Enhancing The Heat Storage Capacity of Evacuated Tube Solar Collectors Integrated With Phase Change Material

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Abstract- *Evacuated tube solar collectors (ETC) are increasingly in use worldwide because of their high thermal efficiency and high working temperature compared to the flat plate solar collectors. The efficiency of ETC is substantially enhanced due to the presence of vacuum between the absorber and the cover of evacuated tube solar collector (ETC). This is mainly attributed to the reduction in heat losses by convection ad conduction. This research could help to find the suitable PCM for heat exchanger with ways to enhance the heat transfer and provide the various designs to store the heat using PCM for different applications. It will also show the comparative study of the performance conventional system and system with thermal energy storage with PCM.*

Keywords- Thermal energy storage systems, Phase change material, Solar energy, Latent heat.

I. INTRODUCTION

Solar water heater is most popular solar equipment in India. It is a relatively mature solar thermal technology. In solar water heating system incident solar radiation is converted to heat and transmitted through a transfer medium such as water. Solar water heater are often viable for the replacement of electricity and fossil fuels used for water heating.

Though it meets the requirement of hot water still it has very low thermal efficiency. In order to increase the thermal efficiency phase change material is used.
phase change material thermal energy storage is based on the

energy absorbed/generated when a material undergoes phase change from solid to liquid, liquid to gas, or vice versa. To lower the energy consumption cost of conventional electrical heaters, PCM thermal energy is stored during the off-peak load period. This energy is then released during the peak period.

II. REVIEW OF LITERATURE

Many researchers have shown the advantages of using PCMs for energy storage. Previous work has resulted in improved LHESS container geometries and heat transfer enhancement designs. LHESS operating parameters, such as flow rates and temperatures of HTFs, have been explored as well using both numerical and experimental studies. Previous work published on LHESS has guided the design of the experimental LHESS used in this thesis. Latent heat thermal storage is one of the most promising technologies in terms of energy conservation, grid load alleviation, and energy security maintaining in a built environment. However, due to the low thermal conductive property of PCMs, thermal energy storage/extraction rates are low and need to be ameliorated through advanced system design with optimized storage layout. It is of primary importance to pursue material development so as to obtain novel PCMs with desired material properties that can provide sufficient thermal storage/extraction power, high ice packing factor (IPF, ratio of PCM volume to total tank volume), and stable charge capacity. This section gives an overview on the currently available TESs and special emphasis will be placed on inorganic Paraffin wax.

As well, literature review clearly demonstrates the need for experimental work in studying the simultaneous charging and discharging mode of a LHESS for use with a SDHW system. The use of finned tubes with different configurations has been proposed by various researchers.

In this chapter the literature related with the study of LHS, properties of heat storage materials, various methods and conditions i.e. temperature range adopted for the experimentation.

Results obtained regarding the performance of Latent heat storage are collected from different research papers, standard books as well as journals. With the literature review the following objectives are to be achieved by performing the various stages of experimentation.

Foudaet. al. [1984] [01] studied the characteristics of Glauber's salt as a LHS medium in solar storage system. The effect of several variables was studied over many complete cycles of the unit, including variable HTF flow rate and inlet temperature, wall thickness etc.

Saitoh and Hirose [1986] [02] performed theoretical and experimental investigation of the transient thermal characteristics of a phase-change thermal energy storage unit using spherical capsules. The effects of variation in the capsule diameter, the flow rate of the heat transfer fluid, the inlet temperature difference, the capsule material, and the PCM on the thermal performance of this storage unit were studied in detail using computer simulation and compared with the experimental results of a prototype LHS unit with a capacity of 300 liters.

Ananthanarayananet. al. [1987] [03] developed a computer model for the estimation of temperature profiles of the solid and the fluid along the length of the packed bed of self-encapsulated Al-Si PCM shots as functions of distance along the bed and time during a series of heat storage and utilization cycles. Air was used as heat transfer fluid in their study.

Beasley et. al. [1989] [04] developed a computational model to study the transient thermal response of a packed bed of spheres containing a phase change material using one dimensional separate phases formulation. Results from the model were compared with the experimental results of a commercial size thermal storage bed packed with polypropylene spheres containing paraffin wax for both the energy storage and recovery periods using air as heat transfer fluid.

Esenet. al. [1998] [05] made numerical investigation on the thermal performance of solar water heating systems integrated with cylindrical LHS unit using various PCMs.

Ismail and Henriquez [2002] [06] presented a numerical model to simulate the process of heat transfer (charging and discharging) in a LHS system of packed bed of spherical capsules filled with PCM (Water). The effect of heat transfer fluid (ethylene glycol) entry temperature, the mass flow rate and material of the spherical capsule on the performance of the storage unit were investigated both by numerically and experimentally.

Mehlinget. al. [2003] [07] presented the experimental and numerical simulation results of energy storage density of solar hot water system using different cylindrical PCM modules. Their results show that adding PCM modules at the top of the water tank would give the system higher storage density and compensate heat loss in the top layer.

AjeshVijayanet. al.[2016] [08] 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 4670 kJ. 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.

S. BharathSubramaniamet. al.[2016] [09] Regardless of the daily operations the Integrated Collector Cum Storage Solar Water Heater (ICSSWH) gives better thermal efficiency for longer period of time by using paraffin wax as PCM. When compared with the solar water heater the integrated PCM storage tank with solar water heater was found to be more efficient and cost effective. During the discharging period, the heat transfer fluid gained enormous amount of heat from the PCM. Hence paraffin wax can be used for solar application from techno economical aspects.

Ettouney et al. [2005] [10] presented a detailed picture of the temperature field inside the PCM encapsulated spherical capsule during melting and solidification processes using paraffin as PCM and air as HTF. The results indicated that the Nusselt number for melting has strong dependence on the sphere diameter, lower dependence on the air temperature and negligible dependence on the air velocity. Works in the related area (i.e. energy storage in spherical capsules) are also reported by Prudhomme et al. (1989) and Cho and Choi (2000). He et al. (2004) used the liquid-solid phase diagram of the binary system of tetradecane and hexadecane to obtain information on the phase transition processes and differential scanning calorimetry to determine the thermo-physical properties of the binary system. They presented a reliable method to incorporate both the heat of phase change and the temperature range of paraffin by combining phase equilibrium.

Closure

It is seen from the reported works that most of the researchers emphasized on the use of high temperature paraffin wax as LHS material. However, there is a lack of research on solid LHS systems based on using water as the HTF and specially by using the phase change material inside the evacuated tube the present work seeks to remedy this perceived lack by investigating the thermal storage performance of solid state LHS systems, using paraffin wax material in solar water heating system.

III. EXPERIMENTAL SETUP

A schematic diagram of the experimental set-up is shown in Figure 3.1.This consists of an insulated cylindrical TES tank, which contains PCM encapsulated cylindrical capsules, solar ETC, flow control valve, cold water storage tank and thermocouples. The stainless steel TES tank has a capacity of 15 liters(300 mm diameter and 480 mm length). There are two plenum chambers on the top and the bottom of the tank and a flow distributor is provided on the top of the tank to make uniform flow of HTF. The storage tank is insulated with glass wool of 40 mm thick. The inner diameter of cylindrical capsules is 10 mm. The total number of capsules in the TES tank is 7. The PCM capsules occupy 12% of the total volume of storage tank and the remaining volume is occupied by SHS material. The paraffin is used as PCM that has a melting temperature of 45 ± 1 ^{o}C and latent heat of fusion of 213 kJ/kg. Water is used as both SHS material and HTF.

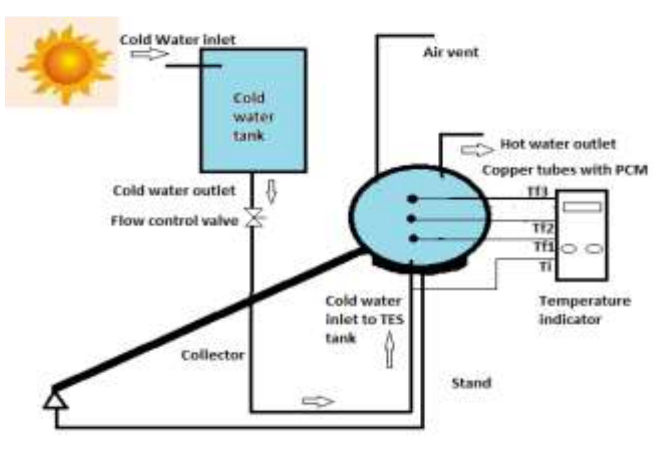

Fig.3.1: Schematic of TES system.

A cold water tank is provided on top its height 1.2 m is to circulate the HTF through the storage tank. The TES tank is divided into four segments along its axial direction and the thermocouple with an accuracy of ± 0.3oC are placed at the inlet, outlet and three segments of the TES tank to measure the temperatures of HTF. Another one of thermocouple is inserted into the PCM capsules and it is placed at one segments of the copper tube containing PCM inside evacuated tube to measure the temperatures of PCM.. The thermocouples (Resistance temperature detector) are connected to a temperature indicator, which provides instantaneous digital outputs.

Where,

T_i – inlet temperature of heat transfer fluid,

T_o –outlet temperature of heat transfer fluid,

T_{PCM}–temperature of PCM,

T_{f1}, T_{f2}, T_{f3}– temperatures of HTF at four different points,

L –length of heat storage tank (mm).

d **-** Diameter of PCM copper tube = 10

L_c – Length of PCM copper tube = 300 mm

C_{pw} - is the specific heat of capacity of water J/kg k

3.3.2Evacuated Tube Collector

Solar hot water systems that use Evacuated Tube Collectors as their heat source overcome this problem because the solar collector uses individual rounded tubes which are always perpendicular to the sun's rays for most of the day. This allows a solar hot water system using an evacuated tube collector to operate at a much high efficiency and temperature for a much longer period than a conventional single flat plate collector installed system. Also, another advantage of solar evacuated tube technology is that the weight and roof structural problems caused by standard flat plate systems are eliminated as the solar tubes are not filled with large amounts of heavy water.

The Evacuated tube collector consists of a number of rows of parallel transparent glass tubes connected to a header pipe and which are used in place of the blackened heat absorbing plate we saw in the previous flat plate collector. These glass tubes are cylindrical in shape. Therefore, the angle of the sunlight is always perpendicular to the heat absorbing tubes which enables these collectors to perform well even when sunlight is low such as when it is early in the morning or late in the afternoon, or when shaded by clouds. Evacuated tube collectors are particularly useful in areas with cold, cloudy wintry weathers.

Fig.3.3 Evacuated tube inserted with copper tube

Figure 3.3 shows separate view of evacuated tube inserted with two capper tube filled with PCM. In each copper tube this same arrangement is present.

In our experiment evacuated tube contains two copper tube and water in the annular space.

IV. IMPORTANTFORMULAE

4.1 Calculating efficiency TES system for without PCM

i) Heat energy input

$$Q_{in} = P_{in} \times \text{area of panel} \times \text{time elapsed} \quad \ldots\ldots\ldots\ldots\ldots(4.1)$$

ii) Heat energy output

$$Q_{out} = \text{Heat energy absorb by water}$$
$$= m_w C_{pw} (T_o - T_i)$$
$$= \rho_w V_w C_{pw} (T_o - T_i) \qquad (4.2)$$

iii) Efficiency of TES system without PCM

$$\eta_{without\ PCM} = \frac{Q_{out}}{Q_{in}} = \frac{\textbf{Heat energy output}}{\textbf{Heat energy input}} \quad \ldots\ldots\ldots\ldots\ldots \quad (3.3)$$

Where,

m - is the mass of water in kg.

P_{in} - is heat supplied by solar radiation is 1170 W/m^2.

ρ_w - is the density of water kg/m^3.

T_o - Outlet temperature of water in ^0C.

T_i - Inlet temperature of water in ^0C.

A_c - Cross section area of tank = $\frac{\pi}{4} D^2$

A_s - Surface are of TES tank = $\frac{\pi}{4} DL$

V- is volume of tank 15liter = $\frac{\pi}{4} D^2 L$

Net volume of TES tank $V = \frac{\pi}{4}(D^2)L_t - \frac{\pi}{4}(d^2)L_c$

D - Diameter of TES tank = 300 mm

4.2 Calculating efficiency TES system for with PCM

i) Heat energy input

$$Q_{in} = P_{in} \times \text{area of panel} \times \text{time elapse} \ldots\ldots(4.4)$$

ii) Heat energy output

Q_{out} = Energy gained by water (E1) + Energy gained by PCM (E2) .....(4.5)

$$E1 = m\, C_{pw} (T_o - T_i)$$
$$= \rho_w V\, C_{pw} (T_o - T_i) \quad \ldots(4.6)$$

E2 = energy absorbed by solid PCM (E_{solid}) + energy absorbed by liquid PCM (E_{liquid}) + Latent heat of fusion (λ) (3.7)

$$E_{solid} = \rho_{solid} \times V_{solid} \times C_{psolid} \times (T_{fs} - T_{is})$$
$$E_{liquid} = \rho_{liquid} \times V_{liquid} \times C_{pliquid} \times (T_{fl} - T_{il})$$

iii) Efficiency of TES system with PCM

$$\eta_{with\ PCM} = \frac{Q_{out}}{Q_{in}} = \frac{\textbf{Heat energy output}}{\textbf{Heat energy input}} \quad \ldots\ldots\ldots\ldots (4.8)$$

Where,

ρ_{solid}, V_{solid}, C_{psolid}, T_{fs}, T_{is} are the density, volume , specific heat, final temperature and initial temperature of solid.

ρ_{liquid}, V_{liquid}, $C_{pliquid}$, T_{fl}, T_{il} are the density, volume , specific heat, final temperature and initial temperature of liquid.

Latent heat of fusion (λ) = mass of PCM X Heat fusion of PCM

V. OBSERVATION TABLE

5.1 Charging Processes for without PCM.

Hours	Outlet temperature of heat transfer fuel(^0C)					Average temperature
	Day1	Day2	Day3	Day4	Day5	(^0C)
1	34	32	32	33	32	32
2	37	36	37	38	37	37
3	44	42	43	44	43	43
4	48	45	47	47	47	47
5	49	48	49	50	49	49
6	51	49	51	50	51	50

5.3Charging Processes for with PCM

Hours	Outlet temperature of heat transfer fuel(^{0}C)					Average temperature (^{0}C)
	Day 1	Day 2	Day 3	Day 4	Day 5	
1	32	32	35	33	37	33
2	36	36	43	41	45	40
3	44	44	48	48	49	47
4	48	48	51	52	52	50
5	52	54	55	56	56	54
6	58	57	56	53	57	57

VI. RESULTS AND DISCUSSION

6.1. Introduction

The temperature distributions of water and the PCM in the water tank for different time intervals are recorded during charging and discharging processes. The cumulative heat stored and system efficiency of process is studied in detail during the discharging process.

6.2 Output Result Table

Table 5.1: Energy efficiency for without PCM and with PCM

Sr. No.	Time (hrs) T	Energy Efficiency (%)	
		Without PCM	With PCM
1	6	27.49	30.88
2	12	26	32.07
3	18	25.28	32.07
4	24	25.29	32.09
5	30	26.38	32.09

6.3. Charging process:

6.3.1 Temperature of water without PCM and with PCM at charging process.

Fig 5.1 shows the temperature variation of water without PCM and with PCM during the charging process. The inlet temperature of the

HTF from the collector increases continuously with time at a uniform rate.While in charging the solar water heater in the case of without PCM the water ran up to low temperature in 6 hrs time elapsed but with PCM the water ran up to high temperature in 6 hrs time elapsed. 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. fig 5.1 shows the temperature of water increasing rate is higher using with PCM.

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 collectorareato reduce the charging time.

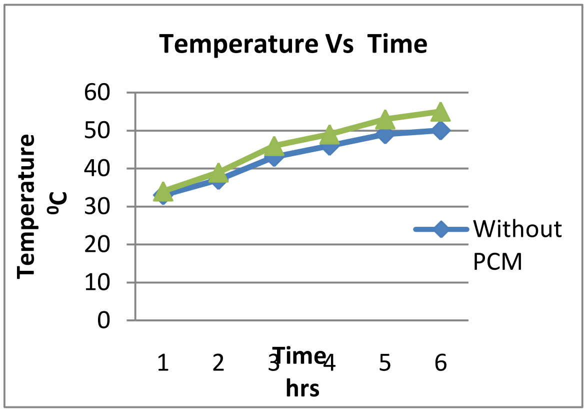

Fig.6.1: Temperature of water without PCM and with PCM at charging process.

6.4. Instantaneous heat stored

Fig.5.2 shows the instantaneous heat stored in the storage tank during the charging process. This is estimated based on the instantaneous inlet and outlet temperatures of the HTF. It is observed that during the initial period of charging the instantaneous heat stored is high and it is decreasing till 50 to 60 minutes. This drop in heat stored is due to the decrease in temperature difference between the HTF and the temperature of the storage tank. As the charging process proceeds, the PCM starts melting and the heat stored remains almost uniform due to constant temperature difference between the HTF and the storage tank. This is the major advantage of a combined system where a uniform rate of charging and discharging is possible for a longer period, which will be useful for many practical applications.

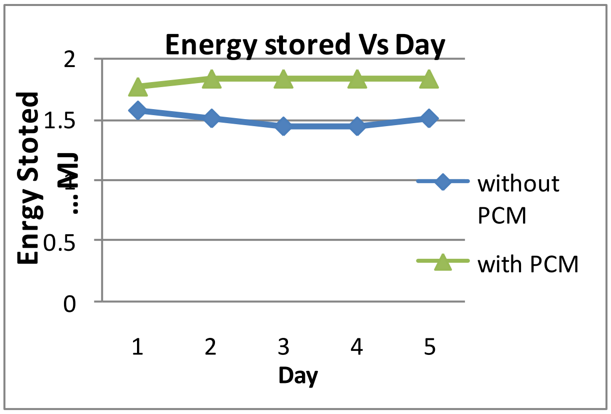

Fig.6.2: Instantaneous heat stored

6.5. System Efficiency

Fig 6.3 shows the system efficiency of the storage system for TES tank without PCM and with PCM It is defined as the ratio of the amount of energy stored by tank (Q_{out}) 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, remain constant during phase change period. Figure 5.3 shows the efficiency variation without using PCM and using PCM.

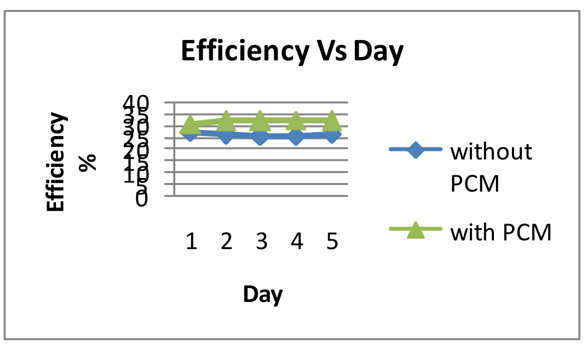

Fig.6.3: Efficiency variation without using PCM and using PCM.

6.6. Discharging process:

The temperature water without PCM and with PCM during discharging process (heat recovery) for batch wise discharging methods are reported. A comparative study is made between the conventional SHS system and combined storage system and conclusions based on this study are presented.

Fig. 6.4 represents the temperature variation of PCM during batch wise discharging process. It is seen from the figure that the temperature drop is large until the PCM reaches its phase transition temperature as the hot water in the storage tank loses its sensible heat due to the mixing of inlet water at a temperature of 31°C. After that the temperature drop in the PCM is negligible for a long duration as the PCM releases its latent heat. In the case of batch wise method it occurs over duration of 2 minutes as the inlet water is supplied intermittently to extract heat from the storage tank. After complete solidification of the PCM, its temperature starts decreasing however the rate of temperature drop is not as high as in the beginning of the discharging process. This is due to low temperature difference between the PCM and inlet temperature of TES tank though the solid PCM releases its sensible heat.

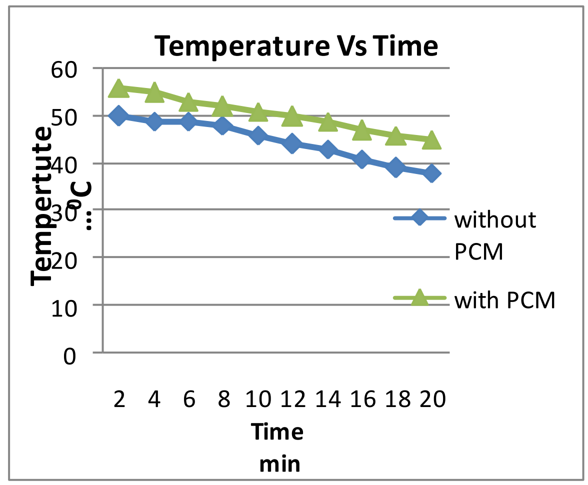

Fig.6.4: Variation in temperature at discharging process

VII. CONCLUSION

The present study investigated the heat transfer process and the convective flow regime during the phase transition period in a PCM. The copper tubes filled with PCM, used during the study was inserted into evacuated tubes of ETSC. A thermal energy storage system has been developed for the use of hot water at an average temperature of 45°C for domestic applications using combined sensible and latent heat storage concept. Charging experiments are conducted on the TES unit to study its performance by integrating it with constant heat source. The temperature of water & PCM and energy storage characteristics during charging process for copper tubes inside each evacuated tube and PCM (Paraffin and wax) are studied. The use of PCM in solar water heater helps to reduce cooling rate of water, thus it enhance the maximum utilization of solar energy and hence improves efficiency of system. In this research with use of PCM efficiency of solar water heater increase from 26.38% to 32.09% and also heat storage capacity increase from 1507.320 kJ to 1820.91 kJ. Hence with using PCM material efficiency & heat capacity of solar water heater increases at reduced initial heating rate because PCM take heat to get heated. As PCM based solar water heater store maximum solar energy, it reduces the size of tank and hence can reduce cost of Solar

Water Heater. The use of PCM in solar water heater helps to reduce cooling rate of water, thus it enhance the maximum utilization of solar energy and hence improves efficiency of system.

VIII. FUTURE OBJECTIVE

In future this project will also help to find the suitable PCM and provide the various designs for solar water heating systems to store the solar thermal energy. In the next study the modified model analysis include the change of parameter TES tank and different material and shape of capsule. PCMs can be used in storing solar energy for building application, greenhouse and solar thermal power plant also.

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