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Using Evacuated Tube Collectors (ETC) As Micro-Encapsulation For Thermal Energy Storage: Comparative Charging-Discharging Characteristics Of A Phase Change Material (PCM) And Water

Shailendra Kumar and Priya Bisht

Forest Products Division, Forest Research Institute, Dehradun

Abstract

The study centered on a comparison between phase change materials (PCM) and water integration with evacuated tube collectors (ETC). Temperature behavior in ETC filled with PCM and water separately was studied. Charging and discharging of PCM and water in ETC were studied. The amount of heat transferred from both systems was evaluated. During charging of PCM integrated with ETC, a steeper thermal stratification was observed as compared with water. The heat stored in PCM (ETC) was significantly higher; however, the heat discharge from PCM (ETC) was very slow as compared with that of water (ETC). Heat transfer efficiency was significantly higher in water (ETC) as compared with the PCM (ETC).

Keywords: *Evacuated tube collectors, phase change material, charging and discharging*

Introduction

At present solar energy is a fast-developing industry for various domestic and commercial practices. The utilization of solar-assisted processing techniques is, however, limited and not continuous (through-out the day and night) due to the sun's diurnal nature. The ability to operate continuously is important in order to reduce processing time and largely to present solar energy as a reliable source of energy. Since solar energy is not available at night, it presents the biggest impediment in its utilization for industrial purposes. Therefore, energy storage can be undertaken to explore the available resources and improve their utilization. Storage of some kind of energy that can be drawn upon at a later time and usefully re-applied in a given operation is called energy storage [1]. [2] Identified three main parts of the energy storage unit as storage medium, containment system, and heat transfer mechanism.

The successful storage of solar energy would ensure a constant and smooth supply of heat without any external aid, and thus, it will be helpful in improving the efficiency of the solar-based processing systems in terms of a shorter processing period. Hence, energy storage helps to increase the reliability of the system, capital cost-saving, and lower emissions. Solar thermal energy storage has many applications, such as solar water heating [3], space heating [4], [5], space cooling [6], greenhouse heating [7], waste heat recovery system [8], etc.

Phase change material (PCM) is an effective medium for thermal energy storage due to their high latent heat of fusion and high energy storage density [9]. Heat is basically absorbed or liberated when material changes its phase from solid to liquid and vice-versa. Basically, PCM operates at low to moderate temperatures while storing a large amount of heat energy [10], [1]. For its optimum utilization, PCM is encapsulated in suitable containment. Evacuated tube collectors (ETC) are popular means of heating water using solar heat. Using ETC for PCM containment is a very innovative way of storing solar thermal energy in the heating system itself. Additionally, efficient encapsulation of PCM has been shown to improves heat transfer areas, preventing PCM reactivity with the outside environment [11]. [12] Evaluated the performance of a solar water heater with evacuated tubes integrated with PCM. [13] presented review problems and prospects of PCM integration. [14] Investigated the thermal characteristics of charging and discharge processes of a fabricated thermal energy storage system using PCM, where the PCMS was filled in spherical capsules.

This work is centered around the studies on charging and discharging characteristics of a PCM integrated with ETC and its comparison with water as heat storage media. The main idea is to enable solar irradiance to melt solid PCM encapsulated in ETC to allow to store heat energy and release it during the night while solidifying. The paper further investigates the storage performance analysis and the heat transfer rates of PCM and water-based heat storage medium.

Materials and methods

PCM encapsulation in ETC tube

Two evacuated tube collector (ETC) tubes were taken and placed on a wooden stand in a slant position, making an approximate angle of 45° from the horizontal plane (fig. 1a and 1b). The specifications of the ETC tubes are given below in table 1. U-shaped bent copper pipes (length 150 cm) was inserted inside the tubes (fig. 1a).

Table 1: ETC tubes specifications

Material	Borosilicate glass
Total length	150 cm
Inner length	147.5 cm
Inner diameter	3.5 cm
Outer diameter	4.5 cm
Weight	1.347 kg
Capacity	1.4 l

The outer and inner diameters of the copper pipe were 4 mm and 3.5 mm. Three temperature probes (PT-100) were placed in the ETC tubes at the bottom (141 cm), middle (72 cm), and top (12 cm), measuring from the upper end of ETC (fig. 1a). The temperature sensors were attached in such a way that they didn't make any contact with either ETC or copper pipes. The first ETC tube was filled with 1.2 kg commercial-grade, fatty acid-based PCM, and the second one was filled with the same weight of water. A space of approximately 10% from the top was left to allow thermal expansion in the PCM. The thermophysical properties of the PCM are given below (Table 1).

Table 2: Thermos-physical properties of PCM

Material	A mixture of fatty acids
Melting point	48 ºC
Liquid density	875 kg/m³
Solid density	900 kg/m³
Latent heat	275 KJ/kg
Specific heat	2.11 KJ/kg ºC
Specific heat	1.71 KJ/kgºC
Liquid thermal	0.12 W/mk
Solid thermal	0.20 W/mk

An insulated jar filled with water for retrieval of stored thermal energy

A high-grade glass jar, with a capacity of 7 *l* and an external and internal diameter of 47 cm and 34 cm, respectively, were used to collect discharged heat energy. The jar was insulated with 50 mm thick glass wool and placed inside a closed aluminum container to prevent heat losses. The jar had two openings on the top; inlet and outlet. The outlet opening was connected with a small submersible water pump (180-250V, 18 W, maximum capacity 6.6 l/ m) which was connected with the U-shaped copper pipe placed in the ETCs using an insulated hose pipe. The other end of the copper pipe was connected with the inlet of the jar, as shown in fig. 1a. The jar was filled with water.

Charging- discharging of PCM

The experiments on charging and discharging of the PCM were carried-out in the second-third week of February at location Dehradun (India) by exposing the ETCs filled with PCM and water to direct sunlight. The temperatures at three locations in ETC were recorded simultaneously till all the PCM was molten.

During the discharging experiments, the ETC tubes were fully covered with a heavy insulation cloth to prevent further heating. To extract the heat stored in PCM encapsulated with ETC, the water pump was allowed to circulate water (as a heat transfer fluid) through the copper tube to the water storage tank at a uniform rate. During the discharging process, the temperature of PCM/ water in ETC started to fall, and that of water in the jar started to rise. The discharging continued till the temperatures of PCM and water became approximately equal. The same process of charging and discharging was repeated for water-filled ETC.

The charging and discharging experiments were carried out for three and four consecutive days for water and PCM-filled ETCs separately. For calculation of stored heat in the media (water and PCM), mean temperatures were taken.

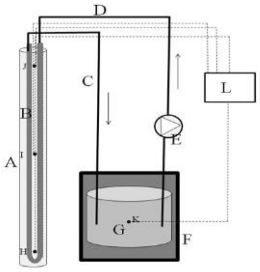

Fig. 1a

Fig. 1b

Fig. 1a and 1b: Experimental arrangement. ETC (A), U-shaped copper pipe (B), incoming water pipe to jar (C), outgoing water pipe to ETC (D), water pump (E), insulated enclosure for jar (F), jar (G), Lower, middle and upper-temperature sensor positions in ETC (H, I, J), temperature sensor in the jar (K), temperature data logger (L)

The amount of the stored heat stored in water (ETC) was calculated using expression 1:

$$Q = \int_{T_i}^{T_f} mC_p \, dT = mC_{ap} \left(T_f - T_i\right) \ldots\ldots\ldots..1$$

The amount of the stored heat in PCM (ETC) was calculated using expression 2 & 3:

$$Q = ma_m \Delta h_m + \int_i^m mC_p \, dT + \int_m^f mC_p \, dT \ldots\ldots 2$$

Or

$$Q = m[a_m \Delta h_m + C_{sp}(T_m - T_i) + C_{lp}(T_f - T_m)] \ldots\ldots 3$$

Where,

Q= quantity of heat stored (KJ)

m= mass of heat storage medium (kg)

a_m = fraction molten

Δh_m = heat of fusion per unit mass (KJ/kg)

C_{sp} = average specific heat between T_f and T_i $(\frac{KJ}{kg\ K})$

T_m= melting temperature (°C)

Ti= initial temperature (°C)

C_{lp} = average specific heat between T_m and T_i $(\frac{KJ}{kg\ K})$

T_f= final temperature (°C)

C_p= specific heat of material (KJ/kg K)

C_{ap}= average specific heat between initial and final temperature (KJ/kg K)

The realization of stored heat

The heat transferred from ETC to water in the jar was used to increase the temperature of the water. The amount of heat transferred to water in the jar was calculated using equation 1.

The efficiency of the heat transfer from both types of storage media in PCM encapsulation was estimated using equation 4.

$$Efficiency\,\% = \frac{Heat\ transferred\ to\ water\ in\ jar}{Heat\ stored\ in\ ETC} X100 \ldots\ldots.4$$

Results and Discussion

Charging in ETC tube

Figure 2 shows temperatures of the PCM during charging in ETC.

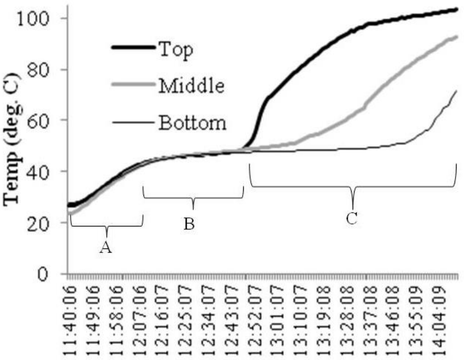

Fig. 2: Charging curve of the PCM in ETC encapsulation

It can be seen from fig. 2 that vertical stratification in the temperature of PCM during heating occurred. The temperatures of three vertical points in PCM in ETC went up gradually till the melting temperature was attained (stage A). Stage A is marked by sensible heat storage in the solid phase of the PCM. The specific heat capacity of the solid PCM is 1.71 KJ/kg °C. As the melting point is achieved, the PCM started to melt, and the heat was absorbed in the form of latent heat (275 KJ/kg). Once the PCM was molten completely, a rise in its temperature beyond its melting point was observed. The rise of temperature is marked by thermal storage in the form of specific heat in liquid form (2.11 KJ/kg °C). The sequence of the melting of the PCM occurs in two stages [15]: heat transfer through conduction till melting temperature is achieved (first phase) followed by melting and resultant natural convection (second phase).

As the charging continues, it can be observed that the top layer exhibited a rapid rise in temperature after attaining its melting point with completing the melting phase very early in just 68 minutes. Following, the middle layer showed smooth and steady heating with faster charging rates later on. Slow and delayed melting was observed in the bottom-most layers. This may be attributed to the poor thermal conductivity of PCM due to which thermal resistance increases, which in turn reduces the surface heat flux [14]. The total completion time for melting phases (charging) being 89 minutes and 140 minutes in the middle and bottom layer, respectively. It can be seen from the top layer, where the temperature sensor was placed at 12 cm from the top, completed its melting phase very early (68 minutes), followed by the middle layer, a sensor placed at a distance of 72 cm from the top (89 minutes), whereas, for the bottom layer, it took 140 minutes for completion of melting.

Table 2: Total time to complete melting in the top, middle, and bottom layer

Charging cycles	Time is taken for complete melting (min)		
	Top	**Middle**	**Bottom**
Cycle I	77	137	177
Cycle II	100	133	169
Cycle III	73	103	141
Mean	**83.3**	**124.3**	**162.3**
S.D	**14.6**	**18.6**	**18.9**
CV%	**17.49**	**14.95**	**11.64**

Table 2 suggests that the temperature of the topmost layer was much higher than the melting point while the bottom portion of the PCM was still in the solid phase. Melting of the PCM is marked by the evolution of melt front and convection [16]. During the melting process, molten PCM becomes lighter and starts moving to the upper surface, and continues to increase its temperature by absorbing heat in the form of sensible heat. In turn, the solid PCM starts to sink to the bottom side of the container.

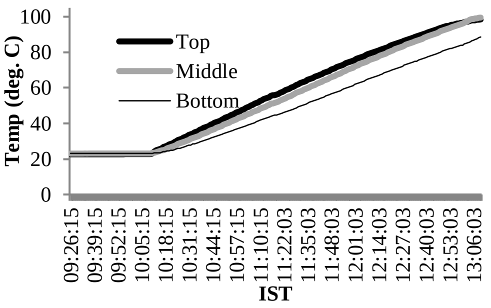

Fig. 3: Charging curve of water

This natural convection during melting results in thermal stratification in the PCM, as shown in fig. 2 and table 2. However, the resultant thermal stratification is known to slow down the melting process [17].

Fig. 3 presents the heating/ charging curve of water in an ETC tube. The temperature gradient in water in ETC too has occurred but is not as significant as in PCM. The temperature difference between the top, middle layers seems to be very small as compared with the temperature difference between the top and bottom layers. The bottom layer also witnessed a steady increase in temperature; however, it was relatively lower than the top and the middle layer.

Discharging of heat from ETC encapsulation

Freezing curves of PCM offer a great piece of information [18]. The actual phase transition temperature range of the PCM may help in designing a thermal storage system [19]. During the discharging phase, the temperature of molten PCM starts falling at faster rates. Initially, the rate of discharge was higher, followed by a much slower discharge rate (Fig. 4). This is due to the fact that the layers of solid PCM start developing around the outer region of the copper tube, which hinders the heat transfer from the liquid PCM to it. The solidification rate of the PCM is a function of mass and heat transport heat [19]. While the charging of PCM was assisted by convection, the discharging was dominated by conduction. The discharging rate of PCM is limited by the solidification rate and poor thermal conductivity of PCM resulting in slower heat discharge.

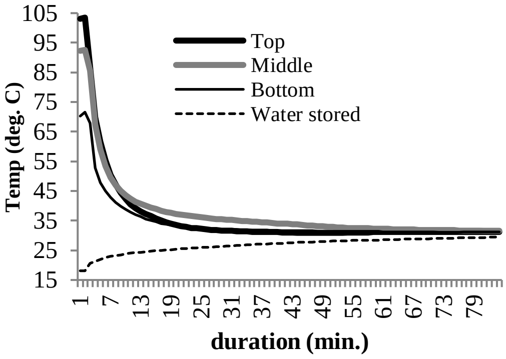

Fig. 4: PCM (ETC) heat discharge

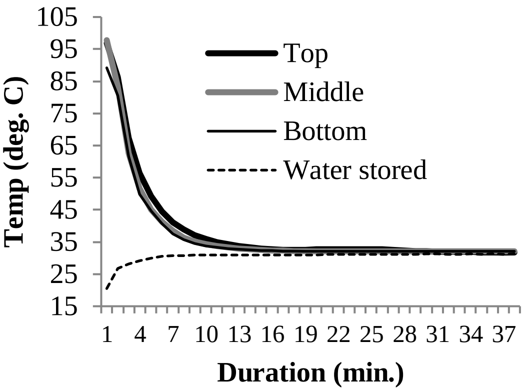

Fig. 5: Water (ETC) heat discharge

Heat discharge curves for water-filled ETC (Fig. 5) reveals that the discharge is very fast as compared with the PCM. It took only 20 min to equalize the temperatures of water in ETC and the jar, whereas, in the case of PCM in ETC, it took nearly 80 min. The faster discharge of heat from water as compared with the PCM may be attributed to the fact that water has higher thermal conductivity (0.66 W m-1 K-1) [20] than that of the PCM, i.e., 0.12 W/mk (liquid) and 0.20 W/mk (solid).

Total heat storage and transfer efficiency

Table 3 presents the amount of heat stored in PCM (ETC) and the heat transferred to water (jar). For the calculations, it was assumed that the heat losses were negligible. It can be seen that the PCM (1.2 kg) placed in ETC was able to store mean heat energy 477.6 KJ, whereas the amount of the heat transferred was very low (253.8 KJ). Thus, the mean heat transfer efficiency of 53.2% was achieved.

Table 4 presents the amount of heat stored in water (1.2 kg) in ETC and the amount of heat transferred to water in the jar.

Table 3: heat storage and transfer efficiency in PCM (ETC)

	PCM			**Water storage tank**					
Cycles	**Initial temperature (°C)**	**Average temperature (°C)**	**Heat stored in PCM (KJ)**	**Initial temperature (°C)**	**Final temperature (°C)**	**mass (kg)**	**Temperature change (°C)**	**Heat transferred (KJ)**	**Efficiency**
I	32.3	100.8	495.9	21.3	30.2	7	8.9	260.4	52.5
II	31	89	468.7	20	28.6	7	8.6	251.6	53.7
III	33.5	91.2	469.1	23.5	31.9	7	8.4	245.8	52.4
IV	31.6	92.6	476.6	20.6	29.4	7	8.8	257.5	54
avg			**478**					**253.8**	**53.2**

The mean heat stored in water was 320.7 KJ and the amount of heat transferred was 283.5 KJ resulting in very good transfer efficiency (88.5%).

Table 4: heat storage and transfer efficiency in water (ETC)

Cycles	Water			Water storage tank				Efficiency%
	Initial temperature (°C)	Average temperature (°C)	Heat stored in Water (KJ)	Initial temperature (°C)	Final temperature (°C)	Temperature change (°C)	Heat transferred (KJ)	
I	33.3	97.9	324	20.6	32.1	11.5	286	88.5
II	33.6	96.1	314	23.4	34.5	11.1	278	88.6
III	33.4	98.1	325	20.7	32.2	11.5	286	88.5
avg			**321**				**284**	**88.5**

It is noticeable that the heat stored in PCM was very large (approximately 1.5 times), but the heat transferred was lower than the water. This indicates the problem of heat transfer in PCMs, as discussed in previous sections. Consequently, the efficiency and discharge rates can substantially be improved using a combined PCM and water integrated system [21].

Fig. 6 presented the temperature curves of water (jar) when the heat transfer was carried out from water (ETC) and PCM (ETC) separately. It can be seen that the temperature rise in water (jar) was very quick when the heat was transferred from water (ETC) as compared with the PCM (ETC). However, it can also be seen that the temperature of the water when heated through PCM (ETC) surpassed that of water (ETC) after the discharging was done for a relatively long period. This indicates that the PCMs can store a large quantity of heat (Table 3) but need efficient heat transfer arrangements.

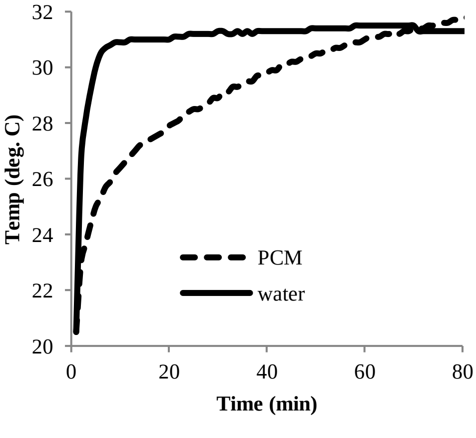

Fig. 6: Temperature rise from heat stored in PCM (ETC) and water (ETC)

Fig. 7 presents comparative heat storage capabilities of two media (water and PCM) at different temperatures. The amount of heat stored in water (up to 100 °C) depends upon the temperature. Its curve is straight up to 100 °C. However, the heat stored in PCM, which involves phase change, witnesses a steep rise in heat storage capabilities (latent heat) from A to B. The storage advantage % of PCM over water rises shapely in this region.

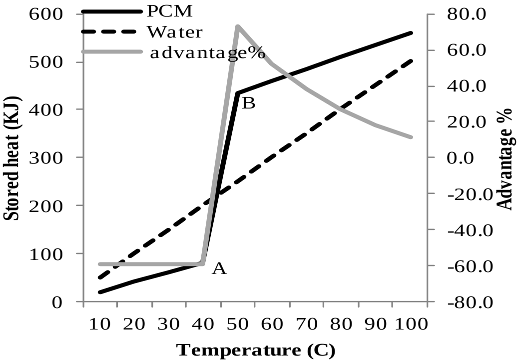

Fig. 7: Heat storage in PCM and water

Increasing water temperature beyond 100 °C will result in boiling and huge volume expansion. This will result in convective heat losses and problems in containment. Moreover, radiation heat losses will also become huge for thermal storage at higher temperatures.

Conclusion

Heat storage in macro-encapsulation of ETC presents an attractive means of storing heat energy that can efficiently be used for the development of thermal storage systems. During the charging of PCM integrated with ETC, a steeper thermal stratification was observed as compared with water. The heat stored in PCM (ETC) was significantly higher; however, the heat discharge from PCM (ETC) was slower as compared with that of water (ETC). The heat transfer efficiency of water (ETC) was significantly higher than PCM (ETC). It is concluded that PCM integration with ETC is a better option as compared with the water in ETC. However, the results also indicated a concern for improving the heat transfer from the PCM integrated into ETC systems for efficient utilization.

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