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Analysis of Thermal Energy Storage system using Paraffin Wax as Phase Change Material

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Abstract

A significant amount of heat is wasted in electricity general, manufacturing, chemical and industrial process. Recovery and reuse of this energy through storage can be useful in conservation of energy and meeting the peak demands of power. A shell and spiral type heat exchanger has been designed and fabricated for low temperature industrial waste heat recovery using phase change material. Paraffin wax (Melting Point 54 ^oC) was used as storage media due to its low cost and large-scale availability in Indian market. Experiments were performed for different mass flow rates and inlet temperature of heat transfer fluid for recovery and use of waste heat. The effect of mass flow rate on the performance of the system was studied. Calculations for overall heat transfer during charging (melting of PCM) and discharging (solidification of PCM) and heat discharging efficiency were also made.
Keyword- Phase Change Material; Paraffin Wax; Charging; Discharging

I. INTRODUCTION

A. General

The increasing gap between the global demand and supply of energy is becoming a major threat as well as a challenge for the engineering community to fulfill the needs of the energy hungry society. Many forums and energy management groups have been formed to emphasize the storage of energy in both industrial and domestic sectors, in any possible form. The utilization of the abundant source solar, thermal energy and hot waste streams available in industries has attracted the scientific community to provide attractive solutions for the problems on energy conservation and storage/ retrieval. Different configurations of latent heat thermal storage (LHTS) units find their wide applications in various engineering fields which are listed in Table 1.1

S. No.	*Fields*
1	*Solar based dynamic space power generation*
2	*Solar thermal applications*
3	*Industrial waste heat recovery*
4	*Automobiles*
5	*Cooling of electronics*
6	*Textiles*
7	*Passive heating of buildings*
8	*Air conditioning systems*

Table 1.1: Applications of LHTS units

LHTS units employ phase change materials (PCMs) which undergo change of phase (solid-to-liquid and vice versa) during the energy transfer process. During the last four decades many such materials, with wide range of melting/freezing point, have been identified and studied extensively.

B. Thermal Energy Storage

Thermal energy can be stored as a change in internal energy of a material as sensible heat, latent heat and thermo - chemical or combination of these. In Sensible Heat Storage (SHS), thermal energy is stored by raising the temperature of a solid or liquid.

The extractable energy from the LHS during the discharge period can be calculated by the following equation under the assumption that there was no heat loss from the system.

$$Q = mCp\Delta T \qquad (1.1)$$

Where Q is the rate of extractable energy from the LHS (KJ/min),
m is the inlet liquid flow rate (kg/ min),
Cp is the specific heat (kJ / kg K) and
ΔT is the temperature difference between inlet and outlet fluid (K)

- A suitable PCM with its melting point in the desired temperature range.
- A suitable heat exchange surface and a suitable container compatible with the PCM.

Any latent heat energy storage system must therefore, possess at least following three properties.

II. PHASE CHANGE MATERIALS & CLASSIFICATION OF PCMS

A. Introduction

A phase change material (PCM) is a substance with a high heat of fusion which, melting and solidifying at a certain temperature, is capable of storing and releasing large amounts of energy. Materials that melt below 15ºC are used for storing coolness in air conditioning applications, while materials that melt above 90ºC are used for absorption refrigeration. PCM formation and classifications are following:

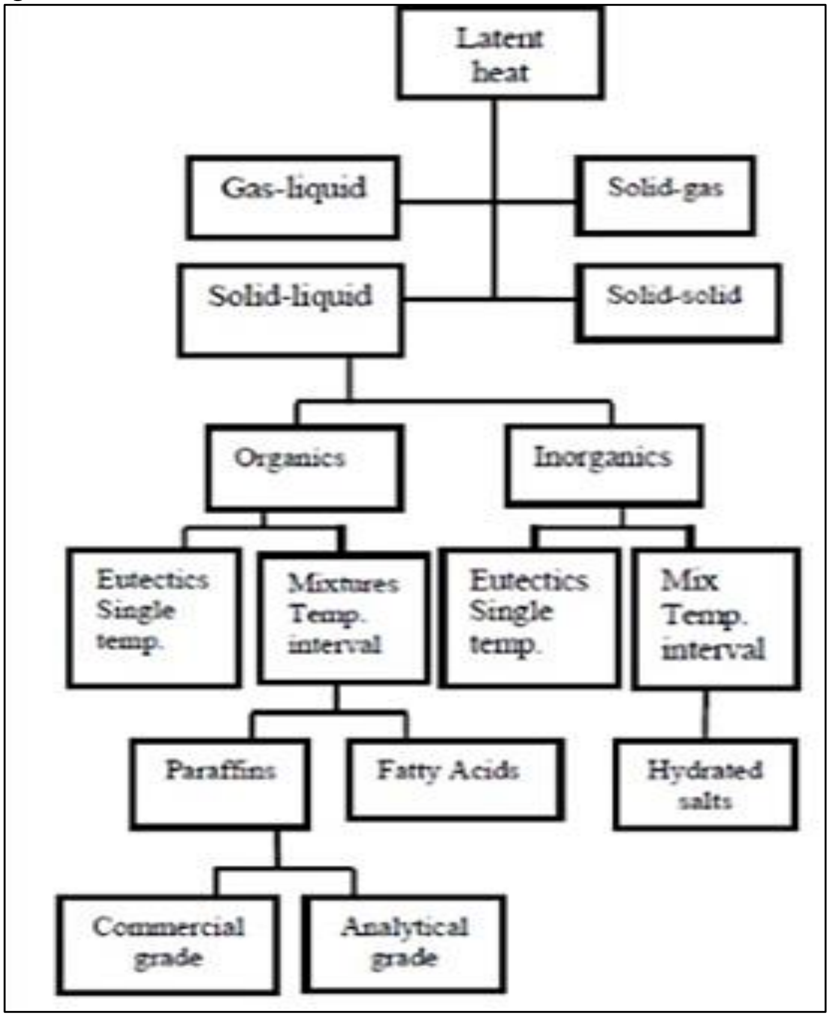

Fig. 2.1: Classification of PCM

	Compound	*Melting temp. (ºC)*	*Heat on fusion (kJ/kf)*	*Thermal conductivity (W/m K)*	*Density (kg/m3)*
Inorganics	*MgC12 6H2O*	*117*	*168.6*	*0.570 (liquid, 120ºC) 0.694 (solid 90ºC)*	*1450 (liquid, 120ºC) 1569 (solid, 20ºC)*

	Mg(NO3)2 6H2O	*89*	*162.8*	*0.490 (liquid, 95ºC) 0.611 (solid, 37ºC)*	*1550 (liquid, 94ºC) 1636 (solid, 25ºC)*
	Ba(OH)2 8H2O	*48265.7*	*265.7*	*0.653 (liquid, 85.7ºC) 1.225 (solid, 23ºC)*	*1937 (liquid, 84ºC) 2070 (solid, 24ºc)*
Organics	*Paraffin wax*	*64*	*173.6*	*0.167 (liquid, 63.5ºC) 0.346 (solid, 33.6ºC)*	*916 (solid, 24ºC) 790 (liquid, 65ºC)*
	Polyglycol E600	*22*	*127.2*	*0.189 (liquid, 38.6ºC)*	*1232 (solid, 4ºC) 1126 (liquid, 25ºC)*

Table 2.1: Measured thermo physical data of some PCMs

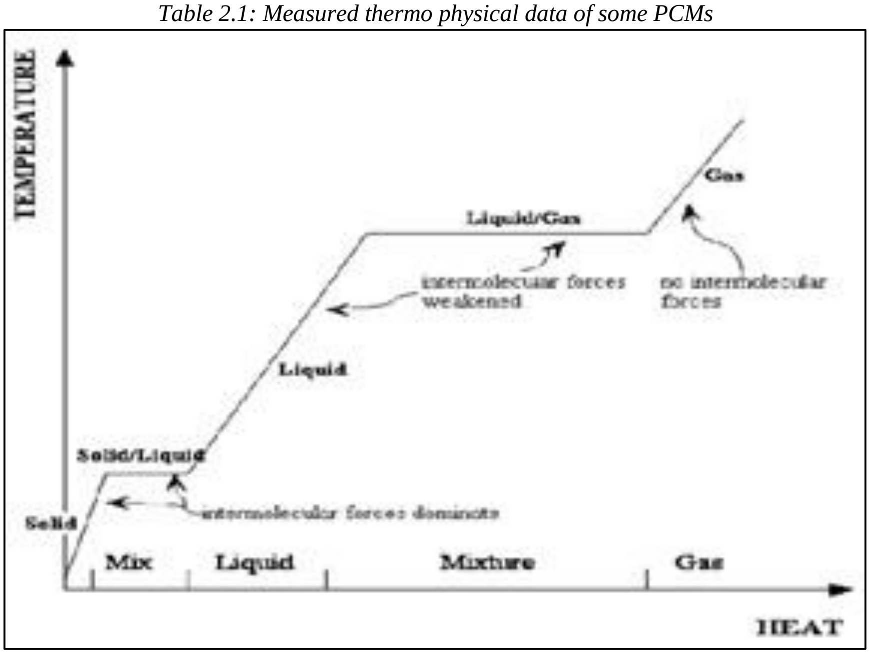

Fig. 2.2: Phase change diagram of materials

B. Required Properties

1) Thermo Physical Properties
- Melting temperature in the desired operating temperature range.
- High latent heat of fusion per unit volume.
- High specific heat.
- High thermal conductivity.

2) Kinetic Properties
- High nucleation rate to avoid super cooling of the liquid phase.
- High rate of crystal growth.

3) Chemical Properties
- Chemical stability, Non-toxic, non-flammable and non-explosive.
- Complete reversible freeze / melt cycle.

Measured thermo physical data of some PCMs

C. Thermal Conductivity Enhancement

1) High Conductivity and Low Density Materials

Due to relatively high density, the metal particles/metal structures may settle on the bottom surface of the container and add considerable weight to the system. All metal particles are not compatible with all PCMs. For example, with paraffin, aluminium is compatible, whereas copper and nickel are not compatible.

Similarly, aluminium and copper are not compatible with some salt hydrates. Hence, there has been a search for low-density high conductivity additives, which should be compatible with all PCMs. Since the densities of carbon fibers are relatively lower than those of metals and the thermal conductivities are almost equal to that of aluminium and copper, these can be better alternatives to enhance the thermal performance of LHTS systems.

The study was extended to investigate the effect of surface characteristics of fibers on solidification rate and found higher transfer rate with surface treated fibers than that with fibers of untreated surface. The study has also revealed the importance of uniform distribution of fibers in the PCM to obtain further enhancement in the performance. In a cylindrical capsule, carbon fibers were added in the PCM in two ways.

In the first case fibers were randomly distributed, where as in the second case brush type fibers were used. The effective thermal conductivity with brush type was found to be three times higher than that with random type. This is because in brush type the fibers were distributed uniformly in such a way all the fibers were arranged in radial direction, which was the heat flow direction.

D. Paraffin WAX

The normal paraffin’s of type CnH2n+2 are a family of saturated hydrocarbons with very similar properties. Paraffins between C5 and C15 are liquids, and the rest are waxy solids. Paraffin wax is the mainly used commercial organic heat storage PCM. It consists of mainly straight chain hydrocarbons that have melting temperature from 23 to 67^{o}C.

1) Advantages

- Paraffin waxes show no tendency to segregate.
- Stable properties after 1500 cycles in commercial grade paraffin wax.
- Paraffin waxes show high heats of fusion, etc.,

Melting temperature of the PCM	*54^{o}C*
Latent heat of fusion	*265.9KJ/Kg*
Density of the PCM (liquid phase)	*775 kg/m^{3}*
Density of the PCM (solid phase)	*833.60 kg/m^{3}*
Specific heat of the PCM (solid phase)	*2.384 kJ/kg^{o}k*
Specific heat of the PCM (liquid phase)	*2.44KJ/kg^{o}K*
Thermal Conductivity	*0.15 W/m^{o}K*

Table 2.2: Thermo-physical properties of commercial grade paraffin wax.

III. EXPERIMENTAL SETUP DESIGN

A. Requirements of This Device

The thermal performance of a heat recovery system with storage, a shell and double pipe type heat exchanger was designed and fabricated. PCM container was filled with 1.5 Kg commercial grades Paraffin Wax being used as Latent Heat Storage media. Type T Copper Constantan thermocouples were used for measuring the inlet & outlet temperature of HTF and the PCM temperature, for the present series of experiment water is used as HTF. A data acquisition system was used for measurement of temperatures. A two-tank system was used for maintaining a constant pressure head for inlet water to maintain nearly constant flow rate.

Heaters are also provided in the water tanks for constant inlet water temperature during charging mode. Flowing hot water through HTF tubes started the energy-charging test, and the stored energy was extracted by passing cold water in the HTF tubes. Ambient temperature and flow rate of water coming out from the heat exchanger PCM temperatures of the heat exchanger at four axial locations (shown in figure 3.1) were also measured simultaneously at an interval of 15 minutes.

Component	*Material*	*Density kg/m3*	*Volume m3*	*Mass Kg*
PCM	*Paraffin wax*	*834*	*0.001963*	*1.637*
Inner pipe	*Copper*	*8816*	*0.00009613*	*0.847*
Outer pipe	*Mild Steel*	*7795*	*0.000110*	*0.859*
Insulation	*Thermo cool*	*150*	*0.000589*	*0.088*
External case	*Pvc*	*1200*	*0.000785*	*0.942*

Table 3.1: Components specifications of model Component

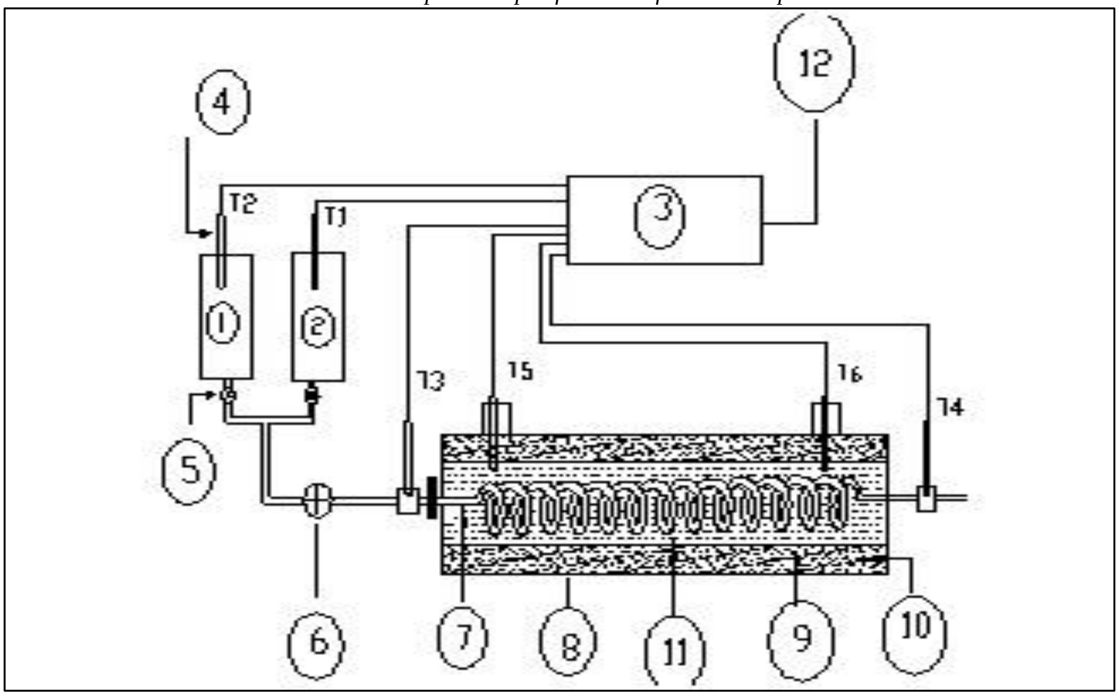

Fig. 3.1: Schematic Diagram of a Double pipe Heat Exchanger with Heat Storage & two stages feed water tank.

1. Cold water tank	2. Hot water tank
3. Temperature indicator	4. Thermocouple
5. Gate valve	6. Flow meter
7. Copper tube	8. Pvc tank
9. PCM tank	10. Thermo cool
11. Paraffin wax	12. Power supply

IV. EXPERIMENTAL RESULTS AND DISCUSSION

A. Charging Process – Heat Stored

The first experiment was conducted with flow rate 10lt/hr and the inlet temperature of the hot water was kept 85-90 ^oC and the atmospheric temperature is 32^oC. Initially, temperature of PCM is 32^oC and as the HTF exchanges its heat energy to PCM, the PCM gets heated up to melting temperature (storing the energy as sensible heat). Later, heat is stored as latent heat once the PCM melts and becomes liquid. The energy is then stored as sensible heat in liquid PCM. Temperature of the PCM and HTF are recorded at intervals of 15 minutes. The charging process is continued until the PCM temperature reaches maximum temperature.

B. Discharging Process-Heat Liberated

The discharging process was conducted with flow rate 10lt/hr and the inlet temperature of the cold water kept at the atmospheric temperature is 32^oC. During the discharging process, the cold water is circulated through the TES tank continuously. Now the heat energy stored in PCM is transferred to the cold water, so the cold water temperature is increased. Temperature of the PCM and HTF are recorded at intervals of 15 minutes.

C. System Efficiency

System efficiency is defined as the ratio of the amount of energy released by the TES tank during discharging to the heat energy stored during charging process. The system efficiency of the TES system for the mass flow rate of 10L/hr and 51/hr calculated. It is seen that the system efficiency decreased when flow rate decreased.

D. Calculations

1) Loading Calculation of PCM

$V_{pcm} = [\pi/4) \text{ x } D^2]*L \text{ m}$ (4.1)
$= [\pi/4) \text{ x } (0.05)^2]*1 \text{ m}$
$= 1.963 \text{ x } 10^{-3} \text{ m}^3$

$V_c = [\pi/4) \text{ x } D^2]*1 \text{ m}$ (4.2)
$= [\pi/4) \text{ x } (0.006)^2]*3.5 \text{ m}$
$= 9.613 \text{ x } 10^{-5} \text{ m}^3$

$M_{pcm} = (V_{pcm} - V_c) * \rho_{pcm}$ (4.3)
$= 1.867 \text{ x } 10^{-3} \text{ m}^3 \text{ x } 833.6 \text{ kg/m}^3$
$= 1.554\text{kg} \approx 1.6 \text{ kg}$

E. Model Calculations

1) Charging Process

Heat Stored = 10*4.186*(76-55)*15/60
= 219.77KJ
Heat available = 10*4.186*(76-32)*15/60
= 460.46KJ
Charging efficiency = (219.77/460.6)*100 = 47.7%

2) Discharging Process

Heat Stored = 10*4.186*(46-32)*15/60
= 146.51KJ
Heat available = 1.55*2.38*(46-32)+(1.55*265.9)
= 146.51KJ
Discharging efficiency = (146.51/498.88)*100
= 29.37%
Set up efficiency = 565.11/1255.8*100
= 45%

MW (L/hr)	*t (mins)*	T_h (°C)	T_{hi} (°C)	T_{pcm1} (°C)	T_{pcm2} (°C)	T_{ho} (°C)	T_{pcm} (°C)	*Qa (KJ)*	*Qs (KJ)*	*η(%)*
Htf Flow rate	*Charging time*	*hot water temp*	*hot water inlet temp*	*pcm temp left position*	*pcm temp right*	*hot water outlet temp*	*average pcm temp*	*Heat available*	*heat stored*	*charging efficiency*
10	*initial*	*88*	*76*	*32*	*32*	*76*	*32*	*460.46*	*0*	*0*
	15	*86*	*76*	*45*	*43*	*55*	*44*	*460.46*	*219.77*	*47.73*
	30	*87*	*75*	*52*	*50*	*55*	*51*	*450.00*	*209.30*	*46.51*
	45	*85*	*74*	*55*	*53*	*54*	*54*	*439.53*	*209.30*	*47.62*
	60	*86*	*74*	*58*	*56*	*54*	*57*	*439.53*	*209.30*	*47.62*
	75	*86*	*74*	*60*	*58*	*54*	*59*	*439.53*	*209.30*	*47.62*
	90	*86*	*74*	*62*	*60*	*54*	*61*	*439.53*	*209.30*	*47.62*
									1266.27	*47.45*

Table 4.1: Charging process for the flow rate of 10L/hr

MW (L/hr)	*t (mins)*	T_c (°C)	T_{ci} (°C)	T_{pcm1} (°C)	T_{pcm2} (°C)	T_{co} (°C)	T_{pcm} (°C)	*Qa (KJ)*	*Qs (KJ)*	*η(%)*

Htf Flow rate	Charging time	cold water temp	cold water inlet temp	pcm temp left position	pcm temp right	cold water outlet temp	average pcm temp	Heat available	heat released	charging efficiency
10	initial	32	32	62	60	32	61	510.14	0	0
	15	32	32	53	55	46	54	498.88	146.51	29.37
	30	32	32	48	50	44	49	475.17	125.58	26.43
	45	32	32	45	47	42	46	465.03	104.65	22.50
	60	32	32	42	44	39	43	454.89	73.26	16.10
	75	32	32	38	40	38	39	441.38	62.79	14.2
	90	32	32	36	38	37	37	434.62	52.33	12.0
									565.12	20.11

Table 4.2: Discharging process for the flow rate of 10L/hr

MW (L/hr)	t (mins)	T_h (ºC)	T_{hi} (ºC)	T_{pcm1} (ºC)	T_{pcm2} (ºC)	T_{ho} (ºC)	T_{pcm} (ºC)	Qa (KJ)	Qs (KJ)	η(%)
Htf Flow rate	Charging time	hot water temp	hot water inlet temp	pcm temp left position	pcm temp right	hot water outlet temp	average pcm temp	Heat available	heat stored	charging efficiency
5	initial	85	79	34	32	79	33	245.93	0	0
	15	86	76	42	40	58	41	230.23	94.19	40.91
	30	87	76	46	44	58	45	230.23	94.19	40.91
	45	87	75	50	48	58	49	225.00	88.95	39.53
	60	86	75	54	52	58	53	225.00	88.95	39.53
	75	86	74	57	55	59	56	219.77	78.49	35.71
	90	85	74	60	58	59	59	219.77	78.49	35.71
									523.26	38.72

Table 4.3: Charging process for the flow rate of 5L/hr

MW (L/hr)	t (mins)	T_c (ºC)	T_{ci} (ºC)	T_{pcm1} (ºC)	T_{pcm2} (ºC)	T_{co} (ºC)	T_{pcm} (ºC)	Qa (KJ)	Qs (KJ)	η(%)
Htf Flow rate	Charging time	cold water temp	cold water inlet temp	pcm temp left position	pcm temp right	cold water outlet temp	average pcm temp	Heat available	heat released	charging efficiency
5	initial	32	32	58	58	32	58	500.00	0	0
	15	32	32	53	55	42	54	492.06	52.33	10.63
	30	32	32	50	52	41	51	481.93	47.09	9.77
	45	32	32	47	49	40	48	471.79	41.86	8.87
	60	32	32	43	45	38	44	458.27	31.40	6.85
	75	32	32	41	43	38	42	451.52	31.40	6.95

	90	*32*	*32*	*37*	*39*	*36*	*38*	*438.00*	*20.93*	*4.78*
									225.01	*7.98*

Table 4.4: Discharging process for the flow rate of 5L/hr

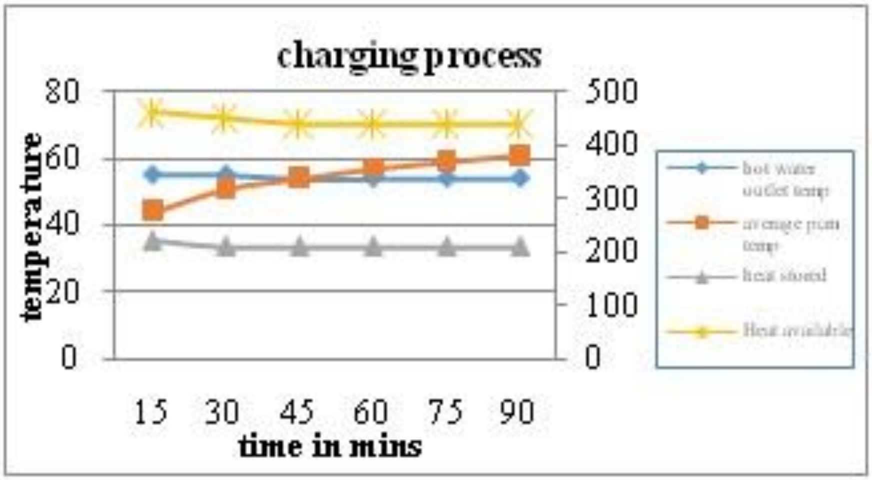

Fig. 4.1: Variation of inlet and outlet water temperature & PCM axial temperature with time during discharging mode with average flow rate of 10L/hr.

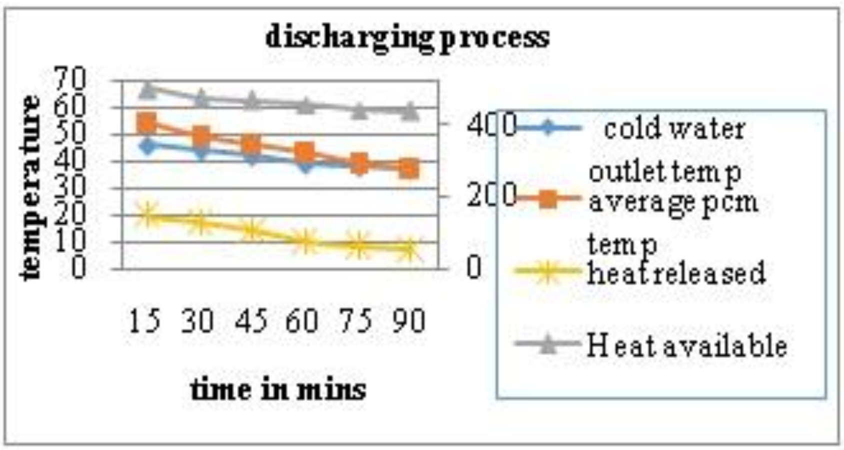

Fig. 4.2: Variation of inlet and outlet water temperature & PCM axial temperature with time during discharging mode with average flow rate of 10L/hr.

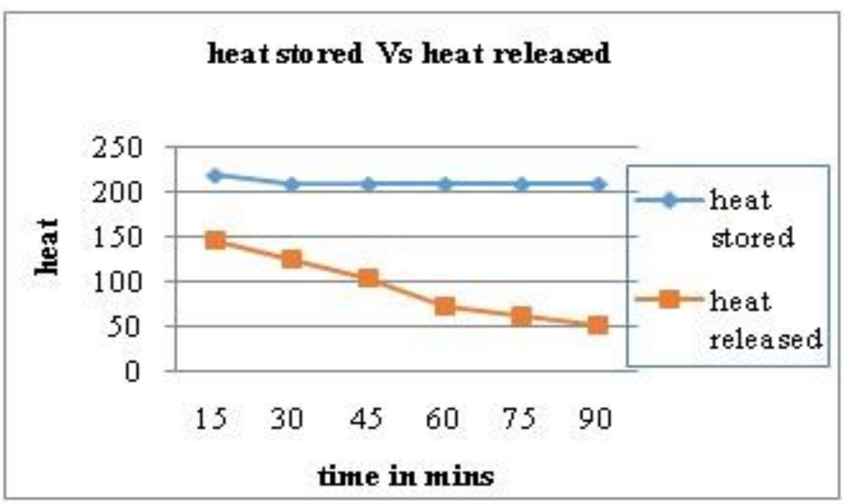

Fig. 4.3: heat stored Vs heat liberated for flow rate 10L/hr

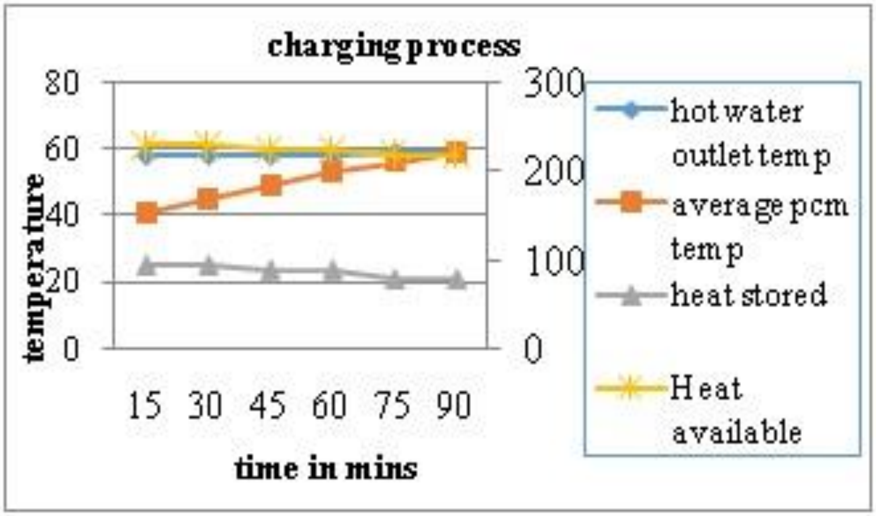

Fig. 4.4: Variation of inlet and outlet water temperature & PCM axial temperature with time during discharging mode with average flow rate of 5L/hr.

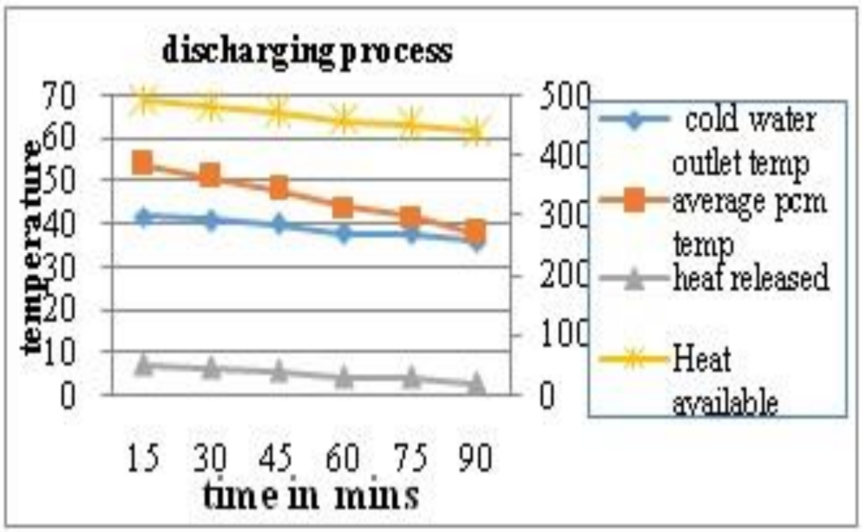

Fig. 4.5: Variation of inlet and outlet water temperature & PCM axial temperature with time during discharging mode with average flow rate of 5L/hr.

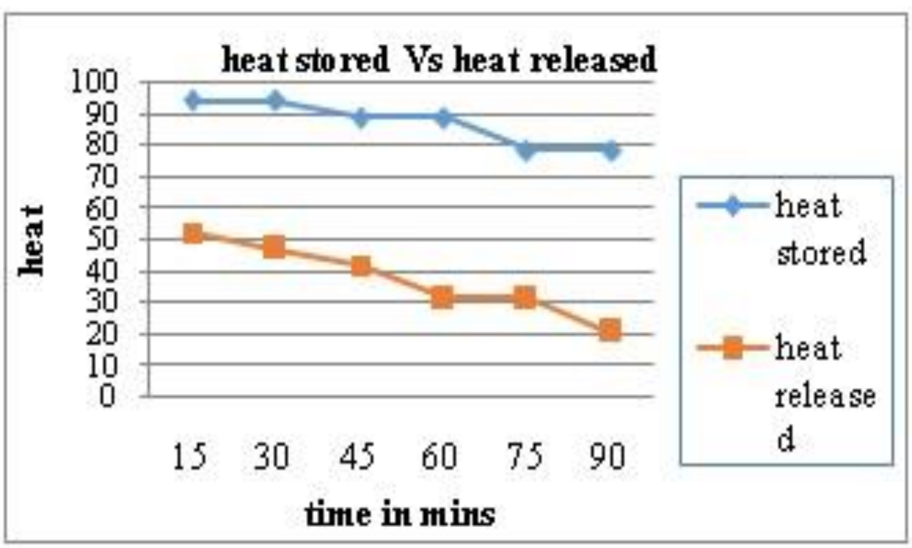

Fig. 4.6: heat stored Vs heat liberated for flow rate 5L/hr.

1	*Experiment No.*	*EXP I*	*EXP II*
2	*Flow rate during charging mode (LPH)*	*10*	*5*
3	*Flow rate during discharging mode (LPH)*	*10*	*5*
4	*Energy released by the hot water during charging mode (KJ)*	*1266.27*	*523.25*
5	*Time Interval during charging mode (mins)*	*15*	*15*
6	*Energy gained by the cold water during discharging mode (KJ)*	*565.11*	*225*
7	*Time Interval during discharging mode (mins)*	*15*	*15*
8	*Setup Efficiency (%)*	*45*	*43*

Table 4.5: Thermal performance of the heat exchanger

V. CONCLUSION

The experimental results show the feasibility of using phase change material as storage media in heat recovery systems. Latent heat system with phase change material can be successfully used for recovery and reuse of water heat. The thermal behavior of the latent heat thermal energy system is investigated experimentally for different operating conditions.

The system's charge and discharge characteristics with respect to the heat transfer fluid are analyzed. So by increasing the heat transfer area or the surface area of the copper pipe with phase change material and increase the heat transfer fluid flow rate the efficiency of the system can be increased.

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