Analysis of Paraffin Wax as a Phase Change Material for Thermal Energy Storage System

Apoorva
Dept. of Sustainable Energy Engineering
Indian Institute of Technology Kanpur
Kanpur, India
apoorva23@iitk.ac.in

Chuskit Dolma
Dept. of Sustainable Energy Engineering
Indian Institute of Technology Kanpur
Kanpur, India
chuskitd23@iitk.ac.in

Mayank Dhattarwal
Dept. of Sustainable Energy Engineering
Indian Institute of Technology Kanpur
Kanpur, India
mayankd23@iitk.ac.in

***Abstract*—Thermal energy storage (TES) system is a crucial technology for addressing energy demand fluctuations and enhancing energy efficiency in various applications. Paraffin wax exhibits exceptional latent heat properties, making it an attractive option for storing and releasing thermal energy during its phase transition between solid and liquid states. This paper briefly discusses TES emphasizing latent heat storage.The experiment is performed keeping mass flux constant, with HTF continuously entering the system during charging. During discharging, the HTF temperature was kept at 10°C by using chiller. The experiment shows that the both during the charging and discharging phases, the system's efficiency declines. The results also shows the change of PCM temperature with time during charging, storing and discharging period.Insights gained contribute to understanding PCM based thermal energy storage, showcasing its potential for efficiently recovering and utilizing waste heat in industrial settings.**

***Index Terms*—Paraffin wax; Phase change material(PCM); Thermal energy storage system.**

Nomenclature

$\dot{q}_2$	Rate of heat transfer from PCM to ambient	HTF	Heat transfer fluid
K_w	Conductivity of water	PCM	Phase change material
N_u	Nusselt Number	T_{HTF1}	Water temp. of HTF source tank
R_1	Total thermal resistance of PCM cylinder during charging	T_a	Ambient Temprature
R_2	Total thermal resistance of PCM during discharging	T_{b1}	Inlet temperature of HTF
h_o	Inner convective heat transfer coefficient	T_{b2}	PCM front end temperature
h_i	Outer convective heat transfer coefficient	T_{b3}	PCM rear end temperature
D_i	Inner dia of copper tube	T_{b4}	Outlet temperature of HTF
A_i	Surface area of inner copper tube	$\dot{m}$	Mass flow rate of water
A_o	Surafce area of outer copper tube	C_p	Specific heat capacity of water
$E_{Hot,water}$	Energy given by Hot water during charging	E_{loss}	Energy loss
$E_{absorbed}$	Energy absorbed by PCM during charging	$E_{recovered}$	Energy gained by hot water during discharge
S, l	Solid, Liquid	$m_{f,pcm}$	Fractional liquefied mass of PCM
m_{pcm}	Total mass of PCM (paraffin wax)	L	Latent enthalpy of PCM
$C_{p,pcm}$	Specific heat capacity of PCM	$\dot{q}_1$	Rate of heat transfer from hot water to ambient

I. Introduction

The escalating global population drives an ever-growing energy demand worldwide. Conventional energy sources such as coal and fossil fuels, being finite and non-renewable, necessitate the exploration of alternative energy reservoirs to meet escalating demands. Non-conventional energy sources like solar and wind power emerge as pivotal players in the quest for sustainable and environmentally friendly energy solutions. The amalgamation of renewable energy into utility grids contributes to mitigating climate change concerns, as renewable energy sources are inherently eco-friendly. However, these renewable energy sources exhibit intermittent availability, operating only for a particular time of day and often unpredictably.To bridge this gap and ensure a consistent energy supply, the implementation of energy storage systems becomes imperative. Thermal energy storage stands out as a critical component in the realm of renewable energy storage solutions, facilitating the seamless retention and utilization of solar and other renewable energies.

A. Thermal Energy Storage (TES) systems

TES technology facilitates the capture and retention of thermal energy for subsequent utilization. This involves storing thermal energy in a medium during periods of surplus or low demand and subsequently accessing it during periods of heightened demand. There exist several class of thermal energy storage systems, mainly-

- Sensible Heat Storage: It involves the alteration of a material's temperature without inducing a change in its phase (solid, liquid, or gas). Examples include water, rocks, and bricks.
- Latent Heat Storage: It revolves around phase transition of the material(e.g., from solid state to liquid state or liquid state to gaseous state) while maintaining a constant temperature.PCMs are frequently employed for latent heat storage, with examples including paraffin wax, and hydrated salts. [1]
- Thermochemical storage: Thermochemical storage hinges on reversible chemical reactions capable of absorbing or releasing heat. It includes chemical reactions such as hydration/dehydration or adsorption/desorption of gases.

The versatility of thermal energy storage systems extends across various sectors, including electricity Grid Management, industrial processes, building HVAC system, and solar thermal plants.

B. Paraffin wax as a phase change material

Among the numerous class of TES approaches, latent heat storage is notable for its capacity to retain substantial energy quantities at the same temperature that blends with the PCM temperature of storage material. PCMs are substances proficient in storing and releasing substantial thermal energy quantities during phase transitions, such as when transforming from solid state to liquid state or liquid state to gaseous state, while maintaining a near-constant temperature. They exhibit large concealed heat of fusion, enabling them to reserve

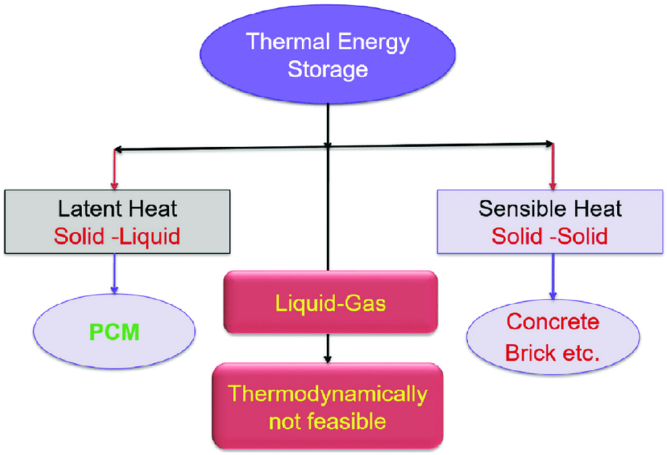

Fig. 1. Types of Thermal Energy Storage. [2]

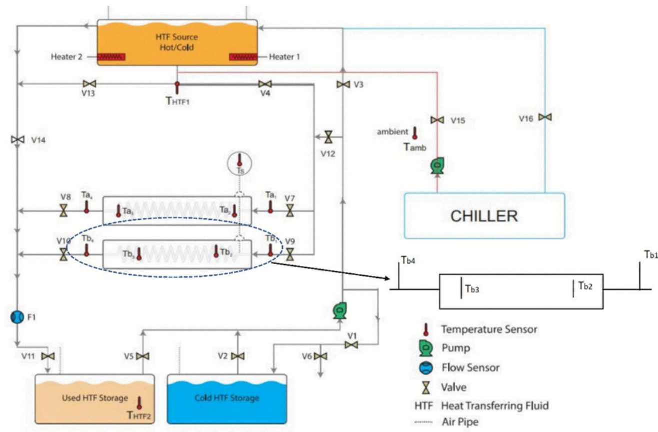

Fig. 2. Schematic diagram of TES [10]

and free substantial energy per unit mass or volume. They can undergo repeated phase transitions without significant degradation, making them acceptable for cyclic thermal energy storage applications. They can be categorized as: inorganic and organic PCMs. Crystalline salt (inorganic) and paraffin (organic) are among the most common substances used. PCMs must possess congruent melting, low cost, strong thermal conductivity during phase transition, compatibility, availability, and high relative latent heat, to undergo continuous phase shifts over their operational lifespan. High molecular mass hydrocarbons, or paraffin, have a waxy consistency at room temperature. While pure paraffin has a narrower melting temperature range, commercial paraffin typically undergoes phase transitions. Paraffin serves as an excellent PCM for storage systems, exhibiting nearly all required characteristics except for limited thermal conductivity. A study by Farid et al. [3] explored the properties of paraffin wax in various thermal implementations. [4].In water heating systems powered by the sun, incorporating paraffins into storing containers heightens thermal energy density, system efficiency, and reduces both size and expenses. For instance, adding paraffin, which melts at 55°C, to a shell-style tank could increase the thermal energy that has been stored by as much as 39%, enhance effectiveness by sixteen percent and increase the hot water supply's duration by up to 25 percent. [5] Additional analysis showed that incorporating paraffin wax of commercial grade having a melting point of approximately 55 degree celcius in a devoid tube collector/storage system setup increased useful heat by up to 79%, enabling better regulation of the heating medium and prolonged solar system operation [6]. Similarly, PCMs having melting temperatures of 30°C to 60°C can reduce operating costs and enhance the effectiveness of air conditioners and heat pumps utilized in various applications. [7]

C. Objective

This study examines the use of paraffin wax as a phase-change material in thermal energy storage systems for both charging and discharging period. The temperature changes of PCM about time throughout the charging, storing and discharging period is studied. Thereby effectively filling in the gaps that exist between the development of these PCMs and their application in real TES systems.

II. Methodology

A. Experimental Set-up

Fig.2 and Fig. 3 depict the experimental setup and the schematic representation of the TES. and Paraffin wax cylinder, respectively. Tables II and III provide the heat exchanger's technical specs. Copper tubing is coiled and spaced 24 cm apart to increase the system's effective heat conductivity. To minimize heat loss when the PCM is being charged and discharged, the exterior of the outer pipe was insulated. Commercial-grade paraffin wax weighing 2.5 kg was inserted into the outer tube to serve as a medium for latent heat storage medium. Two places in the study utilized type K copper thermocouples to measure the temperature of PCM and the input and output of heat transfer fluid (HTF). To maintain an almost constant flow rate, a two-tank system was employed to keep the incoming water's pressure head constant. To maintain a constant inflow water temperature during charging mode, heaters with thermocouples were also installed in the water tanks. The inner tube was filled with hot water to initiate the energy-charging test. Cold water was then passed across the inner tube to release the accumulated energy. Using temperature sensors, the water's temperature at the heat exchanger's entrance and exit at four axial positions (T_{b1}, T_{b2}, T_{b3}, and T_{b4} in°C) was simultaneously monitored every two minutes.

B. Experiment Procedure

As the PCM tank is being charged and discharged, the temperature distributions in PCM and HTF at constant mass flow rates are being noted.

1) For charging: During the charging process, a thorough analysis of the system efficiency and total heat stored is conducted. The experiment was carried out with a constant flow rate of 0.68 LPM, hot water input temperature kept

TABLE I
SPECIFICATIONS OF TES

Inner Radius of Copper Tube (r1) =0.00545 m	Outer radius of copper tube (r2) = 0.00635 m
Inner radius of PCM cylinder (r2) = 0.00635 m	Outer radius of PCM cylinder (r3) = 0.085 m
Inner radius of SS pipe (r3) = 0.085 m	Outer radius of SS pipe (r4) = 0.087 m
Inner radius of insulation (r4) = 0.087 m	Outer radius of insulation (r5) = 0.12 m
Inner radius of GI cover (r5) =0.12 m	Outer radius of GI cover (r6) = 0.1229 m
L1 = Length of copper tube = 2.1 m	L2 = Length of PCM cylinder = 0.34 m
L3 = Length of SS pipe = 0.34 m	L4 = Length of insulation = 0.34 m
L5 = Length of GI cover = 0.34 m	k1 = conductivity of copper tube = 390 W/mK
k2 =conductivity of PCM = 0.22 W/mK	k3 = conductivity of SS pipe= 16 W/mK
k4 = conductivity of insulation = 0.033W/mK	k5 = conductivity of GI cover = 16 W/mK
conductivity of water = 0.676 W/mK (90 °C)	$C_{p,\,HTF}$ = specific heat capacity of water= 4180 J/kgK
m_{pcm} = Total mass of PCM (paraffin wax) = 2.5 kg	$Cp,\,pcm$ = specific heat capacity of PCM = 2680 J/kgK
L = latent enthalpy of PCM= 188,000 J/kg	

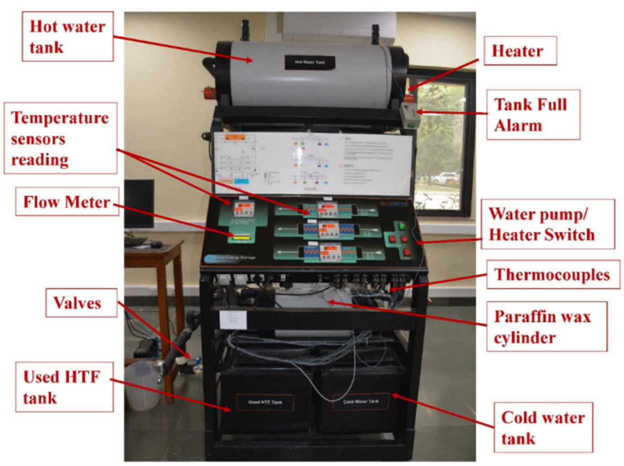

Fig. 3. Experimental set up of thermal energy storage system [10]

between 85 and 90 °C, and ambient temperature about 19-20 °C. The HTF is constantly pumped through the PCM tank throughout the charging operation. As the HTF transfers its heat energy to the PCM, the PCM's initial temperature of 22°C rises to the melting point. Temperature sensors measure the temperature of both PCM and HTF at the inlet and outlet, ambient temperature, HTF tank temperature that need to be noted at every two minutes to calculate heat exchanger efficiency during charging period. The process of charging is kept going until the PCM temperature hits 55°C, which is the melting point of paraffin wax.

2) *For storing:* After the PCM melts and turns liquid, heat is retained during the charging period as latent heat. After that, the energy is kept in liquid PCM as sensible heat during storing period. One goal of system design, is to eliminate temperature drops. The purpose of the storage period is to minimize ambient and storage losses, hence minimizing errors during the discharge phase. The storage period will last until the HTF temperature drops to 10–13°C. Readings from temperature sensors for the PCM's intake and outlet, as well as the ambient temperature, should be recorded every two minutes.

3) *For discharging:* In practical outdoor conditions, water naturally cools down to the ambient temperature for the discharging process. However, in a laboratory setting where time is limited, artificial cooling using a chiller is employed. In the experiment, the water is artificially cooled to approximately 10°C by the chiller. The inlet temperature of the (HTF) in the cold water is set to 10°C, and a pump unit is used to circulate the artificially cooled water from the chiller to the HTF tank. The discharging operation was executed at a flow rate of 0.68 lpm. Throughout this discharging phase, cold water circulated through the (PCM) tank, facilitating the transfer of heat energy from the PCM to the cold water and consequently raising its temperature. Temperature values at 2-minute intervals were recorded for the PCM's inlet and outlet, as well as for the high-temperature fluid (HTF), ambient temperature, and the HTF tank for calculating heat exchanger system efficiency during discharging period. The discharge process continued until the avg. temperature at the PCM's inlet and outlet dropped to 45°C, with the objective of extracting the total energy previously stored during the charging process.

C. Basic Equations

1) *For Charging Period::*

- Energy balance during the charging process:

$$E_{\text{HOT , water}} = E_{\text{absorbed}} + E_{\text{loss}} \ (J) \tag{1}$$

- Energy given by HOT water:

$$E_{HOT,\text{ water}} = \dot{\text{m}} * C_{p,HTF}\left(T_{b1,b4}\right) * t(J) \tag{2}$$

$$T_{b1,b4} = T_{b1,avg} - T_{b4,avg} \tag{3}$$

- Energy absorbed by the PCM material:

$$E_{\text{absorbed}} = E_{\text{Hot, water}} - E_{\text{loss}} \tag{4}$$

$$E_{\text{absorbed}} = m_{pcm} * C_{p,pcm} * \left[\left(T_{avg,pcm}\right)_{t_1} - \left(T_{avg,pcm}\right)_{t_0}\right]$$

$$+\text{m}_{f,pcm} L(J) \quad (5)$$

$$T_{avg,pcm} = \frac{T_{b2} + T_{b3}}{2}$$

$$\text{Charging Efficiency} = \frac{E_{\text{absorbed}}}{E_{HOT,\text{ water}}} \tag{6}$$

- Energy loss E_{loss} calculation:

$$E_{\text{loss}} = \dot{\text{q}}_1 * t(J) \tag{7}$$

$$\dot{\text{q}}_1 = \frac{\text{T}_{\text{avg, HTF}-\text{T}_{\text{avg,a}}}}{\text{R}_1} \tag{8}$$

where $\text{R}_1 = \frac{1}{\text{h}_\text{i}\text{A}_\text{i}} + \frac{\ln\left(\frac{\text{r}_6}{\text{r}_1}\right)}{2\pi\text{k}_2\ \text{L}_1} + \frac{1}{\text{h}_0\ \text{A}_0}$

and $\text{h}_\text{i} = \frac{\text{N}_\text{U} \times K_W}{\text{D}_\text{i}}$

For smooth Circular Tube with constant surface temperature

$$\text{N}_\text{U} = \frac{\text{h}_\text{i} \times \text{D}_\text{i}}{K_w} = 3.66 \tag{9}$$

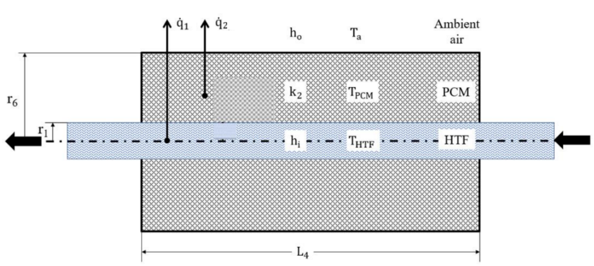

Fig. 4. Heat transfer flow [10]

- Energy balance during the discharging process:

$$E_{\text{released,pcm}} = E_{\text{recovered,water}} + E_{\text{loss}} \ (J) \tag{10}$$

- Energy recovered by the cold water:

$$E_{\text{recovered,water}} = \dot{m} * C_{p,HTF}\left(T_{b4,avg} - T_{b1,avg}\right) * t(J) \tag{11}$$

- Energy loss E_{loss} calculation:

$$\begin{aligned} E_{\text{loss}} &= \dot{\text{q}}_2 * t(J) \\ \dot{\text{q}}_2 &= \frac{\text{T}_{\text{avg,pcm}} - \text{T}_{\text{avg,a}}}{\text{R}_2} \end{aligned} \tag{12}$$

- Energy loss E_{loss} calculation:

$$\begin{aligned} E_{\text{loss}} &= \dot{\text{q}}_2 * t(J) \\ \dot{\text{q}}_2 &= \frac{\text{T}_{\text{avg,pcm}} - \text{T}_{\text{avg,a}}}{\text{R}_2} \end{aligned} \tag{13}$$

$$\text{R}_2 = \frac{\ln\left(\frac{\text{r}_6}{\text{r}_1}\right)}{2\pi\text{k}_2\ \text{L}_4} + \frac{1}{\text{h}_\text{o}\text{A}_\text{o}} \tag{14}$$

- Efficiency during discharging process:

$$\eta_{\text{discharging}} = \frac{E_{\text{recovered,water}}}{E_{\text{recovered,water}} + E_{\text{loss}}} \tag{15}$$

III. Results and Discussions

To understand the performance of PCM for thermal storage, energy transfer and system efficiencies are calculated during charging, storing and discharging period. The results are analysed and discussed in each subsection.

A. Charging Period

This section comprises the analysis of how temperature of paraffin wax,hot water temprature of outlet and inlet and thermal efficiency varies with respect to time. Table II shows the experimentally observed values during the charging period. The energy given by hot water, energy lost to ambient, energy absorbed by the PCM, and the efficiency of TES during the charging period are calculated by using equations (2), (7), (4), and (6) respectively, as given in Table II. The graphs of paraffin wax temperature vs time, inlet and outlet temperature vs time, and thermal efficiency vs time are plotted.

1) PCM temperature variation with time: Fig.5 shows how paraffin wax temperature varies with time. As evident from Fig.5 during charging period, the PCM temperature increases linearly with time. During charging period, heat is transferred to paraffin wax from hot water, increasing the temperature of paraffin wax with time.

TABLE II
OBSERVED VALUES DURING CHARGING PERIOD

S.no	Time (min)	T_{hft1} (°C)	T_a (°C)	T_s (°C)	T_{b1} (°C)	T_{b4} (°C)	T_{b2} (°C)	T_{b3} (°C)	Flow rate (kg/s)
1	0	97.4	19.5	21.1	84.6	61.4	22.3	22.3	0.00947
2	4	96.8	20.3	21.9	90.9	70.8	22.5	23.3	0.00947
3	8	96.4	20.5	22.1	93.4	82	22.8	25.6	0.00947
4	12	95.5	20.7	21.9	93.6	84	24.7	31.6	0.00947
5	16	94.6	20.6	22.3	93.2	84.7	28	35.7	0.00947
6	20	94.2	21.2	22.9	92.8	84.9	32.5	36.6	0.00947
7	24	92.8	20.8	22.6	92.3	84.8	36.1	39.3	0.00947
8	28	91.6	19.8	22.6	91.7	84.3	40.1	43.1	0.00947
9	32	90.9	20.5	23.3	91.1	84.1	43.4	46.1	0.00947
10	36	90.6	20.5	24	90.5	83.8	46.4	48.8	0.00947
11	40	89.5	20	24.2	89.7	83.5	49.1	51.2	0.00947
12	44	88.8	19.8	24.6	89	83.3	51.6	53.9	0.00947
13	48	88.2	20.1	25.7	88.2	82.9	54.1	56	0.00947

2) HTF's inlet T_{b1} and outlet T_{b4} temperature variation with time: Fig.6 shows the inlet and outlet temperature change with time. From Fig. 6 we can observe that temperature difference of working fluid (water) between outlet and inlet decreasing with time. Heat transfers continued from warmer to colder region, till there is a temperature difference between them and this rate of heat transfer is directly proportional to the temperature variation between the two regions (conductive and convective heat transfer). Initially, the temperature difference between hot water and paraffin wax is high, hence heat transfer rate is high leading to higher outlet and inlet temperature difference.Temperature of paraffin wax increases with time due to which the energy transfer (water to paraffin) decreases, thus there is decrease in inlet and outlet temperature of water.

3) Change in system's thermal efficiency with time: Fig. 7 shows how the efficiency of system varies with time. In Fig.7 the system's thermal efficiency decreases with time. From equations (4) and (6) charging efficiency can be written as

$$\text{Charging Efficiency } = \frac{E_{\text{Hot, water}} - E_{\text{loss}}}{E_{\text{Hot, water}}} \tag{16}$$

$$\text{Charging Efficiency } = 1 - \frac{E_{\text{loss}}}{E_{\text{Hot, water}}} \tag{17}$$

The energy loss to ambient is constant with respect to time whereas energy given by hot water decreases as the inlet and outlet temperature difference decreases with time, which decreases system efficiency.

TABLE III
CALCULATED VALUES DURING CHARGING PERIOD

S.no	Time (min)	q1 = ($T_{avg,hft1}$-$T_{avg,a}$)/R1	Energy given by HOT water, $E_{HOT\ water}$ (J)	Energy absorbed by PCM, $E_{absorbed}$ (J)	Energy Loss from system (J)	System efficiency (%)
1	0	15.4	205681.6	201983.8	3697.8	98.2
2	4	15.2	149629.8	145979.9	3649.9	97.6
3	8	15.0	99753.2	96144.0	3609.1	96.4
4	12	14.8	85977.8	82414.1	3563.6	95.9
5	16	14.7	77902.5	74382.0	3520.5	95.5
6	20	14.5	73152.3	69679.7	3472.6	95.3
7	24	14.3	70777.3	67333.4	3443.9	95.1
8	28	14.2	68402.2	64996.6	3405.6	95.0
9	32	14.0	65077.1	61712.2	3364.9	94.8
10	36	13.9	61277.0	57933.6	3343.3	94.5
11	40	13.8	56526.8	53209.8	3317.0	94.1
12	44	13.7	52251.7	48968.2	3283.4	93.7

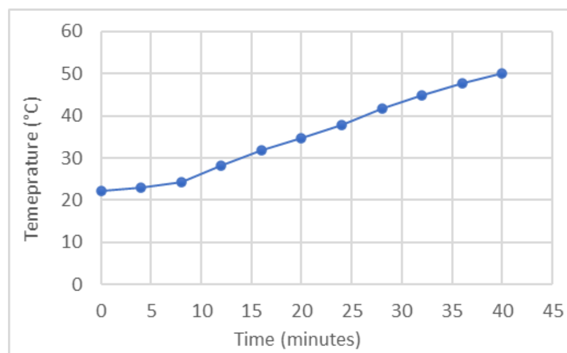

Fig. 5. PCM temperature vs time during charging period

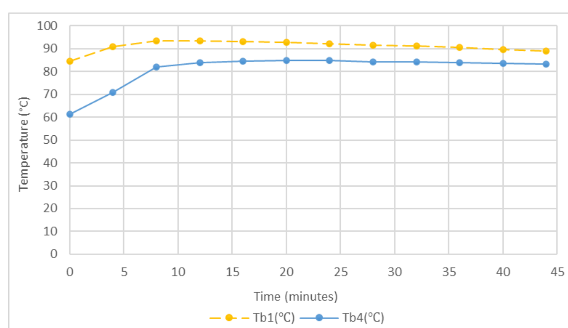

Fig. 6. Inlet and Outlet temperature of water vs time during charging period

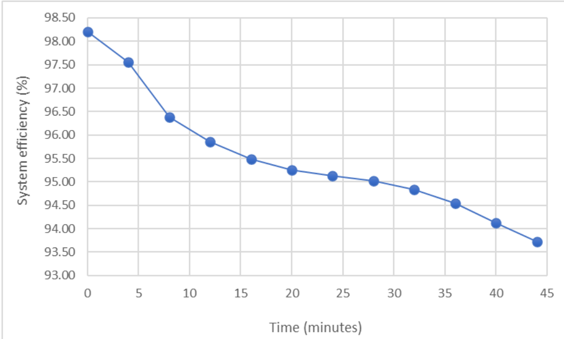

Fig. 7. System thermal efficiency vs time during charging period

TABLE IV
OBSERVED VALUES DURING STORING PERIOD

S.no	Time (min)	T_a (°C)	T_{b2} (°C)	T_{b3} (°C)	$T_{avg, PCM}$ (°C)
1	0	20.8	54.8	56.6	55.7
2	4	21.1	56.5	58.2	57.35
3	8	21.2	57.8	59.2	58.5
4	12	22.3	58.5	59.8	59.15
5	16	22.8	58.9	60.1	59.5
6	20	22.7	58.9	60.2	59.55
7	24	22.4	58.8	60	59.4
8	32	21.3	58.6	59.7	59.15
9	36	28.9	58.1	59.3	58.7

B. Storing Period

This section analyses the variation of paraffin wax temperature with time. Table IV shows the experimentally observed values during the storing period. The graph of paraffin wax temperature vs time is plotted for storing period. Fig. 8 shows the variation pf paraffin wax with time during storing period.

During storing period the temperature of PCM keeps increasing due to the temperature gradient in paraffin wax. Once the charging period is over the temperature of paraffin wax near the copper coil is more compared to rest of the cylinder leading to localized increases in temperature as heat is absorbed, hence temperature of paraffin wax keeps increasing till temperature is uniform throughout the cylinder, then temperature starts decreasing.

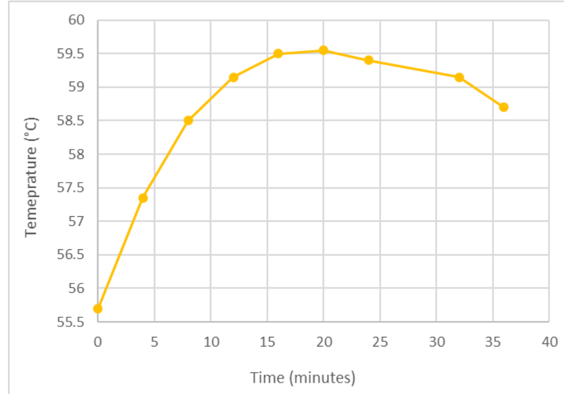

Fig. 8. PCM temperature vs time during storing period

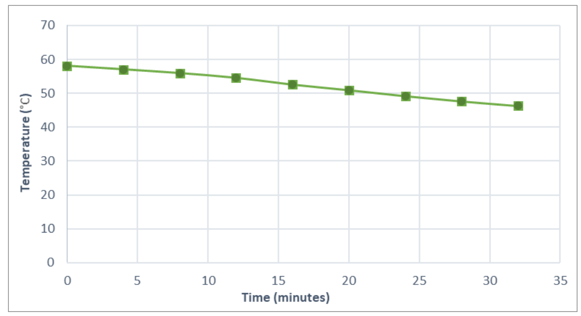

Fig. 9. PCM temperature vs time during discharging period

C. Discharging Period

Analysis of paraffin wax temperature, HTF's inlet and outlet temperature, and thermal efficiency variations with time during discharging period. Table-V shows the experimentally observed values in discharging period. The energy recovery by cold water, heat loss to ambient, sensible energy released by the PCM, and the thermal efficiency of system during discharging period are calculated by using equations (11), (13), (10), and (15) respectively, as given in Table VI.

The graphs of paraffin wax temperature vs time, Inlet and outlet temperature vs time, and thermal efficiency vs time are plotted Fig.9, Fig.10, and Fig.11 respectively.

1) PCM temperature variation with time: As evident from Fig. 6 the PCM temperature decreases linearly with time.

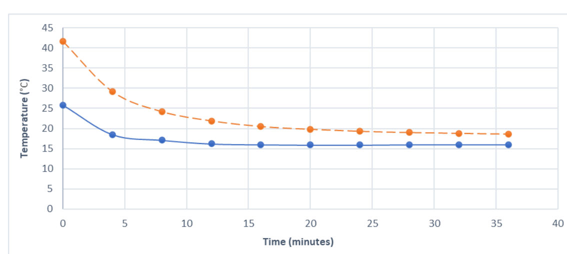

Fig. 10. Inlet and Outlet temperature of water vs time during discharging period

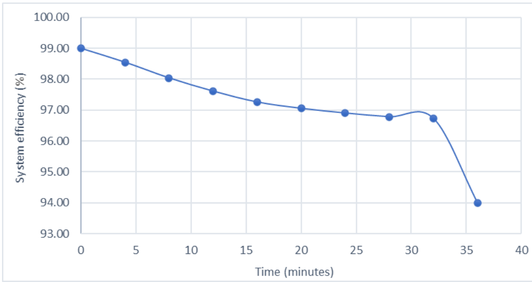

Fig. 11. System thermal efficiency vs time during discharging period

TABLE V
OBSERVED VALUES DURING DISCHARGING PERIOD

S.no	Time (min)	T_{hft1}(°C)	T_a (°C)	T_s (°C)	T_{b1} (°C)	T_{b4} (°C)	T_{b2} (°C)	T_{b3} (°C)	Flow rate (kg/s)
1	0	14.2	21.5	29	25.8	41.7	57.5	58.7	0.68
2	4	14.2	21.5	29	18.5	29.2	56.7	57.4	0.68
3	8	15.1	21.5	29.1	17.1	24.2	55.8	56.1	0.68
4	12	14.8	21.1	29	16.2	21.9	54.5	54.6	0.68
5	16	14.2	20.5	28.2	16	20.5	52.7	52.4	0.68
6	20	14.7	20.6	28.1	15.9	19.8	51.3	50.5	0.68
7	24	14.6	21.3	27.9	15.9	19.3	49.7	48.6	0.68
8	28	14.4	21.7	28.2	16	19	48.3	46.9	0.68
9	32	14.3	21.4	27.4	16	18.8	47	45.5	0.68
10	36	15	21.7	27.3	16	18.6	45.8	44	0.68

TABLE VI
CALCULATED VALUES DURING DISCHARGING PERIOD

S.no.	Time (min)	Energy recovered by cold water, $E_{recovered}$ (J)	E_{loss} to ambient (J)	Sensible energy released by PCM, $E_{released, PCM}$ (J)	System efficiency during Discharging (%)
1	0	126354.0	1286.1	127640.1	99.0
2	4	84552.7	1249.2	85801.9	98.5
3	8	60801.9	1217.6	62019.5	98.0
4	12	48451.6	1185.9	49637.5	97.6
5	16	39901.3	1124.5	41025.7	97.3
6	20	34676.1	1052.4	35728.5	97.1
7	24	30401.0	971.6	31372.6	96.9
8	28	27550.9	915.4	28466.3	96.8
9	32	25650.8	867.9	26518.8	96.7
10	36	24700.8	1577.7	26278.5	94.0

During discharging paraffin wax transfers the stored heat to cold water thus reducing its temperature with time.

2) Water Inlet T_{b1} and outlet T_{b4} temperature variation with time: Fig. 10 shows that inlet and outlet water temperature differential gets smaller with time, due to decrease in the temperature of paraffin wax with time leading to reduced heat transfer rate.

3) Changes in the thermal efficiency of the system with time: Fig. 11 shows the gradual shift in the system's thermal efficiency.From Fig. 11, system efficiency decreases with time.

D. Errors

The experiment had certain errors that need to be acknowledged.

- T_{b2} is lower than T_{b3}. This might be due to placement of thermocouple in PCM cylinder or due to inclination of PCM cylinder towards rear.
- The ambient temperature varies from 19.5 to 20.8°C, this might be due to disturbance in the ambient (fan, heater, etc.)
- T_{hft1} and T_{b1} should be same, but due to losses there is a difference between the two.
- During discharging T_{b1} is higher than T_{hft1}, because the discharging process was done right after charging and storing period and the pipes had absorbed heat during this period which led to rise in T_{b1} temperature during discharging.

IV. Conclusion

In this paper, the performance of paraffin wax as a PCM in TES system is analysed. The variation of paraffin wax temperature, inlet and outlet working fluid (water) temperature, and system efficiency with time is calculated for charging and discharging period. The analysis shows that during charging period, paraffin wax temperature increases with time, the difference in temperature of inlet and outlet working fluid diminishes over time and the system efficiency diminishes over time. Throughout the discharging time, temperature of paraffin wax decreases linearly with time, inlet and outlet working fluid temperature difference decreases with time and the system efficiency decreases with time.One of the major challenges associated with paraffin wax is its limited heat conductivity, which restricts the efficiency of TES system. Further research could be done to enhance the thermal conductivity of paraffin wax, also the use of composite PCM should be studied in thermal energy storage system.

ACKNOWLEDGMENT

We're grateful to the department of Sustainable Energy Engineering for the hands-on experiment experience. Special thanks to Dr. Sudarshan Narayanan and Dr. Jishnu Bhattacharya for their valuable guidance. Thanks to teaching assistant Mr. Sabyasachi Mohanty for his guidance during the experiment, and the technical staff—Mr. Chandan Kumar, Mr. Ajay Singh Chauhan, and Dr. Deepika Jhajhria—for setting up the system.

REFERENCES

[1] Britannica, The Editors of Encyclopaedia. "latent heat". Encyclopedia Britannica, 19 Jan. 2024, https://www.britannica.com/science/latent-heat. Accessed 25 February 2024.

[2] Srinivasaraonaik, Banavath Sinha, Shishir Singh, Lok. (2021). Phase Change Materials for Renewable Energy Storage Applications.

[3] Farid, Mohammed M., et al. "A review on phase change energy storage: materials and applications." Energy conversion and management 45.9-10 (2004):

[4] Shukla, Anant, D. Buddhi, and R. L. Sawhney. "Solar water heaters with phase change material thermal energy storage medium: A review." Renewable and Sustainable Energy Reviews 13.8 (2009): 2119-2125.

[5] Fazilati MA, Alemrajabi AA. Phase change material for enhancing solar water heater, an experimental approach. Energy Convers Manag 2013.

[6] Felinski P, Sekret R. Experimental study of evacuated tube collector/storage system containing paraffin as a PCM.

[7] Pardinas A, Alonso MJ, Diz R, Kvalsvik KH, Fern andez-Seara J. State-of-the-art for the use of phase-change materials in tanks coupled with heat pumps.

[8] Tiyasha, Shaktibala Suraj Kr Bhagat. "Phyto-filtration: a new approach of waste water treatment." Waste management 3.2 (2013).

[9] Khyad, A., et al. "Energy storage with PCMs: Experimental analysis of paraffin's phase change phenomenon improvement of its properties." J. Mater. Environ.

[10] Lab Manual Thermal Energy Storage, IIT Kanpur.