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Experimental Analysis of Thermal Storage Systems using Phase Change Materials

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Abstract **- The use of Phase Change Materials as latent heat storage medium is an effective way of storing thermal energy. PCMs offer the advantages of having high energy storage density and its isothermal nature. PCMs have been widely used in latent heat thermal storage systems for heat pumps, solar systems and spacecraft applications. This Study is undertaken to investigate about the effectiveness of heat transfer using PCMs through storing solar energy for domestic water heating. The experimental setup consist of simultaneous functioning heat absorbing units. One is a solar water heater and the other is a heat storage unit consisting of phase change materials. The storage unit stores heat in PCM during the day and supplies hot water during night hours. This storage unit utilizes thermal storage tank filled with industrial granulated paraffin wax (PCMs) as the heat storage medium integrated with the solar collector to absorb energy. The setup compares the difference in the efficiency of the storage system without using PCMs and using PCMs and thereafter the graphical study of the entire setup is conducted.**

Index Terms – Charging, Discharging , Latent heat storage , Paraffin wax , Phase change material , Solar water heating

1. INTRODUCTION

Energy Storage has only recently been developed to a point where it can have a significant impact on modern technology. In particular energy storage is critically important to the success of any intermittent energy source in meeting demand. Energy storage can contribute significantly to meeting society needs for more efficient, environmentally benign energy use in building, heating and cooling, aerospace power and utility applications.

The use of energy storage systems have the following benefits:

- Reduced energy costs
- Reduced energy consumption
- Improved indoor air quality
- Reduced initial and maintenance costs
- Reduced equipment size

Energy storage systems have an enormous potential to increase the effectiveness of energy conservation, equipment size and for facilitating large scale fuel substitutions in the world economy. Energy demand in the commercial, Industrial, Public, Residential Varies on a daily, weekly and seasonal basis.. Some details on these ES applications are given below:

- Utility- relatively inexperience base load electricity can be used to charge ES systems during evening or off peak, weekly or seasonal periods.
- Industry- High temperature waste heat from various industrial process can be stored for use in pre heating and other heating operations.
- Cogeneration: Coupled production of heat and electricity by a cogeneration system rarely matches demand exactly.

Current researches is going on in the field of

1.2 ENERGY STORAGE METHODS

For many technologies, storage is a crucial aspects.

ES includes heat storage hold transferred heat before it is put to useful purposes. Advanced new storage devices are often an integral part of new technologies and these sometimes can be made more feasible by innovations in storage.

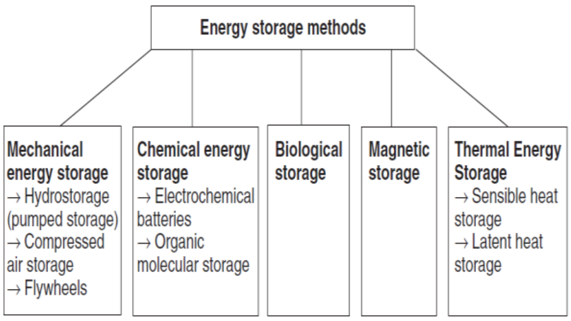

Fig 1- Types of energy storage methods

1.2.1 Mechanical Energy storage

It can be stored as the kinetic energy of linear or rotational motion, as the potential energy in an elevated object, as the compression or strain energy of an elastically material.

There are three main mechanical storage types:

(i) Hydro storage
(ii) Compressed air storage
(iii) Fly wheels.

1.2.2 Chemical Energy storage

Energy may be stored in systems composed of one or more chemical compounds that release or absorb energy when they react to form other compounds. The most familiar chemical energy storage device is battery. Energy stored in batteries are referred to as electro chemical energy because the chemical reactions in the battery are caused by electrical energy and subsequently produced electrical energy.

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1.2.3 Biological storage

Biological storage is the storage of energy in chemical form by means of biological processes and is considered as an important method of storage for long periods of time. If the quantum efficiency of biological processes can be increased by a factor of ten over its present efficiency of about 1 percent interest in bio conversion for ES will likely increased.

1.2.4 Magnetic storage

Energy can be stored in magnetic field. An advanced scheme that employees superconducting materials is underdevelopment. At temperature near absolute 0, certain metals have almost no electrical resistance and thus large currents can circulate in them with almost no losses. Over all storage efficiencies of 80-90% are anticipated for these superconducting magnetic ES systems. Magnetic storage is considered for two main purposes:

(i) Large superconducting magnets capable of storing (1000-10,000MWh) of electricity would be attractive as load leveling devises.

(ii) Smaller magnet with storage capacities in 10 KWh range.

1.3 Thermal Energy Storage.

Thermal energy storage deals with the storage of energy by cooling, heating, melting, solidifying or vaporizing a material, the thermal energy becomes when the process is reversed.

Storage by causing a material to rise or lower in temperature is called sensible heat storage, its effectiveness depends on the specific heat of the storage material and if volume is important, on density.

Storage by phase change (Transition from solid to liquid or from liquid to vapor with no change in temperature) is a mode of thermal energy storage known as latent heat storage.

Thermal energy storage quantities differ in temperature. As the temperature of a substance increases, the energy content also increases. The energy required E to heat a volume V of a substance from a temperature (T1) to a temperature (T2) is given by:

$$E = mc\,(T2-T1) = \rho\, V\, c\,(T2-T1\,,$$

Where C' is the specific heat of the substance. The value of 'C' may vary from $1kCal/kg^0C$. For water to $0.0001kCal/kg^0C$ for some materials at very low temperature.

m is the mass in kg

1.4 Sensible Heat Thermal Energy Storage(SHS)

In sensible TES, energy is stored by changing the temperature of a storage medium such as water, air, oil, rock beds, bricks, sand etc. The amount of energy input into the TES by a sensible heat device is proportional to the difference between the storage final and initial temperatures, the mass of the storage medium and its heat capacity. Sensible TES consists of a storage medium, a container and input, output devices. Containers must both retain the storage material and prevent losses of thermal energy. Sensible TES materials undergo no change in phase over the temperature encountered in storage process.

The amount of heat stored in a mass of a material can be expressed as :

$$Q = mCp\,\Delta T = \rho CpV\Delta T$$

Cp is the specific heat of the storage material.

ΔT – temperature change

V - volume of storage material.

ρ- density of storage material.

The ability to store sensible heat for a given material strongly depends on the value of the quantity ρCp.

Water has a high value and is inexpensive, but being liquid must be contained in a better quality container.

1.5 Latent Heat Thermal Energy Storage (LHS)

Latent Heat storage is based on the heat absorption or release when a storage material

undergoes a phase transition from solid to liquid (or) liquid to gas or vice versa. The storage capacity of the LHS system with a Phase change material (PCM) is given by:

$$Q = \int_{T_i}^{T_m} mC_p\,dT + ma_m\Delta h_m + \int_{T_m}^{T_f} mC_p\,dT$$

$$Q = m[C_{sp}(T_m - T_i) + a_m\Delta h_m + C_{lp}(T_f - T_m)]$$

- Tm – melting temperature (^{0} C)
- Ti – initial temperature (^{0} C)
- Tf – final temperature (^{0} C)
- Cp – specific heat (J/kg K)
- am – fraction melted
- dT – temperature difference
- Δhm – heat of fusion per unit mass (J/kg)
- Cap – Avg specific heat between Ti and Tf (J/kg K)
- Csp- Avg specific heat between Tm and Tf (J/kg K)
- Clp –Avg specific heat between Ti and Tm (J/kg K)
- m – mass of heat storage medium (kg)

1.5.1 Overview –Latent Heat Storage Systems:

Among the thermal storage techniques, latent heat thermal energy storage is particularly attractive due to its ability to provide high energy density and its characteristic to store heat at constant temperature, corresponding to the phase transition of the phase change material.

Any latent heat energy storage system therefore, posses at least following 3 components:

- A suitable PCM with its melting point in the desired temperature range.
- A suitable heat exchanger.
- A suitable container compatible with PCM.

Phase Change Materials(PCMs) are latent heat storage materials. Thermal energy storage The thermal energy transfer occurs when a material changes from solid to liquid

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or liquid to solid. This is called Change in state or Phase. PCMs absorb and release heat at constant temperature. They store 5 – 4 times more heat per unit volume than sensible heat storage materials such as water,masonry or rock. A large number of PCMs are known to melt with a heat of fusion in any required range.

PCMs to be used in the design of thermal storage systems should posses desirable thermo physical , kinetics and chemical properties.

Thermal properties

- Suitable phase transition temperature.
- High latent heat of transition.
- Good heat transfer.

Kinetic properties

- No supercooling
- Sufficient crystallization rate.

super cooling has been a troublesome aspect of PCMs development, particularly for hydrates. Super cooling of 5- 10^0C super cooling can prevent it entirely.

Chemical properties

- Long term chemical stability.
- Compatibility with materials of construction.
- No toxicity hazard.
- No fire hazard.

Economics

- Abundant
- Availability
- Cost effective

Table I: Thermophysical properties of industrial granulated paraffin wax

Melting temperature of the phase change material		$65\pm1\ ^0$C
Latent heat of fusion		213 kJ/kg
Density :	Solid state	861 kg/m3
	Liquid state	778kg/m3
Specific heat	Solid state	1850 J/kg^{0}c
	Liquid state	2384 J/kg^{0}c
Thermal conductivity	Solid state	0.4 w/m^{0}c
	Liquid state	0.15 w/m^{0}c

II. METHODOLOGY

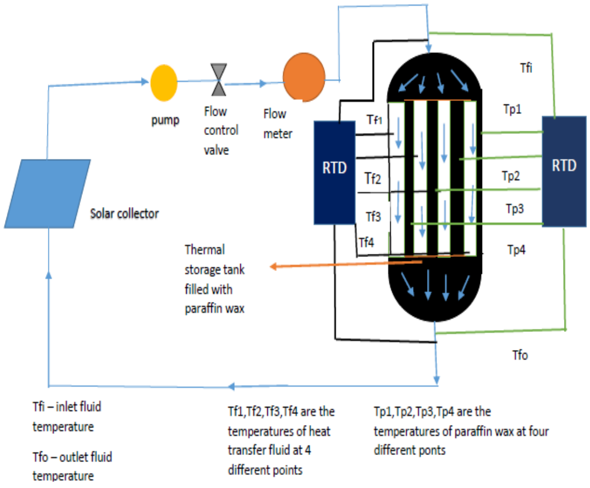

Fig2. Shows the solar water heating system with PCM

Fig.1 shows the experimental set up. The setup consists of a thermal energy storage (TES) tank of cylindrical shape made of stainless steel. The inner portion of the tank is fabricated in a specific manner inorder to provide effective heat transfer. The setup involves a TES tank,a pump, a flowmeter ,Two temperature indicators, solar collector of flat plate type of 2m², a radiation pyranometer. The stainless steel tank is of cylindrical shape of 280 mm diameter, 630 mm height . The tank has 3 segments at the inner. The top and bottom segments are of similar dimensions. The top and bottom portions are surrounded by paraffin wax of melting point 65 ± 1^0C. The middle part consists of numerous number of tubes of diameter 32mm. and height 280 mm through which the heat transfer fluid i.e water flows. The tubular passages are surrounded by paraffin wax in such way to improve the effectiveness of heat transfer and heat storage.There are 13 cylindrical passages in the middle part ,surrounded by PCMs. The total capacity of the tank is 27 litres. Water is used as the heat transfer fluid (HTF)

Nomenclature:

Tfi – inlet temperature of heat transfer fluid

Tfo –outlet temperature of heat transfer fluid

Tpi – initial temperature of PCM

Tf1 ,Tf2 ,Tf3,Tf4 – temperatures of HTF at four different points.

Tp1,Tp2,Tp3,Tp4 – temperatures of the PCM at four different points.

L –length of heat storage tank (mm)

X – axial distance from the top of the TES tank (mm)

X/L – dimensionless axial distance from the top of the TES tank.

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III. EXPERIMENTATION

TES tank is connected with solar flat plate collector of area 2m². Experiment is conducted for varying flow rates and inlet HTF temperatures which varies according to the solar insolation.

Fig.3 Photographic view of setup

Fig.4 Thermal energy storage (TES) tank

Fig.5 Inner view of TES tank

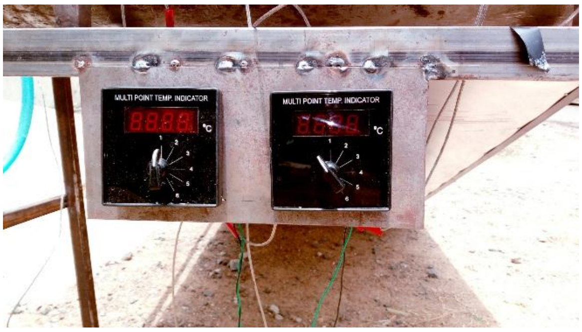

Fig.6 Temperature indicators for measuring HTF and PCM temperatures.

Fig.7 Flow meter to measure the rate of flow of HTF.

Fig.8 Flow control valve

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Fig.9 Tap for extracting hot water and pump for water circulation.

Fig.10 Solar flat plate collector

(a) Charging process

Water the heat transfer fluid and the sensible heat fluid, flows through cylindrical tubular passages surrounded by PCM.During the charging process i.e storing of heat, the HTF transfers the heat to the PCM. At the beginning of the charging process , the temperature of the

PCM (Tpi) inside the tank ranges around 32^0C,which is lower than melting temperature. Initially the heat is stored as sensible heat until the PCM reaches its melting temperature. As the charging proceeds, energy is stored by melting the PCM at a constant temperature of 65 ± 1^0C. Finally the PCM becomes superheated. The energy is then stored as sensible heat in liquid PCM. The temperature of PCM and HTF at different locations of the TES tank are recorded at an interval of 10 mins.The charging continues until thermal equilibrium is attained between the HTF and PCM. PCM is charged during the day whenever hot water is not demanded by the user.

***(b**) Discharging process*

Discharging is done by means of batchwise process. In this method a certain quantity of hot water is withdrawn from the TES tank and mixed with cold water (at 32^0 C) to get the required hot water of 27 litres at an average of 45 ± 0.5^0 C for direct use and the tank is again filled with cold water of quantity equal to the amount of water withdrawn. After an interval of 10 mins, allowing transfer of heat from PCM to water , another batch of hot water is withdrawn and mixed with cold water to get 27 litres at an average temperature of 45 ± 0.5^0 C. This process is combined until PCM reaches 45^0C.

(c) Solar water heating without phase change material:

First doing trial on solar water heater without phase change material . Cooling rates of water in the tank is noted after heating the water for 6 hrs in the sunlight.

TABLE II Cooling rates of solar water heating without PCMs are:

Time (hrs)	Temperature of water (^{0} C)
0	75
3	71
6	65
9	61
12	58
15	55
18	54
21	51

Now calculating the efficiency of the Solar water heater:

Volume of HTF = 27 litres

Initial temperature of water = Ti = 36^0C

Heat radiated in a day = 460w/m²

Final temperature of HTF (after 6 hrs) = 75^0C

Efficiency of the solar water heater = Heat energy output / heat energy input

= Qout / Qin

Qout = Heat energy absorbed by water

= m Cpw (Tf – Ti),

= ρ V Cpw (Tf – Ti),

Where, m is the mass of water (kg) ,

Cpw is the specific heat capacity of water kJ/kg K

ρ is the density of water (kg/m³)

V is the volume (m³)

Heat supplied by solar radiation(Pin) = 460 w/m²

Qin = Pin × area of panel × time elapsed

Qin effective = 0.96 × Qin

Efficiency (ɳ) = Qout / Qin

By calculation ,

Efficiency without PCM = 23.4 %

(d) Solar water heating with PCM

Mass of paraffin wax = 16 kg

Now finding the cooling rate of water after addition of PCM and keeping it for 6 hrs in sunlight.

TABLE III Cooling rates with PCM are:

Time (hrs)	Temperature of water (^{0}C)
0	68
3	65
6	62
9	60
12	59
15	58
18	57
21	56

It is clear that the cooling rates are lower comparatively.
Volume of HTF = 27 litres
Initial temperature of water Ti = 40^{0}C
Heat radiated = 460 w/m²
Time elapsed = 6hrs
Final temperature of water Tf = 68 ^{0}C
Initial temperature of PCM = 36 ^{0}C
Temperature of fusion = 65±1 ^{0}C
Final temperature of PCM (after superheating) = 67^{0}C
Efficiency of solar water heat with PCM (ɳ) = Qout / Qin
Qout =Energy gained by water (E1) +
Energy gained by PCM (E2)
E1 = ρ V Cpw (Tf – Ti),
E2 = energy absorbed by solid PCM (Esolid) + (Eliquid) energy absorbed by liquid PCM + latent heat of fusion
Esolid = ρsolid× Vsolid × Cpsolid (Tfs – Tis)
Eliquid = ρliquid× Vliquid × Cpliquid (Tfl – Til),
Where,
ρsolid, Vsolid , Cpsolid , Tfs ,Tis
ρliquid, Vliquid ,Cpliquid, Tfl, Til
are the density, volume, specific heat ,final temperature, initial temperature of Solid and liquid PCMs respectively.
Latent heat of fusion = mass of PCM × heat of fusion of PCM

Efficiency(ɳ) = Qout / Qin
Efficiency with PCM, by calculation = 45.5%
There will be a efficiency reduction of
4-5 % due to heat loss from the inner lining and other parts.
Therefore considering 5% loss efficiency ranges around 40 %.

III RESULTS AND DISCUSSION

The temperature distributions of HTF and PCM in the TEs tank for varying inlet fluid temperatures and mass flow rates are discussed for charging and discharging process.
The graphical study is also done on efficiency of the system and also instantaneous heat stored.

A. Charging process:

(i) Temperature histories of water and PCM

Fig 11 and Fig 12 shows the temperature histories of HTF and PCM during the charging process of a solar collector integrated water heater encapsulated with PCMs. The inlet temperature of the HTF from the collector increases continuously with time at a uniform rate till the PCM in the storage tank attain the phase change temperature. There is no significant temperature difference between each segments. This is because the temperature of water in the storage tank increases gradually based on the inlet temperature of HTF supplied from the solar collector and PCM temperature also increases along with the HTF inlet temperature.

Hence the temperature difference between the PCM and HTF is less during the sensible heating of solid PCM and also during phase change period. It can be also concluded that heat transfer rate from HTF to PCM in the storage tank higher than heat receiving rate of HTF from the solar collector. Hence it is advisable to increase the collector area to reduce the charging time.

Case – 1: Temperature histories of HTF
At varying inlet HTF temperature Tfi ,
mass flow rate ṁ = 3 litre / min.
(shown in figure 11.)

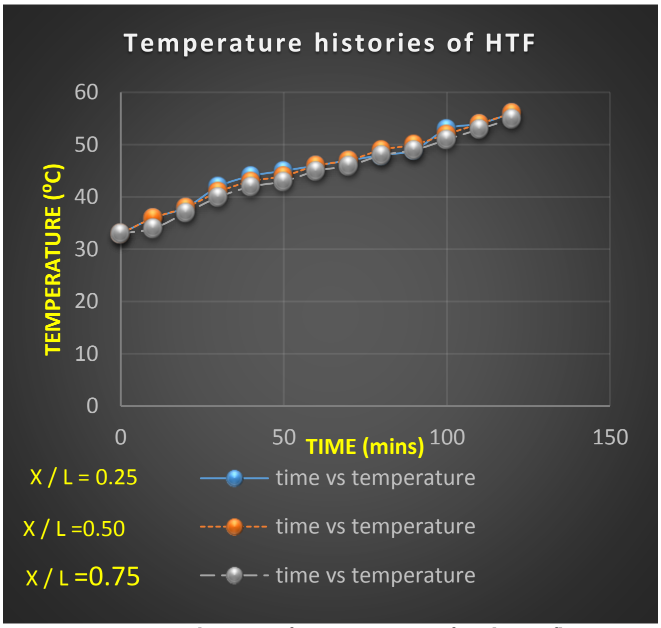

Fig 11. Temperature histories of HTF at varying Tfi and mass flow rate 3litre / min

Case -2: Temperature histories of PCM
At varying Tfi and mass flow rate ṁ = 3 litre / min (shown in figure 12)

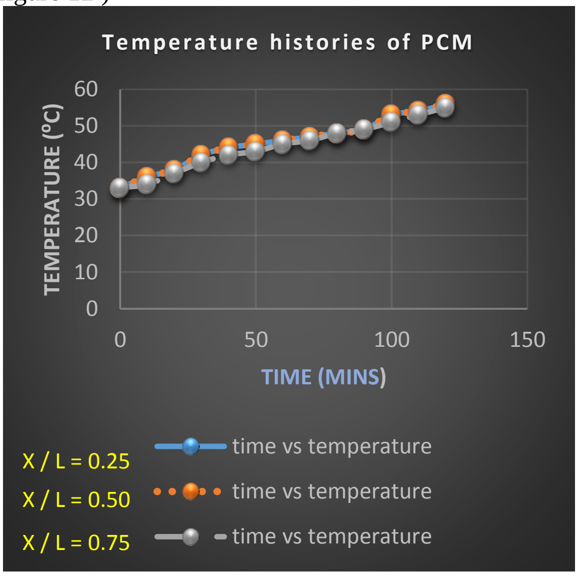

Fig 12. Temperature histories of PCM

At varying Tfi and mass flow rate ṁ = 3 litre / min

(ii) Effect of inlet fluid temperature

Fig 13 and Fig14 shows the effect of the variation in the inlet fluid temperature of HTF on the charging time for flow rates of 3 litre / min and 5 litre / min.

It can be identified that as the inlet temperature increases , the time required for charging decreases. As the temperature goes on increasing from 65 ^{0}C to 71 ^{0}C , the time required for complete charging reduces by 40 % for flow rates 3 litre /min and 5 litre / min.

Case – 1 : Effect of inlet fluid temperature on charging time. At X/ L = 0.50 , ṁ = 3 litre / min. , varying Tfi (shown in figure 13)

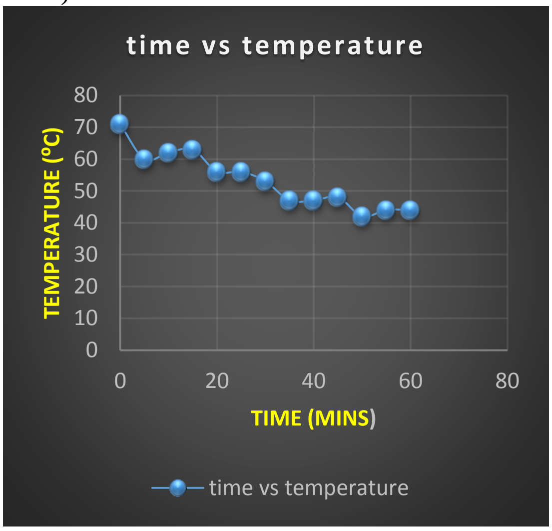

Fig.13 . Effect of inlet fluid temperature on charging time. at X/ L = 0.50 , ṁ = 3 litre / min. , at varying Tfi.

Case – 2: Effect of inlet fluid temperature on charging time. At X/ L = 0.50 , ṁ = 5 litre / min. , varying Tfi (shown in figure 14)

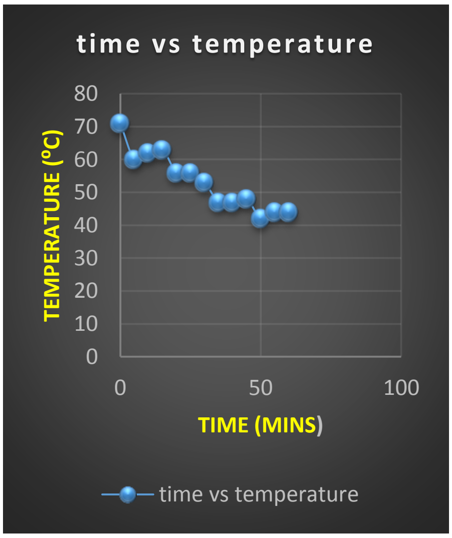

Fig.14. Effect of inlet fluid temperature on charging time.

At X/ L = 0.50 , ṁ = 5 litre / min. , varying Tfi.

(iii) Effect of flow rate of the HTF

From Fig .15 it is observed from the graphical analysis that charging time decreases by 22 – 25 % for varying Tfi and when the flow rate is changed from 3 to 5 litre / min.

Case – 1: At varying Tfi , X /L = 0.50, and mass flow rates

ṁ = 3 litre / min

ṁ = 5 litre / min

ṁ = 7 litre / min.

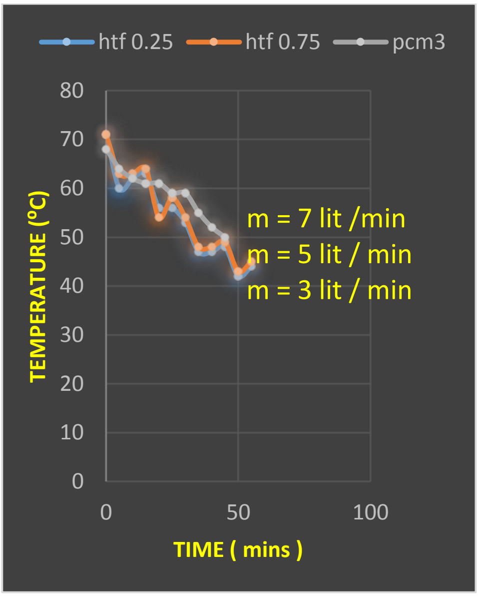

Fig .15 Effect of flow rate of the HTF, At varying Tfi , X /L = 0.50, and mass flow rates
ṁ = 3 litre / min
ṁ = 5 litre / min
ṁ = 7 litre / min.

(iv) Instantaneous heat stored

It is calculated based on the inlet and exit temperatures of the HTF. It is observed that during the initial phase of charging process , the instantaneous heat stored is enormous and decreases as the time proceeds around (45 – 50 mins.) of the charging process. The drop in temperature occurs because as the charging time proceeds , the temperature difference between HTF and PCM decreases since the PCM starts melting . As it proceeds temperature becomes almost uniform due to constant temperature difference between HTF and storage tank.

Fig.16 shows the instantaneous heat stored (in watts) for mass flow rates

ṁ = 3 litre / min

ṁ = 5 litre / min

ṁ = 7 litre / min.

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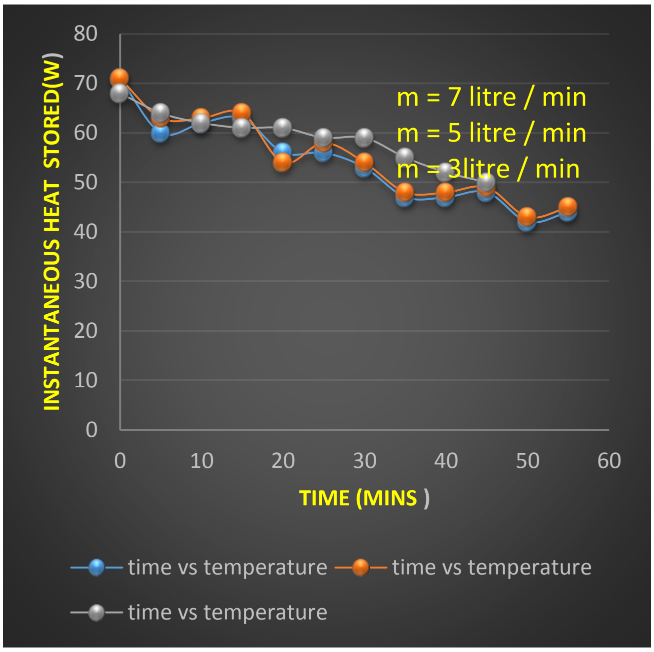

Fig.16 Instantaneous heat stored (in watts) for mass flow rates
$\dot{m}$ = 3 litre / min
$\dot{m}$ = 5 litre / min
$\dot{m}$ = 7 litre / min.

(v) System Efficiency

It is defined as the ratio of the amount of energy stored by tank (Qout) to the heat energy from solar radiation (Qin). It is observed that the system efficiency increases with time during the sensible heating of solid PCM , reamin constant during phase change period , then further increases during sensible heating of liquid PCM.

Figure 17 shows the efficiency variation without using PCM and using PCM.

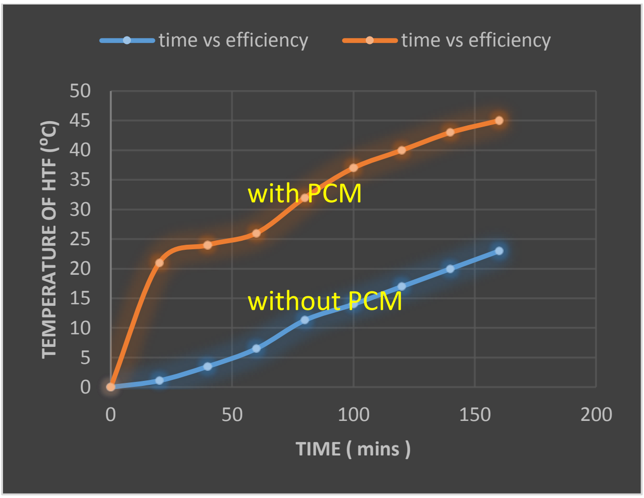

Figure 17 shows the efficiency variation without using PCM and using PCM.

B. Discharging process:

The temeprature histories of PCM and HTF during the discharge process through batchwise method is noted.

(i) Variation of PCM temperatures

In batchwise method , the temperature drop is large until PCM reaches its phase transition temperature as the hot water in the tank loses its sensible heat by the addition of inlet water at a temperature of 32 ^{0} C. Here the PCM temperature is nearly constant over a duration of 30 to 40 minutes, as the inlet water is supplied intermittently to extract heat from the storage tank.After the solidification of PCM , its temperature starts decreasing , but the rate of heat drop is not as high as in the beginning of the discharge process. Figure 18 shows the variation in the temperature of PCM during discharge process.

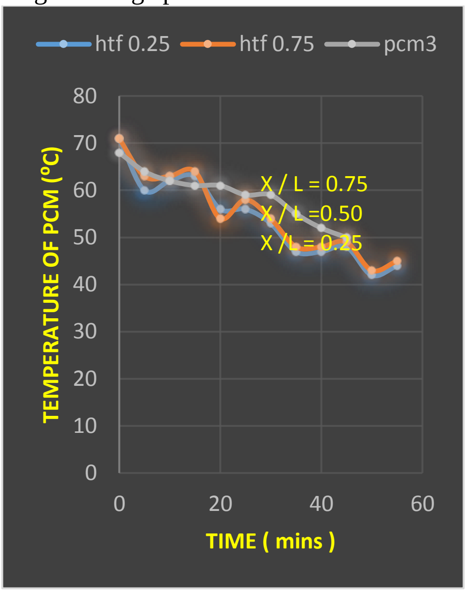

Figure 18 Variation in the temperature of PCM during discharge process

(ii) Variation of HTF temperatures.

In this batchwise method discharging process , a certain quantity of hot water is withdrawn from the storage tank and mixed with cold water to attain hot water of 27 litres at an average temperature of 45 ^{0} C. The storage tank is again filled with cold water of quantity equal to amount of hot water withdrawn. The temperature of HTF increases and after a retention period of 10 minutes , another batch of hot water is withdrawn and mixed with cold water. This process is continued until PCM reaches 45 ^{0} C.The variation of HTF temperature during discharge process is shown in figure 19.

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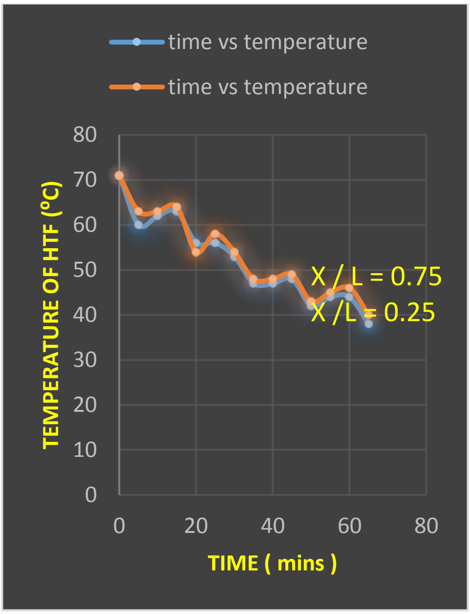

Fig.19.variation of HTF temperature during discharge process

IV.CONCLUSION

Solar water heating systems with PCM shows efficiency variation compared to the traditional method. In this work the efficiency variation is studied by calculation and also through graphical analysis.In the traditional method without PCMs the efficiency was found to be in the range of 23.4% while in the PCM encapsulated system the efficiency got boosted up to 40 %. Also the heat storage capacity showed variation.In the traditional system the energy stored was 3270kJ, while in the PCM nased system it has increased to 4670kJ. The PCM based technologies may show a great progress in the future and this may be great boon to avoid the energy crisis in the future to some extent.

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