

Development and Performance Analyses of Thermal Energy Storage System using Shea Butter as Phase Change Material

Muhammad Ahmad¹, Ibraheem Shehu Diso², Koliya Laye²

¹Department of Mechanical Engineering, School of Engineering and Engineering Technology, Federal University of Technology Owerri, Imo State Nigeria.

²Department of Mechanical Engineering, Faculty of Engineering, Bayero University Kano, Kano State Nigeria.

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fluid.

Abstract— The focus of this study is to experimentally determine the performance of latent heat thermal energy storage using shea butter as a phase change material (PCM) in a heat exchanger (shell and tube). This involved determination of the thermo-physical properties of the PCM, design of a suitable heat exchanger (shell and tube) to serve as the storage system where the shell (mild steel) will contain the PCM in direct contact with the tube (copper), construction of the system based on the designed parameters and performance evaluation of the system through experiments (water used as heat transfer fluid), energy and exergy analyses. DSC analysis reveals a transition temperature in the range 31.26°C to 40.16°C and latent heat of 50.36kJ/kg. These values are low compared to other commonly used PCMs such as paraffin wax (100°C, 140kJ/kg), stearic acid (55.8°C, 160kJ/kg) and Acetamide (82°C, 263kJ/kg). The system is designed to heat water from 25°C to 35°C, however the maximum temperature achieved is 31°C. Melting and solidification curves shows non uniform melting and solidification of the PCM during charging and discharging operations. The overall performance of the system based on energy and exergy analyses revealed satisfactory performance with minimum energy efficiency of 59.04% and maximum of 89.88% and minimum exergy efficiency of 20.37% and 30.44% maximum.

I. INTRODUCTION

Thermal Energy extracted from solar thermal energy systems or energy recovery systems such as waste/excess heat from industrial heat processes are often more than demanded and are therefore allowed to waste. This is because like solar energy, waste heat demand and supply tends to be in mismatch. In order to meet with the out of phase demands for the aforementioned systems and their likes, there is need for supplementary or recovery system(s). One of the available options is to develop energy storage devices, which are as important as developing new sources of energy. Energy storage not only

reduces the mismatch between supply and demand but also improves the performance and reliability of energy systems and plays an important role in increasing the efficiency of energy utilization. Thermal energy can be stored in three different forms namely sensible heat storage, latent heat storage and thermochemical heat storage.

The use of a thermal storage system using phase change materials (PCMs) is one of the most effective ways of storing thermal energy and has the advantages of high-energy storage density (amount of energy stored in a given system or region of space per unit volume). Phase

transformation occurs at relatively constant temperature hence the isothermal nature of the storage process is of great advantage, (Sharma and Sagara 2005). Phase change materials (PCMs) have been widely used in latent heat thermal storage systems for heat pumps, solar engineering, and spacecraft thermal control applications. There are large numbers of PCMs that melt and solidify at a wide range of temperatures, making them attractive in a number of applications.

Many researchers have worked on thermal energy storage systems for more than four decades using different kinds of phase change materials and system configurations for different applications. Thirugnanam and Marimuthu (2013) have investigated experimentally the feasibility of using PCM in heat recovery system, in their study; a double pipe type heat exchanger was designed and fabricated for low temperature heat recovery system using paraffin wax as PCM. Two mass flow rates of 15lph and 20lph were used in the experiment. It is observed that the heat stored in 20lph is higher than 15lph. So when flow rate is increased the heat storing as well as heat releasing capacity increased. Their result shows the feasibility of using PCM in heat recovery system. Furthermore, Jesumathy et al. (2014) evaluated the thermal behavior of 0.7 kg of commercial paraffin in a shell-and-tube heat exchanger, placed both horizontally and vertically, under the influence of different heat transfer fluid (HTF) (water) mass flow rates and inlet temperatures during the melting and solidification processes. Results showed no subcooling of the paraffin and demonstrated that the modification of the HTF operating conditions has a higher influence during melting than during solidification.

A numerical study was conducted by Zhinuo Zhou et al. (2015) to explore the effectiveness of $\text{NH}_4(\text{SO}_4)_2 \cdot 12\text{H}_2\text{O}$ as a new inorganic phase change material used for solar thermal energy storage in residential building in cold climate. The heat transfer pattern was studied both experimentally and simulation. The charging heat efficiency was optimized when the heat source temperature was 26.5°C higher than the phase transition temperature. This helps satisfy the storage demand and also the utilization of solar thermal energy.

El-Kaddadi and Asbik (2017) carried out experimental study of heat transfer during latent heat storage cycle (charging/discharging) in a vertical cylindrical system. The experimental setup consists of two cylindrical tanks filled respectively with hot and cold water, a test bench, and measurement instruments. They observed that the convective heat transfer coefficient between the heat

transfer fluid (HTF) and the annular space is improved by increasing of the mass flow rate of the heat transfer fluid. Niu et al., (2019) carried out experimental investigations on thermal storage performance of a shell and tube unit with a metal-foam composite heat exchanger (Mtube) with pure paraffin (smooth tube) as the basis of comparison. The complete heat storage time of the Mtube unit was found to be 63.6% shorter than the smooth tube unit at the same flow rates. By comparing the temperature distribution of the two heat storage units, flow rate is found to have little effect on metal-foam-tube unit and relatively strong influence on the smooth-tube unit. The result also shows that compared to the smooth tube unit, the M-tube unit due to the expanded heat transfer area have improved heat transfer coefficient and weakened natural convection hence the bottom PCM in the M-tube unit melts faster.

Bayomy et al., (2019) developed a three dimensional numerical model of a water based thermal storage tank using phase change material. A computational fluid dynamics CFD numerical code was developed for a domestic hot water tank using PCM to the demand of a family of one, two, three and four. It was observed that for a given hot water supply, increasing the number of families increases the efficiency from 35% for family of one to 82% for four families. Also, increasing the hot water supply during the charging periods increased the storage efficiency from 35% to 39%. It was observed that increase in family demands improve the thermal efficiency of the storage system due to the increase in the portion of energy recovered during the night time.

In choosing a phase change material for thermal energy storage, the transition temperature and latent heat of fusion are the major properties considered. The transition temperature must correspond to the desired application temperature and the latent heat should be relatively large for a high storage density and to reduce the overall system size. Other properties such as thermal conductivity and specific heat capacity are also essential in the design of thermal storage system with phase change material.

This work aims at investigating the feasibility of using shea butter as phase change material for thermal energy storage. The latent heat of fusion and transition temperature were determined using differential scanning calorimetry and presented in figure 2.1 while other properties such as density, thermal conductivity and specific heat capacity were determined using appropriate laboratory equipments. The thermo-physical properties of the shea butter used are presented in table 2.1 below

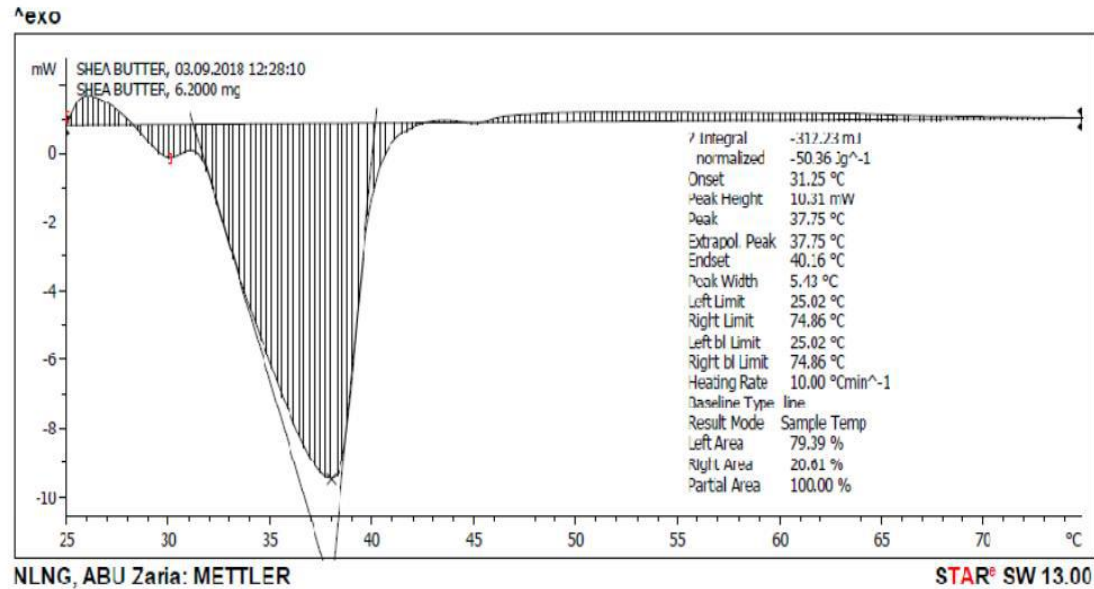


Fig.1.1: Result of Differential scanning calorimetry analysis of shea butter

Table 1.1: Thermo-physical properties of shea butter

Transition temperature	31.26 – 40.16 °C
Latent heat of fusion	50.36 kJ/kg
Density (liquid phase)	880 kg/m ³
Density (solid phase)	910 kg/m ³
Specific heat capacity (solid phase)	3.19 kJ/kg°C
Specific heat capacity (liquid phase)	3.32 kJ/kg°C
Thermal conductivity	0.26 W/m ⁰ K

II. METHODOLOGY

The experimental setup consists of two 50 liters plastic containers for hot and cold water supply which is the heat transfer fluid for charging and discharging processes. An electric heater of power rating of 1500W with thermostat for generating hot water at controlled temperature. Each of the containers have a control valve for adjusting the flow rate of the heat transfer fluid and are connected to a digital flow meter using a T-joint. The digital flow meter has a temperature sensor that indicates the temperature of the fluid passing through it. A total of four thermocouples, three within the thermal energy storage system and one at the outlet of the TES are connected to a multipoint digital

thermocouple meter to record the outlet temperature and the axial temperature distribution within the phase change material over a time interval. The technical specification of the heat exchanger, schematic diagram and the experimental setup are shown in table 2.1 and figures 2.1 and 2.2 respectively.

Table 2.1: Technical specification of the thermal storage system

Part Name	Material	Size
PCM	Shea Butter	7kg
Inner pipe	Copper	10mm diameter, 5m length
No of coil	Copper	15
Coil diameter	Copper	104mm
Coil pitch	Copper	30mm
Outer pipe	Mild steel	152.4mm diameter, 0.45m length
Insulation	Fiber glass	5cm
External case	Aluminum	0.5mm

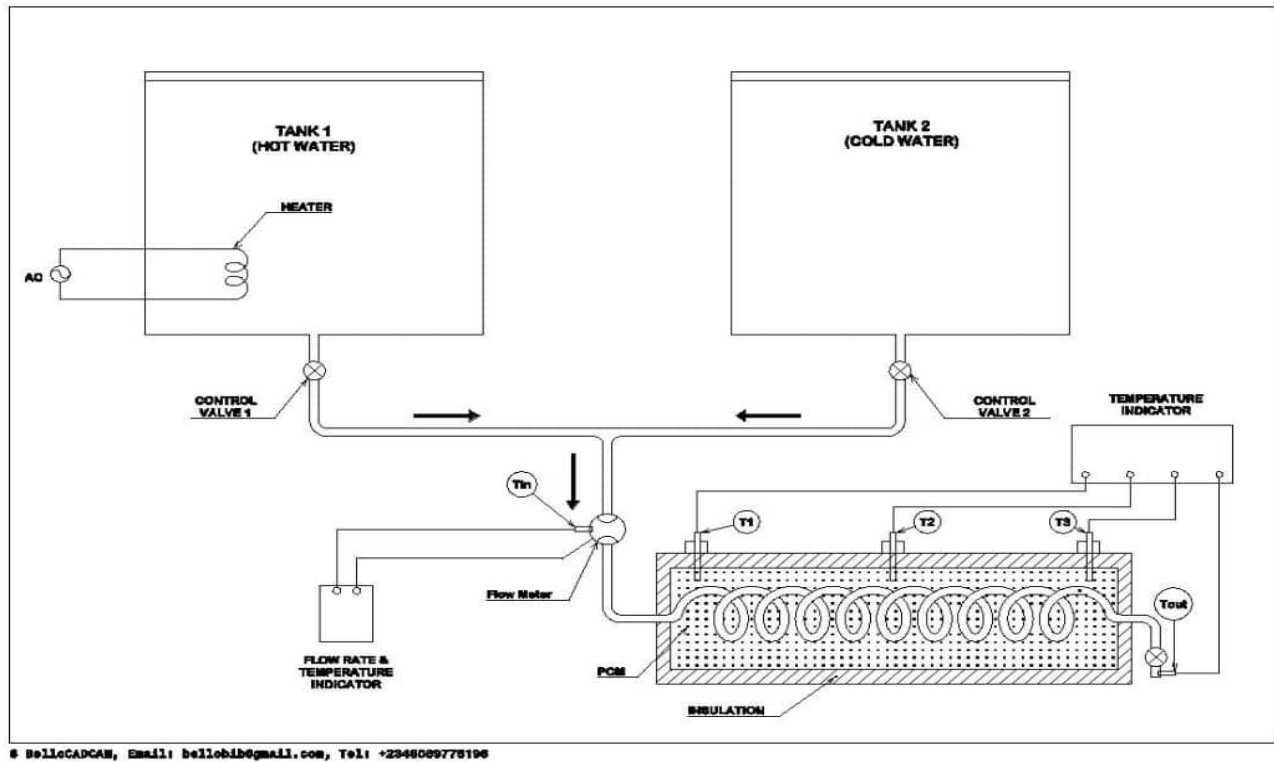


Fig.2.1: Schematic Diagram of the Experimental Setup



Fig.2.2: Experimental setup

III. RESULTS AND DISCUSSION

3.1 Energy and Exergy Analyses

The performance of the developed thermal storage system is analyzed by experiment. Four experiments were conducted for different heat transfer fluid flow rates of 0.0145, 0.0180, 0.021, and 0.0245 kg/s and hot water inlet temperature in the range 60°C to 70°C. The cold water inlet temperature during discharging process is the ambient temperature

For experiment 1

Rate of Energy storage is determined from the equation

$$\begin{aligned} \text{rate of Energy in, } \dot{Q} &= \dot{m}_f(T_{in} - T_{out}) \\ &= \dot{m}(h_{in} - h_{out}) \end{aligned}$$

Average $T_{in} = 68^\circ\text{C}$

Average $T_{out} = 64^\circ\text{C}$

$$h_{in} = h_f \text{ at } 68^\circ\text{C} = 284.6 \text{ kJ}$$

$$h_{out} = h_f \text{ at } 64^\circ\text{C} = 267.82 \text{ kJ}$$

Flow rate = 0.89 lpm = 0.00089 m³/min

Mass flow rate of heat transfer fluid = volumetric flow rate × density

$$\text{Density of HTF} = 1/v_f \text{ at } 68^\circ\text{C}$$

$$v_f \text{ at } 68^\circ\text{C} = 0.10218 \times 10^{-2} \text{ m}^3/\text{kg}$$

$$\text{Density of HTF at } 68^\circ\text{C} = 978.66 \text{ kg/m}^3$$

$$\begin{aligned} \text{Mass flow rate } \dot{m} &= 0.00089 \text{ m}^3/\text{min} \times \\ &978.66 \text{ kg/m}^3 \times \frac{1 \text{ min}}{60 \text{ sec}} = 0.0145 \text{ kg/s} \end{aligned}$$

$$\begin{aligned} \text{rate of Energy in, } \dot{Q} &= \dot{m}(h_{in} - h_{out}) \\ &= 0.0145 \times (284.6 - 267.82) \end{aligned}$$

$$\dot{Q} = 0.2433 \text{ kW}$$

Energy stored over 44 mins of charging

$$Q = \dot{Q} \times \text{time} = 0.2433 \times 44 \times 60 = 642.312 \text{ kJ}$$

$$\text{Exergy stored} = \text{Energy stored} * \left(1 - \frac{T_e}{T_{pcm}}\right)$$

T_e = ambient temperature = 25°C = 298 K

$T_{pcm} = 52.67^\circ\text{C}$

$$\text{exergy stored} = 642.312 \left(1 - \frac{298}{325.67}\right) = 54.57 \text{ kJ}$$

For Discharging Process,

$$\begin{aligned} \text{rate of Energy retrieved, } \dot{Q}_r &= \dot{m}_f(T_{out} - T_{in}) \\ &= \dot{m}(h_{out} - h_{in}) \end{aligned}$$

Average $T_{in} = 29^\circ\text{C}$

Average $T_{out} = 30.30^\circ\text{C}$

$$h_{in} = h_f \text{ at } 29^\circ\text{C} = 121.5 \text{ kJ}$$

$$h_{out} = h_f \text{ at } 64^\circ\text{C} = 126.945 \text{ kJ}$$

$$\dot{m} = 0.0145 \text{ kg/s}$$

$$\dot{Q}_r = 0.0145(126.947 - 121.5) = 0.079 \text{ kW}$$

Energy retrieved over 80 minutes of discharge

$$Q_r = 0.079 \times 80 \times 60 = 379.20 \text{ kJ}$$

$$\text{Exergy released by the PCM} = Q * \left(1 - \frac{T_e}{T_{pcm}}\right)$$

$$\begin{aligned} \text{Exergy released by PCM} &= 379.2 \left(1 - \frac{298}{307}\right) \\ &= 11.117 \text{ kJ} \end{aligned}$$

$$\text{Energy efficiency, } \eta = \frac{\text{energy recovered from TES}}{\text{energy input to TES}}$$

$$\eta = \frac{379.20}{642.312} = 0.5904 = 59.04\%$$

$$\text{Exergy efficiency, } \psi = \frac{\text{Exergy recovered from TES}}{\text{Exergy input to TES}}$$

$$\psi = \frac{11.117}{54.57} = 0.2037 = 20.37\%$$

In the same way the rate of energy storage, rate of energy retrieval, energy stored during charging, energy retrieved during discharge, exergy stored, exergy retrieved, energy efficiencies and exergy efficiencies for experiments 2, 3 and 4 are determined and presented in table 3.1 below.

Table 3.1: Results of energy and exergy analysis for the four experiment

No.	Mass flow rate (kg/s)	Rate of charging (kW)	Rate of Discharge (kW)	Energy stored (kJ)	Energy retrieved (kJ)	Energy efficiency (%)	Exergy stored (kJ)	Exergy retrieved (kJ)	Exergy efficiency (%)
1	0.0145	0.243	0.061	642.312	379.2	59.04	54.57	11.117	20.37
2	0.0180	0.272	0.103	326.400	271.92	83.30	27.116	8.255	30.44
3	0.0245	0.589	0.264	706.800	635.27	89.88	59.376	17.27	28.08
4	0.0210	0.370	0.120	444.000	316.00	71.17	39.346	9.26	29.53

3.2 Melting/Solidification and Temperature Distributions

The melting/solidification of the PCM and temperature readings at three points ($T_{1\text{pcm}}$, $T_{2\text{pcm}}$ and $T_{3\text{pcm}}$) for the charging and discharging processes for the four experiments are depicted in figures 3.1a,b,c,d to 3.4a,b,c,d.

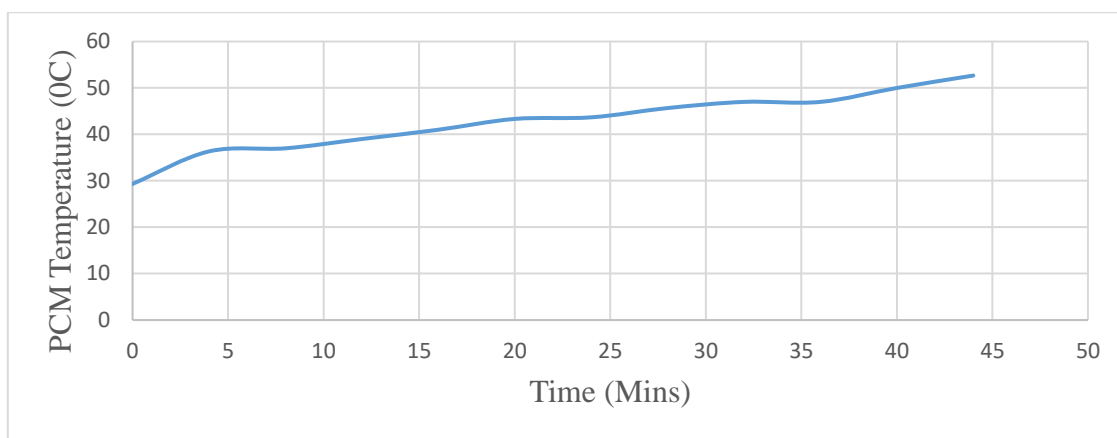


Fig.3.1a: Melting curve for charging process of experiment 1 (mass flow rate-0.0145, average T_{in} -68°C, charging period-44min, energy stored-642.312kJ, exergy stored-297.39kJ)

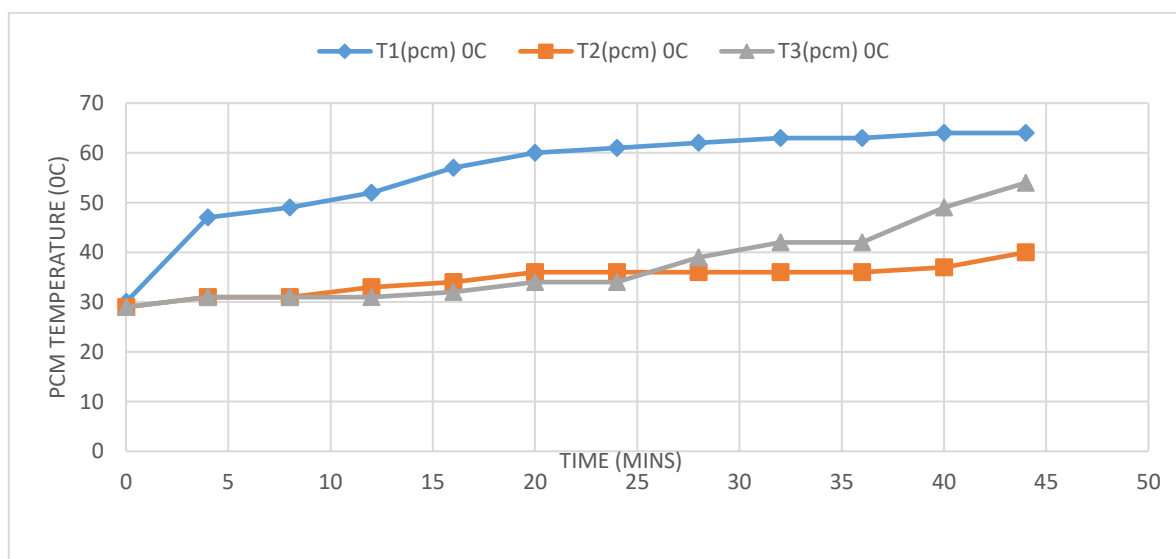


Fig.3.1b: Temperature distribution in the PCM during charging in experiment 1

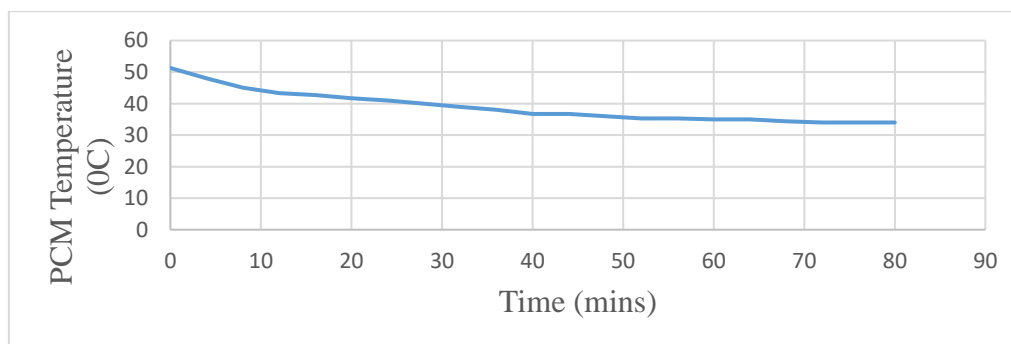


Fig.3.1c: Solidification curve for discharging process of experiment 1 (mass flow rate-0.0145kg/s, average T_{in} -29°C, average T_{out} -30.30°C, discharging period-80mins, energy retrieved-379.2kJ, exergy retrieved-55.78kJ)

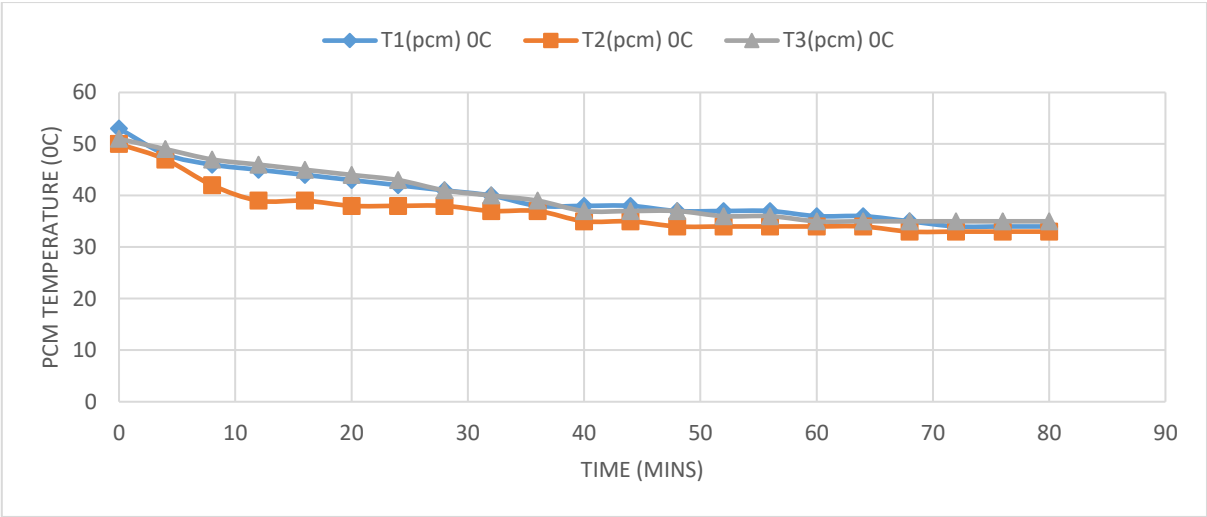


Fig.3.1d: Temperature distribution during discharge process for experiment 1

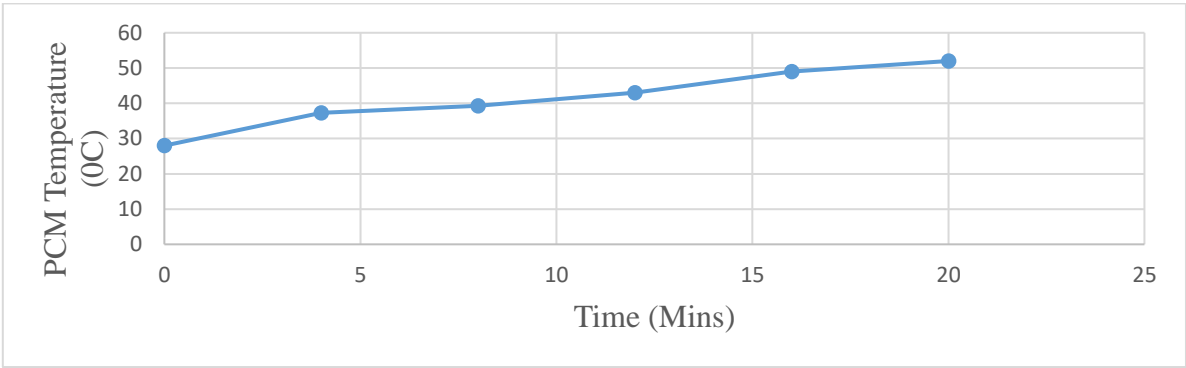


Fig.3.2a: melting curve for charging process of experiment 2 (mass flow rate-0.018kg/s, average Tin-69°C, charging period-20mins, energy stored-326.4.312kJ, exergy stored-150.674kJ)

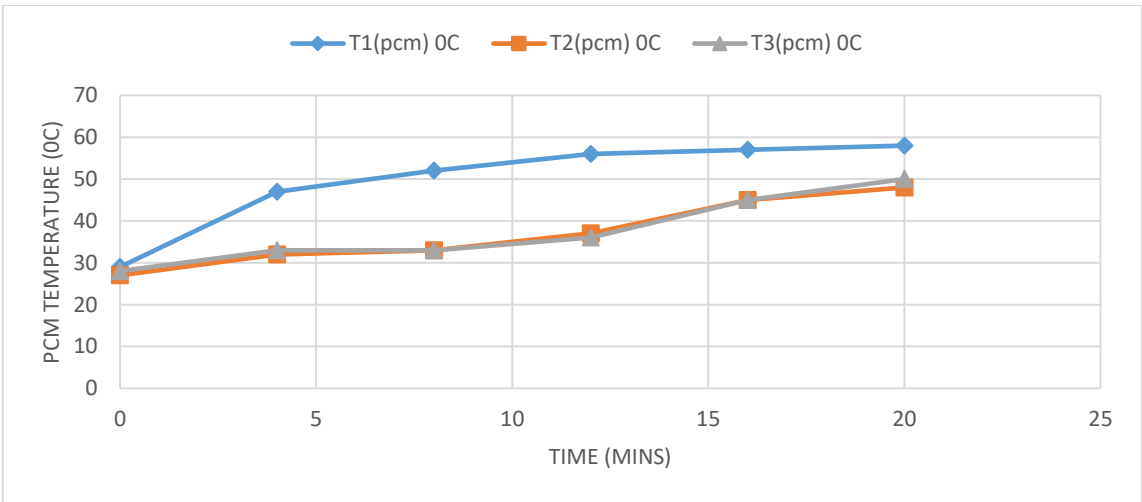


Fig.3.2b: Temperature distribution in the PCM during charge process for experiment 2

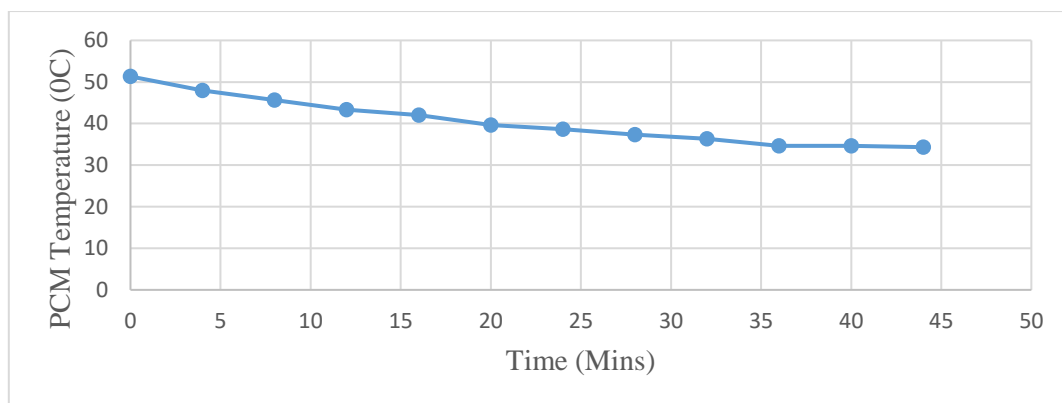


Fig.3.2c: Solidification curve for discharging process of experiment 2 (mass flow rate-0.018kg/s, average T_{in} -28°C, average T_{out} -29.36°C, discharging period-44mins, energy retrieved-271.92kJ, exergy retrieved-50.142kJ)

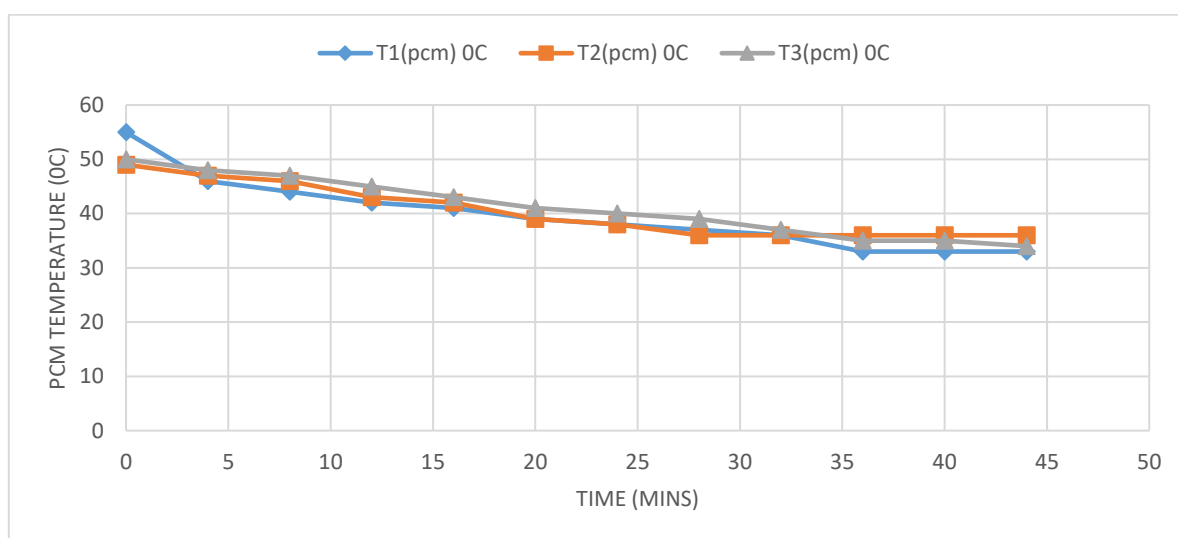


Fig.3.2d: Temperature distribution in the PCM during discharge process for experiment 2

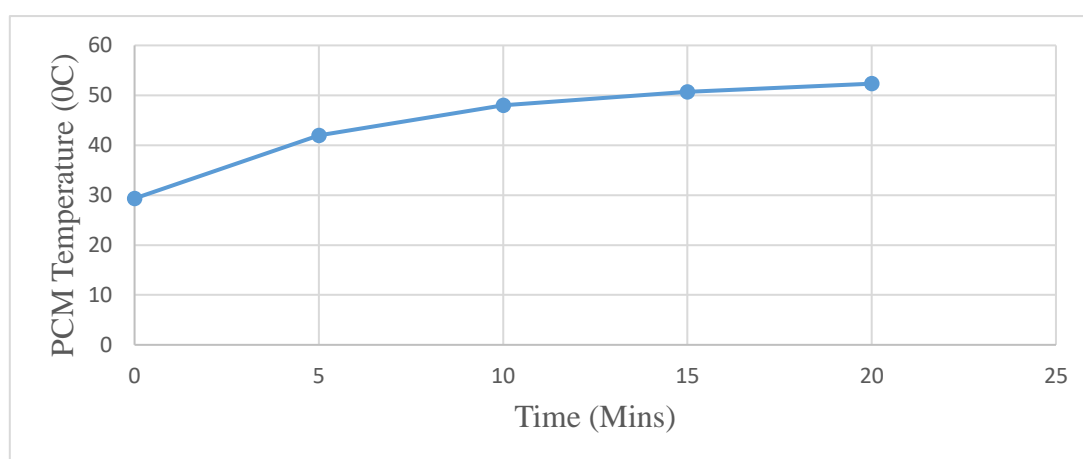


Fig.3.3a: Melting curve for charging process of experiment 3 (mass flow rate-0.0245kg/s, average T_{in} -66.25°C, charging period-20mins, energy stored-706.8kJ, exergy stored-328.662kJ)

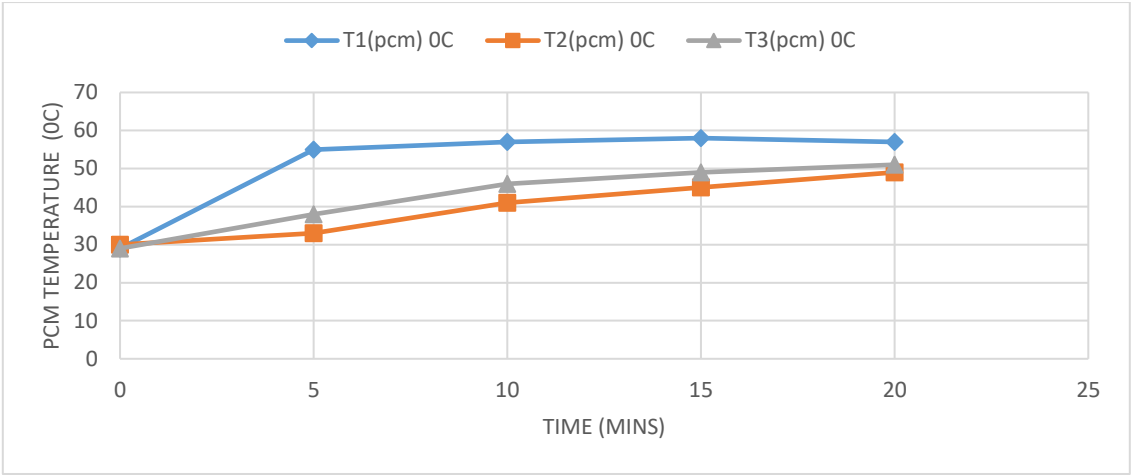


Fig.3.3b: Temperature distribution in the PCM during charging for experiment 3

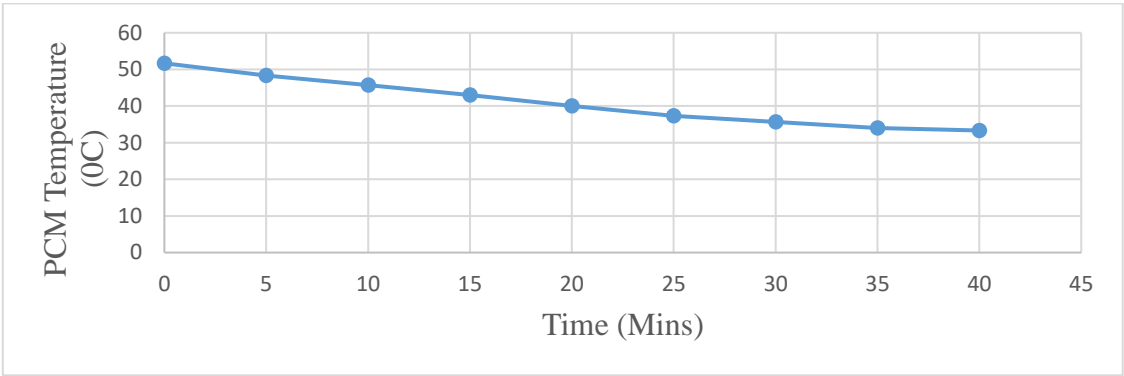


Fig.3.3c: Solidification curve for discharging process of experiment 3 (mass flow rate-0.0245kg/s, average T_{in} -28°C, average T_{out} -29.62°C, discharging period-40mins, energy retrieved-635.27kJ, exergy retrieved-101.643kJ)

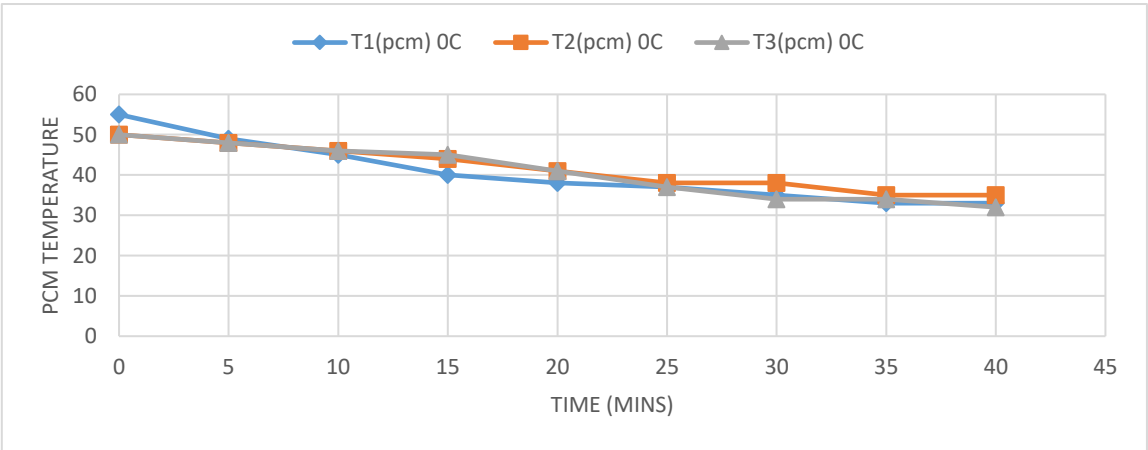


Fig.3.3d: Temperature variation in the PCM during discharge process for experiment 3

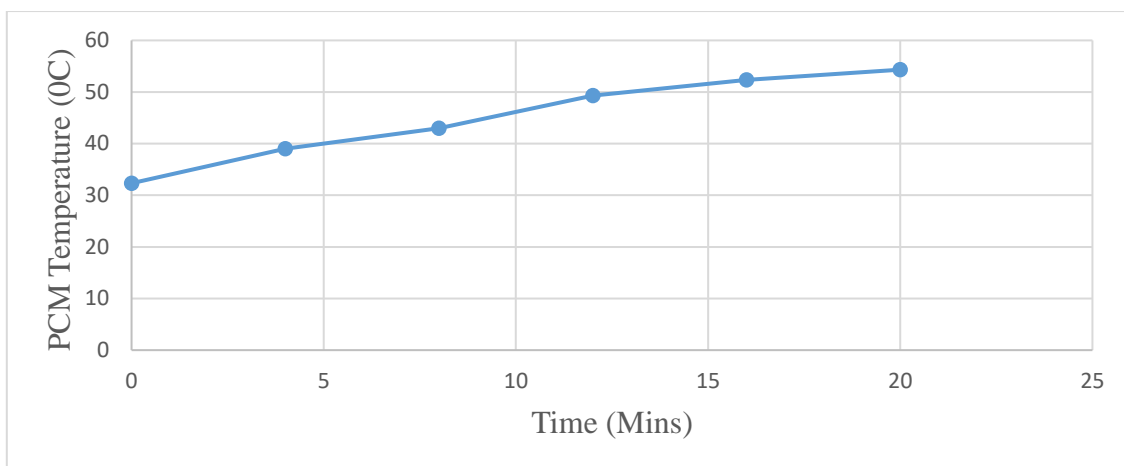


Fig.3.4a: Melting curve for charging process of experiment 4 (mass flow rate-0.021kg/s, average T_{in} -69°C, charging period-20mins, energy stored-444kJ, exergy stored-215.176kJ)

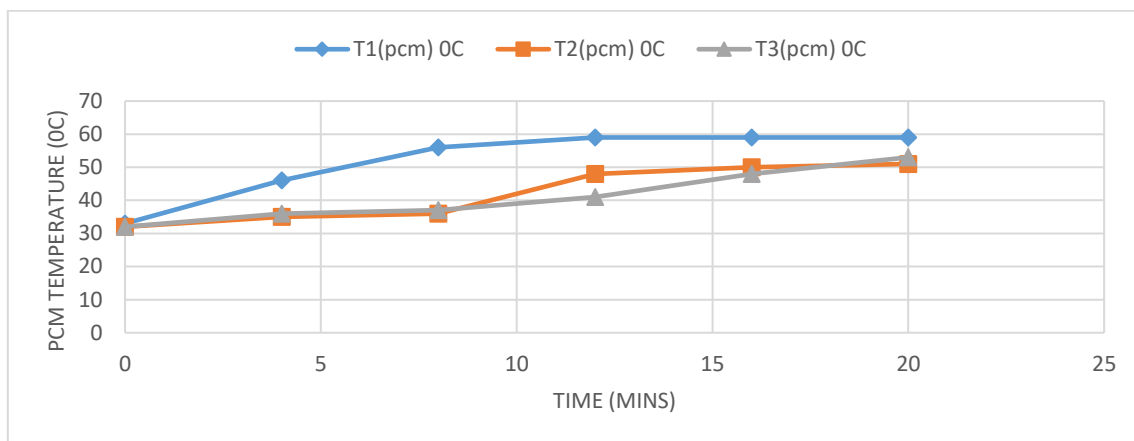


Fig.3.4b: Temperature distribution in the PCM during charging process for experiment 4

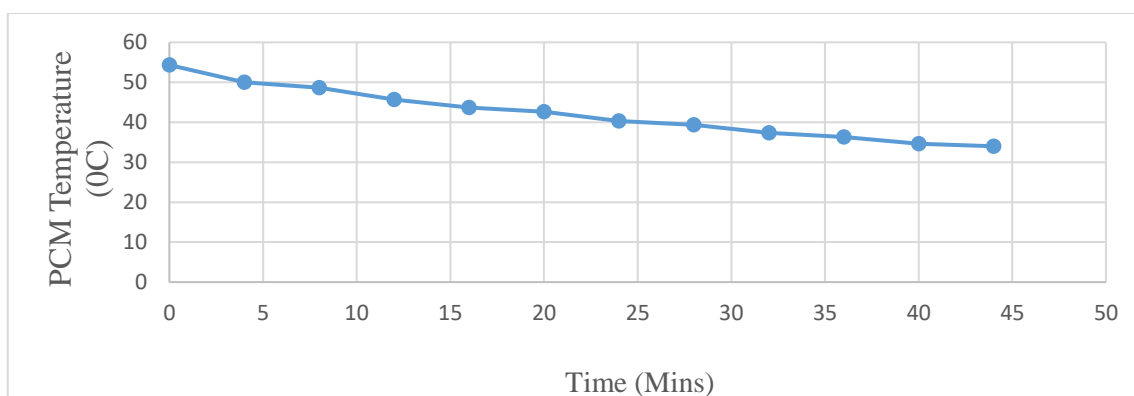


Fig.3.4c: Solidification curve for discharging process of experiment 4 (mass flow rate-0.021kg/s, average T_{in} -28°C, average T_{out} -29.36°C, discharging period-44mins, energy retrieved-316kJ, exergy retrieved-55.774kJ)

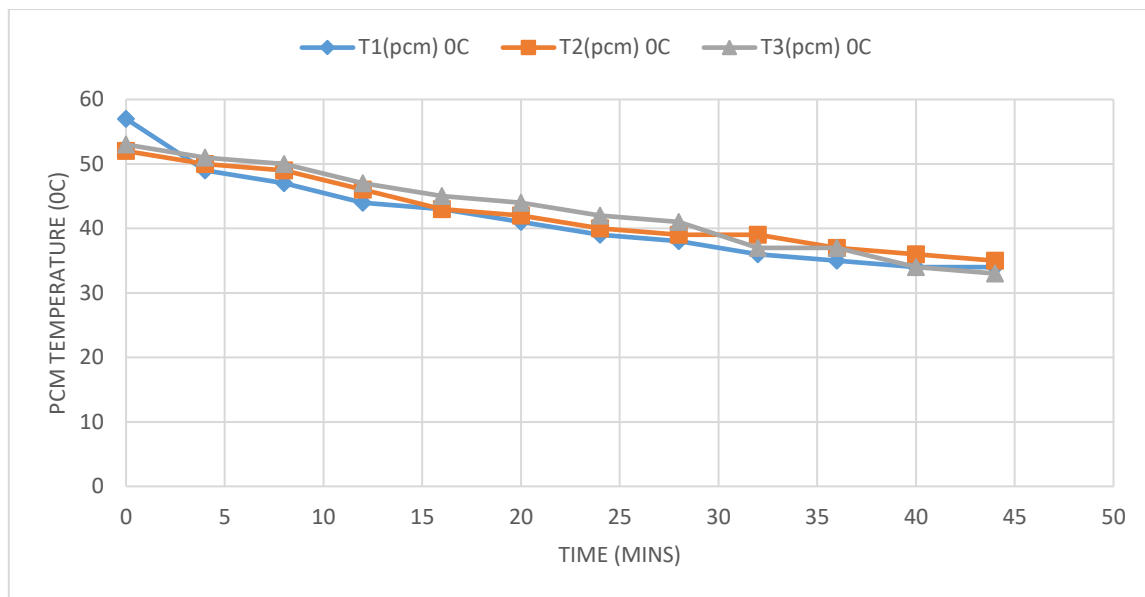


Fig.3.4d: Temperature distribution in the PCM during discharge for experiment 4

IV. DISCUSSION OF RESULTS

The performance of the developed thermal storage system is analyzed by experiment. Four experiments were conducted for different heat transfer fluid flow rates of 0.0145, 0.0180, 0.021, and 0.0245 kg/s and hot water inlet temperature in the range 60°C to 70°C. The cold water inlet temperature during discharging process is the ambient temperature. The flow rates were measured using a digital flow meter with a thermocouple that reads the inlet temperature of the heat transfer fluid. Temperatures within the PCM and the outlet temperature were measured using a multipoint digital thermocouple meter.

The selected phase change material like most of phase change materials available for thermal energy storage suffers low thermal conductivity which results in high charging and discharging period and incomplete melting and solidification of the PCM during operations. Characterization of the shea butter reveals low thermal conductivity of 0.26 W/mK at 35°C and Latent heat of fusion of 50.36 kJ/kg. This value is low compared to paraffin wax which is one of the most commonly used PCM for low temperature applications. The low latent heat of this PCM will lead to low energy storage density and by implication a large in size energy storage unit with low energy to be stored.

The temperature readings from three points ($T_{1(pcm)}$, $T_{2(pcm)}$ and $T_{3(pcm)}$) within the PCM during charging and discharging were found to vary considerably as depicted in figures 3.1b, 3.1d, 3.2b, 3.2d, 3.3b, 3.3d, 3.4b and 3.4d. It was observed that the maximum temperature attained by the heat transfer fluid in discharge process of all the experiments is 31°C and a maximum temperature

increment (ΔT) of 3°C (28°C to 31°C). This could be attributed to the low thermal conductivity of the PCM and non-uniform solidification of the PCM.

Generally, low thermal conductivity of phase change materials results to poor performance of thermal energy storage system and local concentration of heat which tends distorts the thermal properties of PCM and may also lead to system failure.

The energy stored, energy retrieved, exergy stored and exergy retrieved were computed using equations. Table 3.1 above give the summary of computed results. It could be observed that the heat transfer fluid flow rate has significant effect on the charging and discharging times. The energy stored is observed to increase with increase in HTF flow rate for the same charging time of 20 minutes for experiments 2, 3, and 4 except for experiment 1 which has high melting time of 44 minutes and relatively high energy stored. This variation might be attributed to the degree of melting of the PCM. This same behavior is observed for energy retrieved, exergy stored and exergy retrieved.

Energy and exergy efficiencies were also evaluated using equations and presented in table 4.5. Since exergy is a measure of the quality of energy, exergy efficiency is more significant than energy efficiency and should therefore be considered in the evaluation of thermal energy storage systems. Energy and Exergy efficiencies for experiments 1, 2, 3 and 4 were found to be 59.04, 83.83, 89.88, 71.17 and 18.76, 33.28, 30.92 and 25.92% respectively.

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