 LPH by adjusting the valve number 8 at regular interval

Result:

Draw the following curves

1. **For charging period**

- Change in PCM-1 temperature during the charging period ($T_{pcm,ch}$) with different HTF flow rate (10 ,15 and 20 LPH)
- Change in inlet and outlet HTF temperature during charging period of PCM-1 corresponding to flow rate (10 , 15 and 20 LPH)
- Change in energy input to the system during charging period of PCM-1 corresponding to flow rate (10 ,15 and 20 LPH
- Change in energy loss from the system during charging period of PCM-1corresponding to flow rate (10 ,15 and 20 LPH)
- Change in energy accumulation in the system during charging period of PCM-1 corresponding to flow rate (10 ,15 and 20 LPH)
- Change in system thermal efficiency during charging period of PCM-1 (η_{ch}) corresponding to flow rate (10 ,15 and 20 LPH)

2. **<u>For storing period</u>**

- Change in PCM-1 temperature during storing period ($T_{pcm,st}$) corresponding to flow rate (10 ,15 and 20 LPH)
- Change in energy loss from the system during storing period corresponding to flow rate (10 ,15 and 20 LPH)
- Change in system thermal efficiency during energy storing period (η_{st}) corresponding to flow rate (10 ,15 and 20 LPH)

3. **<u>For discharging period</u>**

- Change in PCM-1 temperature ($T_{pcm,dis}$) during the discharging period corresponding to flow rate (10 ,15 and 20 LPH)
- Change in inlet and outlet water temperature during discharging ($T_{i,HTF,dis}$, $T_{o,HTF,dis}$) period of PCM-1 corresponding to flow rate (10 ,15 and 20 LPH)
- Change in energy recovered with time during discharging period of PCM-1 corresponding to flow rate (10 ,15 and 20 LPH)
- Change in system thermal efficiency with time during discharging period of PCM-1corresponding to flow rate (10 ,15 and 20 LPH)

6.9 Experiment on PCM-2 with different HTF flow rate during charging and discharging

In this experiment the user will have to perform all the sub-processes with at least three flow rates of the HTF

- 1st flow rate (10 LPH)

- **<u>Charging period analysis of the system containing PCM-2</u>**

Methodology

- Same as charging stage of experiment number-2 except setting the flow rate at 10 LPHby adjusting the valve number 10.
- Adjust the valve number at regular interval to maintain the flow rate at the required value

<u>Observation during charging period of the system containing PCM-2 corresponding to flow rate (10 LPH)</u>

Table-25: Observed values during charging period of the system containing PCM-2 corresponding to flow rate (10 LPH)

Sl No.	Time (t) min	Water temperature of HTF hot/cold source tank (T_{14}) ^{0}C	Ambient temperature ($T_a = T_{16}$) ^{0}C	Cylinder's surface temperature ($T_{s,cy} = T_1$) ^{0}C	Inlet temperature of HTF during charging ($T_{i,HTF,ch} = T6$)^{0}C	Outlet temperature of HTF during charging ($T_{0,HTF,ch} = T_7$) ^{0}C	PCM-2 front end temperature (T_8) ^{0}C	PCM-2 rear end temperature (T_9) ^{0}C	Water flow rate $\dot{m}$ ($\frac{kg}{sec}$)
1	0								
6	60								

Calculations: Storing period

On completing the charging stage the user can calculate/ observe the following aspects

- Calculate rate of heat transfer from the cylinder by using equation (1) through (11)
- Calculate energy input to the TES system during charging period by using equation (12)
- Calculate energy accumulated in the TES system during charging period by using equation (13)
- Evaluate the system thermal efficiency during charging period by using equation (16)

Table-26: Calculated values during charging period of the system containing PCM-2 corresponding to flow rate (10 LPH)

Sl No.	Time in (min)	Average temperature of PCM during charging period $T_{pcm,ch}$ ($= \frac{T_8+T_9}{2}$) ^{0}C	Energy input to the system during charging period E_{in} (J)	Energy loss from the system (J)	Energy accumulated in the system during charging period ΔE_1(J)	system thermal efficiency during charging period η_{ch}
1	0					

6	60					

- **<u>Storing period analysis of the system containing PCM-2 with HTF flow rate (10 LPH) during charging period</u>**

Table-27: Observed values during energy storing period of the system containing PCM-2 with HTF flow rate (10 LPH) during charging period

SL NO.	Time (hour)	Ambient temperature $(T_{16})\,^0$C	PCM-2 front end temperature (T_8) ^{0}C	PCM-2 rear end temperature (T_9) ^{0}C
1	0			
6	60			

<u>Calculation: storing period</u>

- Calculate Energy accumulation/loss in TES during storing by using equation (17)
- Calculate storing period efficiency by using equation (19)

Table-28: Calculated values for energy storing period of the system containing PCM-2 with HTF flow rate (10 LPH) during charging period

SL NO.	Time in (min)	Average temperature of PCM during storing period $T_{pcm,st}$ $(=\frac{T_8+T_9}{2})\,^0$C	Energy stored in the system (J)	Energy a loss from the system during storing period ΔE_2 (J)	System thermal efficiency during storing period η_{st}
1	0				
6	60				

6.10 Discharging period Analysis of the system containing PCM-2 with HTF flow rate (10 LPH)

Methodology

- Same as discharging stage of experiment number-2 except adjusting the valve number 10 for a flow rate 10 LMP
- Adjust valve number 10 at regular interval to maintain the required flow rate

Observation during discharging period of the system containing PCM-2 with HTF flow rate (10 LPH)

Table-29: Observed values during discharging period of the system containing PCM-2 with HTF flow rate (10 LPH)

Sl No.	Time (t) min	Water temperature of HTF hot/cold source tank (T_{14}) ^{0}C	Ambient temperature (T_a= T_{16}) ^{0}C	Cylinder's surface temperature ($T_{s,cy}=T_1$) ^{0}C	Inlet temperature of water during discharging ($T_{i,HTF,dis}$ = $T6$)^{0}C	Outlet temperature of water during discharging ($T_{0,HTF,dis}$ = T_7) ^{0}C	PCM-2 front end temperature (T_8) ^{0}C	PCM-2 rear end temperature (T_9) ^{0}C	Water flow rate $\dot{m}$ ($\frac{kg}{sec}$)
1	0								
6	60								

Calculations: Discharging period

On completing the discharging stage the user can calculate/ observe the following aspects

- Calculate the Energy recovered from TES during discharging period by using equation (20)
- Calculate amount of energy available to discharge by using equation (21)
- Evaluate the system thermal efficiency during discharging of the system by using equation (23)
- Calculate the overall system efficiency (24)
- Calculate the value of FOM by using equation (25)

Table-30: Calculated values during discharging of the system containing PCM-2 with HTF flow rate (10 LPH)

SL NO.	Time in (min)	Average temperature of PCM-2 during discharging period $T_{pcm,dis}$ $(=\frac{T_8+T_9}{2})$ ^{0}C	Energy loss from the system (J)	Energy available to discharge from the system (J)	Energy recovered from TES during discharging period E_{dis} (J)	system thermal efficiency during discharging period (η_{dis})
1	0					
6	60					

- **2^nd flow rate (15 LPH)**

Perform all the above steps in similar ways with a HTF flow rate 15 LPM for charging and discharging the PCM-2. Observed and calculate all the required parameters. Use above tables.
All steps in this experiment are same except setting the flow rate at 15 LPHby adjusting the valve number 10 at regular interval

- **3^rd flow rate (20 LPH)**

Similar to the above experiments except setting the flow rate at 20 LPH by adjusting the valve number 12 at regular interval

Result:

Draw the following curves

1. **Charging period**

- Change in PCM-2 temperature with time during the charging period $(T_{pcm,ch})$with different HTF flow rate (10 ,15 and 20 LPH)

- Change in inlet and outlet HTF temperature with time during charging period of PCM-2 with different HTF flow rate (10 , 15 and 20 LPH)
- Change in energy loss from the system during charging period of PCM-2 with different HTF flow rate (10 , 15 and 20 LPH)
- Change in energy input energy to the system during charging period of PCM-2 (E_{in}) with different HTF flow rate (10 , 15 and 20 LPH)
- Change in energy accumulation in the system during charging period of PCM-2 with different HTF flow rate (10 , 15 and 20 LPH)
- Change in system thermal efficiency during charging period of PCM-2 (η_{ch}) with different HTF flow rate (10 , 15 and 20 LPH)

2. <u>Storing period</u>

- Change in PCM-2 temperature during storing period ($T_{pcm,st}$) corresponding to different HTF flow rate (10 , 15 and 20 LPH)
- Change in energy accumulation or loss of the system during energy storing period corresponding to different HTF flow rate (10 , 15 and 20 LPH)
- Change in system thermal efficiency during energy storing period (η_{st}) corresponding to different HTF flow rate (10 , 15 and 20 LPH)

3. <u>Discharging period</u>

- Change in PCM-2 temperature ($T_{pcm,dis}$) during discharging period corresponding to HTF flow rate 10 , 15 and 20 LPH
- Change in inlet and outlet water temperature during discharging ($T_{i,HTF,dis}$, $T_{o,HTF,dis}$) period of PCM-2 corresponding to HTF flow rate 10 , 15 and 20 LPH
- Change in energy recovered with time during discharging period of PCM-2 corresponding to HTF flow rate 10 , 15 and 20 LPH
- Change in system thermal efficiency during discharging period of PCM-2corresponding to HTF flow rate 10 , 15 and 20 LPH

6.11 Experiment on PCM-1 & 2 in cascading (paraffin plus Fatty acid, unmixed) with different HTF flow rate during charging and discharging

In this experiment the user will have to perform all the sub-processes with at least three flow rates of the HTF

- 1st flow rate (10 LPH)
- **Charging period analysis of the system containing PCM-1&2 in cascading**

Methodology

- Same as charging stage of experiment number-3 except setting the flow rate at 10 LPHby adjusting the valve number 12.
- Adjust the valve number 12 at regular interval to maintain the flow rate at the required value

Observation during charging period of the system containing PCM-1&2 in cascading with HTF flow rate (10 LPH)

Table-31: Observed values during charging period of PCM-1&2 in cascading corresponding to flow rate (10 LPH)

Sl. No.	Time (t) min	Water temperature of HTF hot/cold source tank (T_{14}) ^{0}C	Ambient temperature (T_a= T_{16}) ^{0}C	Cylinder's surface temperature ($T_{s,cy}=T_1$) ^{0}C	Inlet temperature of HTF during charging ($T_{i,HTF,ch}$ = $T10$)^{0}C	Outlet temperature of HTF during charging ($T_{0,HTF,ch}$ = T_{11}) ^{0}C	PCM-1 temperature (T_{12}) ^{0}C	PCM-1 temperature (T_{13}) ^{0}C	Water flow rate $\dot{m}$ ($\frac{kg}{sec}$)
1	0								
6	60								

Calculations

On completing the charging stage the user can calculate/ observe the following aspects

- Calculate rate of heat transfer from the cylinder by using equation (1) through (11). Take average value of the two PCM's wherever required
- Calculate energy input to the TES system during charging period by using equation (12)
- Calculate energy accumulated in the TES system during charging period by using equation (13). Calculate it for both the PCM's separately. Use overall value in calculating the thermal efficiency
- Evaluate the system thermal efficiency during charging period by using equation (16)

Table-32: Calculated values during charging period of PCM-1&2 in cascading corresponding to flow rate (10 LPH)

SL NO.	Time in (min)	Average temperature of PCM during charging period $T_{pcm,ch}$ $\left(=\frac{T_{12}+T_{13}}{2}\right)$ ^{0}C	Energy loss from the system (J)	Energy input to system during charging period	Energy accumulated in 1st half of the system during charging period $\Delta E_{1,1}$ (kJ)	Energy accumulated in 2nd half of the system during charging period $\Delta E_{1,2}$(kJ)	Total Energy accumulated in the system during charging period	system thermal efficiency during charging period η_{ch}
1	0							
6	60							

- **Storing period analysis of the system containing PCM-1 &2 in cascading**

Table-33: Observed values during energy storing period with HTF flow rate (10 LPH) during charging period

SL NO.	Time (hours)	Ambient temperature (T_{16}) ^{0}C	1st half PCM temperature (T_{12}) ^{0}C	2nd half PCM temperature (T_{13}) ^{0}C

1	0			
6	60			

Calculation

- Calculate Energy accumulation/loss in TES during storing by using equation (17). Take average values wherever required
- Calculate storing period efficiency by using equation (19)

Table-34: Calculated values for PCM-1&2 in cascading during storing period with HTF flow rate (10 LPH) during charging period

SL NO.	Time (min)	Energy input to the system (J)	Total energy accumulated in the system (J)	Total Energy loss from the system during storing period (J)	System thermal efficiency during storing period η_{st}
1	0				

6.12 Discharging period Analysis of the system having PCM-1&2 in cascading with HTF flow rate (10 LPH)

Methodology

- Same as discharging stage of experiment number-3 except adjusting the valve number 12 for a flow rate 10 LMP
- Adjust valve number 12 at regular interval to maintain the required flow rate

Observation during discharging period of the system having PCM-1&2 in cascading with HTF flow rate (10 LPH)

Table-35: Observed values during discharging period of PCM-1&2 in cascading with HTF flow rate (10 LPH)

Sl No.	Time (t) mi	Water temperature of HTF	Ambient temperatu	Cylinder's surface temperature	Inlet temperature of water during	Outlet temperature of water during	1st half PCM temperature	2nd half PCM temperature	Water flow rate

	n	hot/cold source tank (T_{14}) ^{0}C	re (T_a= T_{16}) ^{0}C	($T_{s,cy}$ =T_1) ^{0}C	discharging ($T_{i,HTF,dis}$ = T_2)^{0}C	discharging ($T_{0,HTF,dis}$ = T_3) ^{0}C	(T_{12}) ^{0}C	(T_{13}) ^{0}C	$\dot{m}(\frac{kg}{sec})$
1	0								
6	60								

Calculations

On completing the discharging stage the user can calculate/ observe the following aspects

- Calculate the Energy recovered from TES during discharging period by using equation (20)
- Calculate amount of energy available to discharge by using equation (21)
- Evaluate the system thermal efficiency during discharging of the system by using equation (23)
- Calculate the overall system efficiency (24)
- Calculate the value of FOM by using equation (25)

Table-36: Calculated values during discharging of PCM-1&2 in cascading with HTF flow rate (10 LPH)

SL NO.	Time (min)	Energy loss from the system (J)	Energy available to discharge from the system (J)	Energy recovered from TES during discharging period E_{dis} (J)	system thermal efficiency during discharging period η_{dis}
1	0				

- **2nd flow rate (15 LPH)**

  Perform all the above steps in similar ways with a HTF flow rate 15 LPM for charging and discharging the PCM-1. Observed and calculate all the required parameters. Use above tables.

All steps in this experiment are same except setting the flow rate at 15 LPHby adjusting the valve number 12 at regular interval

- **3rd flow rate (20 LPH)**
  Similar to the above experiments, except setting the flow rate at 20 LPHby adjusting the valve number 12 at regular interval

Result:

1. **charging period**

- Change in temperature of the 1stand 2ndhalf PCM during the charging period correspondingto different HTF flow rate (10 ,15 and 20 LPH)
- Change in inlet and outlet HTF temperature during charging period of PCM-1&2 in cascading corresponding to different HTF flow rate (10 ,15 and 20 LPH)
- Change in energy input to the system during charging period of PCM-1&2 in cascading (E_{in}) with different HTF flow rate (10 ,15 and 20 LPH)
- Change in energy loss from the system during charging period of PCM-1&2 in cascading corresponding to different HTF flow rate (10 ,15 and 20 LPH)
- Change in energy accumulation in the system during charging period of PCM-1&2 in cascading corresponding to different HTF flow rate (10 ,15 and 20 LPH)
- System thermal efficiency during charging period of PCM-1&2 in cascading (η_{ch}) corresponding to different HTF flow rate (10 ,15 and 20 LPH)

2. **storing period**

- Change in 1stand 2nd half PCM temperatures during storing period (T_{12}) corresponding to different HTF flow rate (10 ,15 and 20 LPH)
- Change in energy loss from the system during energy storing period corresponding to different HTF flow rate (10 ,15 and 20 LPH)
- Change in System thermal efficiency during energy storing period (η_{st}) corresponding to different HTF flow rate (10 ,15 and 20 LPH)

3. **Discharging period**

- Change in 1stand 2ndhalf PCM temperature during the discharging period of the system containing PCM-1 &2 in cascading corresponding to different HTF flow rate (10 ,15 and 20 LPH)
- Change in inlet and outlet water temperature ($T_{i,HTF,dis}$, $T_{o,HTF,dis}$) during discharging period of the system containing PCM-1&2 in cascading corresponding to different HTF flow rate (10 ,15 and 20 LPH)
- Change in heat recovered from the system corresponding to time during discharging period corresponding to different HTF flow rate (10 ,15 and 20 LPH)

- Change in system thermal efficiency during discharging period of the system containing PCM-1&2 in cascadingcorresponding to different HTF flow rate (10 ,15 and 20 LPH)

6.13 Experiment on PCM-1 (paraffin based) with different HTF temperature during charging period

In this experiment the user will have to charged the PCM with at least three different temperature of the HTF

- 1st HTF temperature (90^0C)

- **Charging period analysis of the system containing PCM-1**

Methodology

- Same as charging stage of experiment number-1 except switching off the electric heater as soon as the water in the HTF hot/cold source tank reached temperature around (90^0C). For this purpose observe the temperature continuously corresponding to meter number T_{14}

Observation during charging period of the system containing PCM-1 with HTF temperature (90^0C)

Table-37: Observed values during charging period of the system containing PCM-1 with HTF temperature (90^0C)

Sl. No.	Time (t) min	Water temperature of HTF hot/cold source tank (T_{14}) ^{0}C	Ambient temperature (T_a= T_{16}) ^{0}C	Cylinder's surface temperature ($T_{s,cy}$ =T_1) ^{0}C	Inlet temperature of HTF during charging ($T_{i,HTF,ch}$ = $T2$)^{0}C	Outlet temperature of HTF during charging ($T_{0,HTF,ch}$ = T_3) ^{0}C	PCM-1 front end temperature (T_4) ^{0}C	PCM-1 rear end temperature (T_5) ^{0}C	Water flow rate $\dot{m}$ ($\frac{kg}{sec}$)
1	0								
6	60								

Calculations

On completing the charging stage the user can calculate/ observe the following aspects

- Calculate rate of heat transfer from the cylinder by using equation (1) through (11)
- Calculate energy input to the TES system during charging period by using equation (12)
- Calculate energy accumulated in the TES system during charging period by using equation (13)
- Evaluate the system thermal efficiency during charging period by using equation (16)

Table-38: Calculated values during charging period of the system containing PCM-1 with HTF temperature (90^0C)

SL NO.	Time in (min)	Average temperature of PCM during charging period $T_{pcm,ch}$ $(=\frac{T_4+T_5}{2})$ ^{0}C	Energy loss from the system (J)	Energy input to the system during charging period E_{in} (J)	Energy accumulated in the system during charging period ΔE_1(J)	system thermal efficiency during charging period (η_{ch})
1	0					
6	60					

- **<u>Storing period analysis of the system containing PCM-1 which was charged with HTF temperature (90^0C)</u>**

Table-39: Observed values during energy storing period of the system containing PCM-1 which was charged with HTF temperature (90^0C)

SL NO.	Time (hour)	Ambient temperature (T_{16}) ^{0}C	PCM-1 front end temperature (T_4) ^{0}C	PCM-1 rear end temperature (T_5) ^{0}C
1	0			
6	60			

Calculation

- Calculate Energy accumulation/loss in TES during storing by using equation (17)
- Calculate storing period efficiency by using equation (19)

Table-40: Calculated values for storing period of the system containing PCM-1 which was charged with HTF temperature (90^{0}C)

SL NO.	Time (min)	Average temperature of PCM during storing period $T_{pcm\ ,st}$ $(=\frac{T_4+T_5}{2})$ ^{0}C	Energy stored in the system (J)	Energy loss from the system during storing period (J)	System thermal efficiency during storing period (η_{st})
1	0				
6	60				

6.14 Discharging period Analysis of the system containing PCM-1 which was charged with HTF temperature (90^{0}C)

Note: *in the system there is no provision to cool the water as per our wish. So during discharging period the HTF temperature will depends upon atmospheric temperature.*

Methodology

- Same as discharging stage of experiment number-1

Observation during discharging period of the system containing PCM-1 which was charged with HTF temperature (90^{0}C)

Table-41: Observed values during discharging period of the system containing PCM-1 which was charged with HTF temperature (90^{0}C)

Sl. No.	Time (t) min	Water temperature of HTF hot/cold sourceta	Ambient temperature (T_a=	Cylinder's surface temperature ($T_{s,cy}=T_1$	Inlet temperature of water during discharging (	Outlet temperature of water during discharging ($T_{0,HTF,dis}$ =	PCM-1 front end temperature	PCM-1 rear end temperature (T_5) ^{0}C	Water flow rate $\dot{m}$ $(\frac{kg}{sec})$

		nk (T14) °C	T16) °C	) °C	$T_{i,HTF,dis} = T_2)^0C$	T_3) °C	$(T_4)^0C$		
1	0								
6	60								

Calculations: discharging period

On completing the discharging stage the user can calculate/ observe the following aspects

- Calculate the Energy recovered from TES during discharging period by using equation (20)
- Calculate amount of energy available to discharge by using equation (21)
- Evaluate the system thermal efficiency during discharging of the system by using equation (23)
- Calculate the overall system efficiency (24)
- Calculate the value of FOM by using equation (25)

Table-42: Calculated values during discharging of the system containing PCM-1 which was charged with HTF temperature (90^0C)

SL NO.	Time in (min)	Average temperature of PCM-1 during discharging period $T_{pcm,dis}$ $(=\frac{T_4+T_5}{2})$ °C	Energy loss from the system (J)	Energy available to recovered from the system (J)	Energy recovered from TES during discharging period E_{dis} (J)	System thermal efficiency during discharging period η_{dis}
1	0					
2	10					
6	60					

- **2^{nd} HTF temperature during charging the PCM-1 (85^0C)**

Perform all the above steps in similar ways with HTF temperature 85^0C for charging. Observed and calculate all the required parameters. Use above tables.
All steps in this experiment are same except switching off the electric heaters as soon as the water temperature in the HTF hot/cold source tank reached the required temperature.

- **3rd HTF temperature during charging the PCM-1 (80^0C)**
  Similar to the above experiments except switching off the electric heaters as soon as the water temperature in the HTF hot/cold source tank reached the required temperature

Result:

Draw the following graphs

1. **Charging period**

- Change in PCM-1 temperature during the charging period ($T_{pcm,ch}$)corresponding to different HTF temperature (90^0,$85^0$and 80^0C)
- Change in inlet and outlet HTF temperature during charging period of PCM-1 corresponding to different HTF temperature (90^0,$85^0$and 80^0C)
- Change in energy input to the system during charging period of PCM-1 (E_{in}) corresponding to different HTF temperature (90^0,$85^0$and 80^0C)
- Change in energy loss from the system during charging period of PCM-1corresponding to different HTF temperature (90^0,$85^0$and 80^0C)
- Change in energy accumulation in the system during charging period of PCM-1 corresponding to different HTF temperature (90^0,$85^0$and 80^0C)
- System thermal efficiency during charging period of PCM-1 (η_{ch}) corresponding to different HTF temperature (90^0,$85^0$and 80^0C)

2. **Storing period**

- Change in PCM-1 temperature during storing period ($T_{pcm,st}$) which was charged with different HTF temperature (90^0,$85^0$and 80^0C)
- Change in energy loss from the system during energy storing period which was charged with different HTF temperature (90^0,$85^0$and 80^0C)
- Change in System thermal efficiency during energy storing period (η_{st}) which was charged with different HTF temperature (90^0,$85^0$and 80^0C)

3. **Discharging period**

- Change in PCM-1 temperature ($T_{pcm,dis}$) during the discharging period which was charged with different HTF temperature (90^0,$85^0$and 80^0C)

- Change in inlet and outlet water temperature during discharging ($T_{i,HTF,dis}$, $T_{o,HTF,dis}$) period which was charged with different HTF temperature (90^0,$85^0$and 80^0C)
- Change in heat recovered with time during discharging period of PCM-1 which was charged with different HTF temperature (90^0,$85^0$and 80^0C)
- Change in system thermal efficiency with during discharging period of PCM-1 which was charged with different HTF temperature (90^0,$85^0$and 80^0C)

6.15 Experiment on PCM-2 (fatty acid based) with different HTF temperature during charging period

In this experiment the user will have to charged the PCM with at least three different temperature of HTF

- 1^{st} HTF temperature (90^0C)
- **Charging period analysis of the system containing PCM-2**

Methodology

- Same as charging stage of experiment number-1 except switching off the electric heater as soon as the water in the HTF hot/cold source tank reached temperature around (90^0C). For this purpose observe the temperature continuously corresponding to meter number T_{14}

Observation during charging period of the system containing PCM-2 with HTF temperature (90^0C)

Table-43: Observed values during charging period of the system containing PCM-2 with HTF temperature (90^0C)

Sl. No.	Time (t) min	Water temperature of HTF hot/cold source tank (T_{14}) ^{0}C	Ambient temperature (T_a= T_{16}) ^{0}C	Cylinder's surface temperature ($T_{s,cy}=T_1$) ^{0}C	Inlet temperature of HTF during charging ($T_{i,HTF,ch}$ = $T6$)^{0}C	Outlet temperature of HTF during charging ($T_{0,HTF,ch}$ = T_7) ^{0}C	PCM-2 front end temperature (T_8) ^{0}C	PCM-2 rear end temperature (T_9) ^{0}C	Water flow rate $\dot{m}$ ($\frac{kg}{sec}$)
1	0								
6	60								

Calculations

On completing the charging stage the user can calculate/ observe the following aspects

- Calculate rate of heat transfer from the cylinder by using equation (1) through (11)
- Calculate energy input to the TES system during charging period by using equation (12)

- Calculate energy accumulated in the TES system during charging period by using equation (13)
- Evaluate the system thermal efficiency during charging period by using equation (16)

Table-44: Calculated values during charging period of the system containing PCM-2 with HTF temperature (90^{0}C)

Sl No.	Time in (min)	Average temperature of PCM during charging period $T_{pcm,ch}$ $(=\frac{T_8+T_9}{2})$ ^{0}C	Energy loss from the system (J)	Energy input to the system during charging period E_{in} (kJ)	Energy accumulated in the system during charging period ΔE_1(kJ)	system thermal efficiency during charging period η_{ch}
1	0					
6	60					

- **<u>Storing period analysis of the system containing PCM-2 which was charged with HTF temperature (90^{0}C)</u>**

The period between the charging and discharging is the storing stage. In this stage the user need only to observed and calculate different parameters of the system.

- Table-45: Observed values during energy storing period of the system containing PCM-2 which was charged with HTF temperature (90^{0}C)

SL NO.	Time (hour)	Ambient temperature (J)	PCM-2 front end temperature (T_8) ^{0}C	PCM-2 rear end temperature (T_9) ^{0}C
1	0			
6	60			

<u>Calculation</u>

- Calculate Energy loss from the system during storing by using equation (17)
- Calculate storing period efficiency by using equation (19)

Table-46: Calculated values for energy storing period of the system containing PCM-2 which was charged with HTF temperature (90^0C)

SL NO.	Time (hour)	Average temperature of PCM during storing period $T_{pcm,st}$ $(=\frac{T_8+T_9}{2})$ ^{0}C	Energy stored in the system (J)	Energy loss from the system during storing period (J)	System thermal efficiency during storing period η_{st}
1	0				
6	60				

6.16 Discharging period Analysis of the system containing PCM-2 with HTF flow rate (10 LPH)

In this stage the energy stored in the PCM is extracted from the system to use in the load

Methodology

- Same as discharging stage of experiment number-2 except adjusting the valve number 12 for a flow rate 10 LMP
- Adjust valve number 12 at regular interval to maintain the required flow rate

<u>Observation during discharging period of the system containing PCM-2 which was charged with HTF temperature (90^0C)</u>

Table-47: Observed values during discharging period of the system containing PCM-2 which was charged with HTF temperature (90^0C)

Sl. No.	Time (t)	Water temperature of	Ambient temp	Cylinder's surface tempera	Inlet temperature of water	Outlet temperature of water	PCM-2 front end	PCM-2 rear end tempera	Water flow rate

	min	HTF hot/cold source tank (T_{14}) ^{0}C	erature (T_a= T_{16}) ^{0}C	ture ($T_{s,cy}=T_1$) ^{0}C	during discharging ($T_{i,HTF,dis}$ = T_6)^{0}C	during discharging ($T_{0,HTF,dis}$ = T_7) ^{0}C	temperature (T_8)^{0}C	ture (T_9) ^{0}C	$\dot{m}(\frac{kg}{sec})$
1	0								
6	60								

Calculations

On completing the discharging stage the user can calculate/ observe the following aspects

- Calculate the Energy recovered from TES during discharging period by using equation (20)
- Calculate amount of energy available to discharge by using equation (21)
- Evaluate the system thermal efficiency during discharging of the system by using equation (23)
- Calculate the overall system efficiency (24)
- Calculate the value of FOM by using equation (25)

Table-48: Calculated values during discharging of the system containing PCM-2 which was charged with HTF temperature (90^{0}C)

SL NO.	Time in (min)	Average temperature of PCM-2 during discharging period $T_{pcm,dis}$ $(=\frac{T_8+T_9}{2})$ ^{0}C	Energy loss from the system (J)	Energy available to recovered from the system (J)	Energy recovered from TES during discharging period (J)	System thermal efficiency during discharging period η_{dis}
1	0					
6	60					

- **2^{nd} HTF temperature during charging the PCM-2 (85^0C)**

  Perform all the above steps in similar ways with HTF temperature 85^0C for charging. Observed and calculate all the required parameters. Use above tables.
  All steps in this experiment are same except switching off the electric heaters as soon as the water temperature in the HTF hot/cold source tank reached the required temperature.

- **3^{rd} HTF temperature during charging the PCM-2 (80^0C)**
  Similar to the above experiments except switching off the electric heaters as soon as the water temperature in the HTF hot/cold source tank reached the required temperature

<u>Result:</u>

Draw the following curves

1. **<u>Charging period</u>**

- Change in PCM-2 temperature during the charging period ($T_{pcm,ch}$) corresponding to different HTF temperature (90^0,$85^0$and 80^0C)
- Change in inlet and outlet HTF temperature during charging period of PCM-2 corresponding to different HTF temperature (90^0,$85^0$and 80^0C)
- Change in energy input to the system during charging period of PCM-2 corresponding to different HTF temperature (90^0,$85^0$and 80^0C)
- Change heat loss from the system during charging period of PCM-2 corresponding to different HTF temperature (90^0,$85^0$and 80^0C)
- Change in energy accumulation in the system during charging period of PCM-2 corresponding to different HTF temperature (90^0,$85^0$and 80^0C)
- Change in system thermal efficiency during charging period of PCM-2 (η_{ch}) corresponding to different HTF temperature (90^0,$85^0$and 80^0C)

2. **<u>Storing period</u>**

- Change in PCM-2 temperature during storing period ($T_{pcm,st}$) which was charged corresponding to different HTF temperature (90^0,$85^0$and 80^0C)
- Change in energy loss from the system during energy storing period which was charged corresponding to different HTF temperature (90^0,$85^0$and 80^0C)
- Change in System thermal efficiency during energy storing period (η_{st}) which was charged corresponding to different HTF temperature (90^0,$85^0$and 80^0C)

3. **<u>Discharging period</u>**

- Change in PCM-2 temperature ($T_{pcm,dis}$) during the discharging period which was charged corresponding to different HTF temperature (90^0,$85^0$and 80^0C)
- Change in inlet and outlet water temperature during discharging ($T_{i,HTF,dis}$, $T_{o,HTF,dis}$) period which was charged corresponding to different HTF temperature (90^0,$85^0$and 80^0C)
- Change in heat recovered with time during discharging period of PCM-2 which was charged corresponding to different HTF temperature (90^0,$85^0$and 80^0C)
- Change in system thermal efficiency with during discharging period of PCM-2 which was charged corresponding to different HTF temperature (90^0,$85^0$and 80^0C)

6.17 Experiment on PCM-1 & 2 in cascading (paraffin plus Fatty acid, unmixed) with different HTF temperature during charging period

In this experiment the user will have to charged the PCMs with at least three different HTF temperature

- 1^{st} HTF temperature (90^0C)

▪ **Charging period analysis of the system containing PCM-1&2 in cascading**

Methodology

- Same as charging stage of experiment number-1 except switching off the electric heater as soon as the water in the HTF hot/cold source tank reached temperature around (90^0C). For this purpose observe the temperature continuously corresponding to meter number T_{14}

Observation during charging period of the system containing PCM-1&2 in cascading with HTF temperature (90^0C)

Table-49: Observed values during charging period of PCM-1&2 in cascading with HTF temperature (90^0C)

Sl. No.	Time (t) min	Water temperature of HTF hot/cold source tank (T_{14})	Ambient temperature (T_a= T_{16})	Cylinder's surface temperature ($T_{s,cy}$ =T_1) ^{0}C	Inlet temperature of HTF during charging ($T_{i,HTF,ch}$ =	Outlet temperature of HTF during charging ($T_{0,HTF,ch}$ =	PCM-1 temperature (T_{12}) ^{0}C	PCM-1 temperature (T_{13}) ^{0}C	Water flow rate $\dot{m}$ ($\frac{kg}{sec}$)

		^{0}C	^{0}C		T_{10})^{0}C	T_{11}) ^{0}C			
1	0								
6	60								

Calculations: charging period

On completing the charging stage the user can calculate/ observe the following aspects

- Calculate rate of heat transfer from the cylinder by using equation (1) through (11). Take average value of the two PCM's wherever required
- Calculate energy input to the TES system during charging period by using equation (12)
- Calculate energy accumulated in the TES system during charging period by using equation (13). Calculate it for both the PCM's separately. Use overall value in calculating the thermal efficiency
- Evaluate the system thermal efficiency during charging period by using equation (16)

Table-50: Calculated values during charging period of PCM-1&2 in cascading with HTF temperature (90^{0}C)

SL NO.	Time in (min)	Average temperature of PCM during charging period $T_{pcm,ch}$ $(=\frac{T_{12}+T_{13}}{2})$ ^{0}C	Energy loss from the system (J)	Energy input to system during charging period E_{in} (kJ)	Energy accumulated in 1st half of the system during charging period $\Delta E_{1,1}$ (kJ)	Energy accumulated in 2nd half of the system during charging period $\Delta E_{1,2}$(kJ)	Total Energy accumulated in the system during charging period ΔE_1 (=$\Delta E_{1,1}$ +$\Delta E_{1,2}$)(kJ)	system thermal efficiency during charging period η_{ch}
1	0							
6	60							

- **<u>Storing period analysis of the system containing PCM-1 &2 in cascading which was charged with HTF temperature (90^{0}C)</u>**

The period between the charging and discharging is the storing stage. In this stage the user need only to observed and calculate different parameters of the system.

Table-51: Observed values during energy storing period which was charged with HTF temperature (90^{0}C)

SL NO.	Time (hour)	Ambient temperature $T_{16})$ ^{0}C	1st half PCM temperature (T_{12}) ^{0}C	2nd half PCM temperature (T_{13}) ^{0}C
1	0			
6	60			

<u>Calculation: storing period</u>

- Calculate Energy accumulation/loss in TES during storing by using equation (17). Take average values wherever required
- Calculate storing period efficiency by using equation (19)

Table-52: Calculated values for PCM-1&2 in cascading during storing period which was charged with HTF temperature (90^{0}C)

Sl. No.	Time in (min)	Average temperature of PCM during storing period $T_{pcm,st}$ $\left(=\frac{T_{12}+T_{13}}{2}\right)$ ^{0}C	Energy accumulation or loss in the 1st half of the system during storing period $\Delta E_{2,1}$ (kJ)	Energy accumulation or loss in the 2nd half of the system during storing period $\Delta E_{2,2}$ (kJ	Total Energy accumulation or loss in the system during storing period ΔE_2 (kJ)	System thermal efficiency during storing period η_{st}
1	0					

6	60					

6.18 Discharging period Analysis of the system having PCM-1&2 in cascading which was charged with HTF temperature (90⁰C)

Methodology

- Same as discharging stage of experiment number-1

Observation during discharging period of the system having PCM-1&2 in cascading which was charged with HTF temperature (90^{0}C)

Table-53: Observed values during discharging period of PCM-1&2 in cascading which was charged with HTF temperature (90^{0}C)

Sl. No.	Time (t) min	Water temperature of HTF hot/cold source tank (T_{14}) ^{0}C	Ambient temperature (T_a= T_{16}) ^{0}C	Cylinder's surface temperature ($T_{s,cy}$ = T_1) ^{0}C	Inlet temperature of water during discharging ($T_{i,HTF,dis}$ = $T2$)^{0}C	Outlet temperature of water during discharging ($T_{0,HTF,dis}$ = T_3) ^{0}C	1st half PCM temperature (T_{12}) ^{0}C	2nd half PCM temperature (T_{13}) ^{0}C	Water flow rate $\dot{m}$ ($\frac{kg}{sec}$)
1	0								
6	60								

Calculations: Discharging period

On completing the discharging stage the user can calculate/ observe the following aspects

- Calculate the Energy recovered from TES during discharging period by using equation (20)
- Calculate amount of energy available to discharge by using equation (21)
- Evaluate the system thermal efficiency during discharging of the system by using equation (23)
- Calculate the overall system efficiency (24)
- Calculate the value of FOM by using equation (25)

Table-54: Calculated values during discharging of PCM-1&2 in cascading which was charged with HTF temperature (90^0C)

SL NO.	Time in (min)	Average temperature of PCM during discharging period $T_{pcm,dis}$ $(=\frac{T_{12}+T_{13}}{2})$ ^{0}C	Energy loss from the system (J)	Energy available to recovered from the system (J)	Energy recovered from TES during discharging period (J)	system thermal efficiency during discharging period (η_{dis})
1	0					
6	60					

- **2nd HTF temperature during charging of PCM-1&2 in cascading(85^0C)**

  Perform all the above steps in similar ways with HTF temperature 85^0C for charging. Observed and calculate all the required parameters. Use above tables.
  All steps in these experiments are same except switching off the electric heaters as soon as the water temperature in the HTF hot/cold source tank reached the required temperature.

- **3rd HTF temperature during charging of PCM-1&2 in cascading(80^0C)**
  Similar to the above experiments except switching off the electric heaters as soon as the water temperature in the HTF hot/cold source tank reached the required temperature

Result:

Draw the following curves

1. **charging period**

- Change in temperature of the 1st and 2nd half PCM during the charging period corresponding to different HTF temperature (90^0,$85^0$and 80^0C)
- Change in inlet and outlet HTF temperature during charging period of PCM-1&2 in cascading corresponding to different HTF temperature (90^0,$85^0$and 80^0C)

- Change in energy input to the system during charging period of PCM-1&2 in cascading corresponding to different HTF temperature (90^0,$85^0$and 80^0C)
- Change energy loss from the system during charging period of PCM-1&2 in cascading corresponding to different HTF temperature (90^0,$85^0$and 80^0C)
- Change in energy accumulation in the system during charging period of PCM-1&2 in cascading corresponding to different HTF temperature (90^0,$85^0$and 80^0C)
- System thermal efficiency during charging period of PCM-1&2 in cascading (η_{ch}) corresponding to different HTF temperature (90^0,$85^0$and 80^0C)

2. <u>storing period</u>

- Change in 1st and 2nd half PCM temperatures during storing period (T_{12}) which was charged with different HTF temperature (90^0,$85^0$and 80^0C)
- Change in energy loss of the system during energy storing period which was charged with different HTF temperature (90^0,$85^0$and 80^0C)
- Change in System thermal efficiency during energy storing period (η_{st}) which was charged with different HTF temperature (90^0,$85^0$and 80^0C)

3. Discharging period

- Change in 1st and 2nd half PCM temperatures during the discharging period of the system containing PCM-1 &2 in cascading which was charged with different HTF temperature (90^0,$85^0$and 80^0C)
- Change in inlet and outlet water temperature ($T_{i,HTF,dis}$, $T_{o,HTF,dis}$) during discharging period of the system containing PCM-1&2 in cascading which was charged with different HTF temperature (90^0,$85^0$and 80^0C)
- Change in heat recovered with time during discharging period of the system containing PCM-1&2 in cascading which was charged with different HTF temperature (90^0,$85^0$and 80^0C)
- Change in system thermal efficiency with during discharging period of the system containing PCM-1&2 in cascading which was charged with different HTF temperature (90^0,$85^0$and 80^0C)

Appendix

Table 3: Nomenclatures and some Constant values

Sl. No.	Symbol	Parameter	Value of constant parameters	Unit
1	A_i	Copper tube inner cross sectional area		(m^2)
2	A_0	Cylinder cover outer cross sectional area		(m^2)
3	C_{HTF}	Specific heat capacity of HTF		$(\frac{kJ}{kg\ K})$
4	$C_{pcm,s}$	Specific heat capacity of PCM in solid state (paraffin wax)		$(\frac{kJ}{kg\,0_C})$
5	$C_{pcm,l}$	Specific heat capacity of PCM in solid state (paraffin wax)		$(\frac{kJ}{kg\,0_C})$
6	$C_{pcm,s}$	Specific heat capacity of PCM in solid state (fatty acid)		$(\frac{kJ}{kg\,0_C})$
7	$C_{pcm,l}$	Specific heat capacity of PCM in solid state (fatty acid)		$(\frac{kJ}{kg\,0_C})$
8	D_i	Internal diameter of the copper tube		(m)
9	D_0	Outer diameter of the cylinder cover		(m)
10	E_{in}	Energy input during charging		(kJ)
11	E_{dis}	Energy recovered from TES during discharging		(kJ)
12	ΔE_1	Energy accumulated during charging,		(kJ)
13	ΔE_2	Energy accumulation in TES during storing		(kJ)
14	ΔE_3	Energy accumulation in TESduring charging and storin ,		(kJ)
15	$E_{f,1}$	Final energy of TES for the charging period		(kJ)
16	$E_{i,1}$	Initial energy of TES for the charging period		(kJ)

17	$E_{i,2}$	Initial energy of the TES during storing		(kJ)
18	$E_{f,2}$	Final energy of the TES during storing		(kJ)
19	$E_{L,pcm,1}$	Latent heat of fusion of PCM (paraffin wax)	173	$(\frac{kJ}{kg})$
20	$E_{L,pcm,2}$	Latent heat of fusion of PCM (fatty acid)	210	$(\frac{kJ}{kg})$
21	G	Acceleration due to gravity	9.81	$(\frac{m}{sec^2})$
22	G_r	Grashof number		
23	h_i	Inner convective heat transfer coefficients		$(\frac{W}{mk})$
24	h_o	Outer convective heat transfer coefficients		$(\frac{W}{mk})$
25	k_4	Thermal Conductivity of insulation		$(\frac{W}{mk})$
26	k_5	Thermal Conductivity of GI		$(\frac{W}{mk})$
27	$\mathrm{k_w}$	Conductivity of water		$(\frac{W}{mk})$
28	k_1	Thermal Conductivity of copper tube		$(\frac{W}{mk})$
29	k_2	Thermal Conductivity of PCM		$(\frac{W}{mk})$
30	k_3	Thermal Conductivity of SS		$(\frac{W}{mk})$
31	L_1	Length of copper tube		(m)
32	L_2	Length of PCM layer		(m)
33	L_3	Length of SS cylinder		(m)
34	L_4	Length of insulation layer		(m)
35	L_5	Length of cylinder cover		(m)
36	$\dot{\mathrm{m}}_{\mathrm{HTF,ch}}$:	Hot HTF flow rate during charging		$(\frac{kg}{sec})$

37	$\dot{m}_{HTF,dis}$	Cold HTF flow rate during discharging	$(\frac{kg}{sec})$
38	m_{pcm}	Mass of PCM	(kg)
39	$\dot{m_w}$	Mass flow rate of water	(m)
40	$\mathrm{N_U}$	Nusselt number	
41	$\mathrm{p_r}$	Pandtl number	
42	$\dot{q}$	Energy loss from the system (J)h of the cylinder	$(\frac{\mathrm{W}}{\mathrm{m}})$
43	R_e	Reynolds number	
44	R	total thermal resistance of the PC cylinder having the heat exchanger	
45	r_1	Internal radius of copper tube	(m)
46	r_2	External radius of copper tube or internal radius of PCM layer	(m)
47	r_3	External radius of PCM layer or internal radius of SS cylinder	(m)
48	r_4	External radius of SS cylinder or internal radius of insulation	(m)
49	r_5	External radius of insulation layer or internal radius of cylinder cover	(m)
50	r_6	External radius of cylinder cover	(m)
51	$\mathrm{T_{i,HTF,ch}}$	Inlet temperature of HTF during charging $\mathrm{T_{i,HTF,ch}} = \mathrm{T_2, T_6, T_{10}}$For cylinder 1,2 and 3 respectively	$(^0\mathrm{C})$
52	$\mathrm{T_{o,HTF,ch}}$	Outlet temperature of HTF during charging $\mathrm{T_{0,HTF,ch}} = \mathrm{T_3, T_7, T_{11}}$For cylinder 1,2 and 3 respectively	$(^0\mathrm{C})$
53	$T_{pcm,f,ch}$	Final temperature of PCM during charging period(Average of $\mathrm{T_4}$&$\mathrm{T_5}$, $\mathrm{T_8}$&T_9 for cylinder 1 and 2) $\mathrm{T_{12}}$ and $\mathrm{T_{13}}$Separately for cylinder 3	$(^0\mathrm{C})$
54	$T_{pcm,i,ch}$	Initial temperature of PCM during charging	$(^0\mathrm{C})$

		period(Average of T_4&T_5, T_8&T_9 for cylinder 1 and 2) T_{12} and T_{13}Separately for cylinder 3		
55	$T_{pcm,st}$	Temperature of stored PCM (Average of T_4&T_5, T_8&T_9 for cylinder 1 and 2) T_{12} and T_{13}Separately for cylinder 3		(^{0}C)
56	$T_{HTF,O,dis}$	Outlet temperature of the HTF during discharging $$T_{0,HTF,dis} = T_3, T_7, T_{11}$$ For cylinder 1,2 and 3 respectively		(^{0}C)
57	$T_{HTF,i,dis}$	Inlet temperature of the HTF during discharging $$T_{i,HTF,dis} = T_2, T_6, T_{10}$$ For cylinder 1,2 and 3 respectively		(^{0}C)
58	$T_{pcm,ml}$	Melting temperature of PCM (paraffin wax)		(^{0}C)
59	$T_{pcm,ml}$	Melting temperature of PCM (fatty acid)		
60	$T_{sol,1}$	Temperature at which the PCM starts to solidify(for paraffin wax)	55	(^{0}C)
61	$T_{sol,2}$	Temperature at which the PCM starts to solidify(for fatty acid)		(^{0}C)
62	T_{max}	Maximum measured temperature of the PCM during the test (=$T_{pcm,f,ch}$) (Average of T_4&T_5, T_8&T_9 for cylinder 1 and 2) T_{12} and T_{13}Separately for cylinder 3		(^{0}C)
63	t_{total}	Total test time		(sec)
64	t_{cool}	Total time of cooling		(sec)
65	$T_{av,HTF,ch}$	Average HTF temperature during charging		(^{0}C)
66	T_a	Ambient air temperature		(^{0}C)
67	$T_{s,cy}$	Cylinder's surface temperature ($T_{s,cy}$ =T_1)		(^{0}C)

68	T_a	Ambient air temperatures(T_a=T_{16})	(^{0}C)
69	V	Velocity of water through the copper tube	($\frac{m}{sec}$)
70	ν	Kinematic viscosity of water	($\frac{kg}{sec}$)
71	ρ_{air}	Density of air	($\frac{kg}{m^3}$)
72	μ	Dynamic viscosity of air	($\frac{N-Sec}{m^2}$)
73	β	Coefficient of volume expansion of the air	($\frac{1}{k}$)
74	η_{ch}	Charging period efficiency	
75	η_{st}	Storing period efficiency	
76	η_{dis}	Discharging period efficiency	
77	$\eta_{overall}$	Overall system efficiency	

Table 4: Properties of water at 90^{0}C (Example)

Properties	Symbols	Values	Unit
Density	ρ_w	964.45	$\frac{kg}{m^3}$
Conductivity of water	k_w	0.676	$\frac{w}{mK}$
Kinematic viscosity	ν	0.000000318	$\frac{m^2}{sec}$
Specific heat capacity	C_{HTF}	4074.7	$\frac{J}{kgK}$
Pandtl number	p_r	1.85	

Link of website to know the properties of fluidhttp://www.mhtl.uwaterloo.ca/old/onlinetools/airprop/airprop.html

Table 5:Values of radius, conductivity and heat transferring cross sectional area of different layers used in the PCM cylinders

Parameters	Copper tube	PCM	SS pipe	Insulation	GI cover	unit

Internal radius	r_1	0.00545	r_2	0.00635	r_3	0.07	r_4	0.071	r_5	0.121	(m)
Outer radius	r_2	0.00635	r_3	0.07	r_4	0.071	r_5	0.121	r_6	0.1219	(m)
Conductivity	k_1	390	k_2	0.22	k_3	16	k_4	0.033	k_5	16	$\left(\frac{W}{mk}\right)$
Length	L_1	0.45	L_2	0.45	L_3	0.45	L_4	0.45	L_5	0.45	(m)