Energy and exergy analysis of heat pipe based SWH system integrated with phase change material for clear and cloudy days: An experimental approach

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Energy and exergy analysisofheat pipe based SWH systemintegrated with phase change material for clear and cloudy days: An experimental approach

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Abstract:

Solar water heating is the most promising way to effectively use solar energy among all other solar energy applications. In this study, an innovative way of incorporatingphase change material (PCM) between the annulusspace of the heat pipe and the evacuated tubes for solar water heaters (SWHs) is used. The proposed system can deliver hot water when demand is high/solar radiation is insufficient by using palmitic acid as PCM. The energetic and exergetic analysis of the developed systemintegrated with PCM is studied on both clear and cloudy days. The results revealed that the maximum daily collected useful energyfor the clear and cloudy days was10.65 MJ & 8.52MJ respectively, whereas the maximum storage tank temperature was found to be 46.2°C and 41.4°C for the corresponding days. The daily average energetic and exergetic efficiencies of the proposed system were found to be 76.57% and 79.64%, and 2.37% and 1.38%, respectively at a fixed mass flow ratefor clear and cloudy days conditions.The results reveal that the designed system eliminates the problem of overheating heat pipes and can supply hot water even under cloudy conditions.

Keywords:*Solar water heater; Phase change material; Heat pipe; Energy; Exergy*

Nomenclature	***Abbreviations***
$C_{p,w}$–Water specific heat (J/kg.K)	DSC-Differential scanning calorimetry
Ex_{gain}- Exergy gain (J)	ET- Evacuated tube
Ex_{out}- Exergy at the outlet (J)	ETSC-Evacuated tube solar collector
Ex_{in}- Exergy at the inlet (J)	LHS-Latent heat storage
Ex_{solar}- Incident solar exergy (J)	TES-Thermal energy storage
Q_{useful}- Useful amount of energy (W)	PCM-Phase change material
$Q_{absorbed}$- Energy absorbed by collector (W)	LPH-Liter per hour
m_w- Mass flow rate of water (LPH)	SWH- Solar water heater
I_T- Solar radiation (W/m^2)	MJ-Mega joule
$A_{aperture}$- Aperture area (m^2)	HP-Heat pipe
η_{DTE}- Daily thermal efficiency	
η_{DEX}-Daily exergy efficiency	

1. Introduction

The energy demand for household hot water production has augmented continuously, especially in cold regions. The non-renewable energy sources utilization to meet the current energy demand must be limited because of their negative impact on the environment. Solar energy is a promising option among all renewable energy sources to reduce the reliance on conventionalenergy sources[1,2].The solar water heating (SWH) systems are mostly used devices to capture and utilize solar energy. The most common type of solar collectors isevacuated-tubecollectors (ETCs)and flat platecollectors (FPCs).In general, ETSC outperformsFPSC in terms of performance, temperature, operation, and cost.As per the current commercial scenario, the water-in-glass system and the heat-pipe type are two popular forms of ETC basedSWHs. [3]. The simple design and low price make the water-in ETC glass SWH a popular choice for domestic purposes, butit has low thermal performance as compared to heat pipe based evacuated tube solar collectors.In the heat pipe, low boiling point heat transfer fluidis utilizedas a working fluid to transferthe heat to the manifold of the SWH system[4]. Due to the low boiling point of fluid, the liquid inside the heat pipe evaporates and travels very quickly towards the condenser of heat pipe. The vapors in the condenser turn into liquid bypassing the water in the manifold over condensers and the heat pipe’s liquid moves back to the downsidedue to gravity. A spring clip holds an aluminum fin in the tube, improving the heat transfer rate and mechanical support.

Besides a lot of advantages of heat pipe ETC, still, conventional heat pipe systemsare facing many challenges with their usage, such as being incapable to supply hot water during, cloudy, rainy, and off sunshine hours and also their low energy and exergy efficiency. Therefore, thermal energy storage (TES) units are required to increase the thermal output of SWH systems and make them efficient for off sunshine hours operation[7]. Other than this integration of the TES system with an SWH system has several benefits, such asincreased overall efficiency of the system and no negative effects on the environment. Various experimental studies have shown that integrating the phase change material (PCM) as TES provides hot water production for an extended period, minimizes the outlet temperature fluctuations, and reduces the thermal losses. So, the application of PCM with ETSC is beneficial[8,9].Wu et *al.,*[10]developed a unique type SWH system that utilizes PCM and an oscillating HP to mitigate the effects of solar radiation intensity changes. It was demonstrated that the variation in collected efficiency with PCM is approximately 30% smaller than without PCM. Chopra et *al*.,[11] tested SWH system equipped with HP-ETC by 3-Eanalysis for climate conditions of Jammu (India). They conducted the experiments for six mass flow rates of 20-60 LPH. The results obtained that maximum energetic and exergeticoutputswere 72% and 5.2%, respectively, at 20 LPH. The economic analysis suggested the cost of hot water was INR 0.12 per liter, which is less than electric and gas geysers. The payback time of the developed SWH system was four years which is less than other two SWH systems. Abokersh et *al.,*[12] developed a new U-tube evacuated tube collector based SWH system filled with paraffin wax (PCM).They explored the system under real-time operation and real water usage profiles.The results demonstrate thatthe use of fin in an SWH system also increases the PCM's heat transfer properties and overall stability of the system. During real-time operation, the un-finned system's total actual energy discharged is 35.8% more than the conventional SWH system. However, the finned system outperforms the conventional SWH system by 47.7%. The average annual efficiency for unfinned, finned, and conventional SWH systems is 71.8%, 85.7%, and 40.5%, whereas the daily energy efficiency of system is 33%, 26%, and 20% respectively.Shafieian et al.[13] examine the efficiency of the SWH system to fulfil the demandfor hot water in a residential building inthe winter season. The ideal glass tubes numersin the HPbased solar collector was calculated using a mathematical model. An experimental setup of 25 glass tubes is designed, constructed, and tested. The output results revealed that hot water extraction increased the quantity of absorbed energy and the overall efficiency of SWH systems while lowering exergy destruction.The collector's predicted and experimental outlet temperatures agreed quite well, with the highest absolute and standard deviation of 5.6% and 1.77%, respectively.Alshukri et *al.,*[14]performed the experiments on ET-SWH and HP-ETC SWH systems integrated with PCM. They filled the evacuated tubes and two separate tanks with medical grade paraffin wax as TES. This novel technology provides hot water for an extended period due to late heat releasedwhen demand is high/solar intensity. A study compared four HP/ETSCs with thermosyphonHP rigs at two flow rates of 1 and 2 L/h, respectively. TheHP was filled with pure acetone at (0.7). The results reveal that filling PCM in the ETs and isolated tanks increases efficiency by 55.7% while filling PCM only in ETs improves thermal output by 49.9%. Adding PCM to the separated tanks improved efficiency by 36.5% to a PCM-free reference collector.Felinski and Sekret[15]analyze the outcome of PCM, which is filled in space between the evacuated tubes and HP of the SWH system. The results revealed that charging efficiency of ETC/storage varies from 33 to 66 %. The use of technical grade paraffin as LES inside the ETC allowed for delayed heat release at night when solar radiation was not available. And, hot water temperature inside the tank increased during peak loads of hot water throughout the year. Moreover, an ETC with storage boosted the yearly solar fraction by 20.5% in a SWH system used for hot water application in a household. Bazri et al. [16]analytically (using MATLAB) investigated compact design HP-ETC solar water heater integrated with LES tank. They filled the tank with paraffin was as PCM. As per the results, the system efficiency is ranged from 32-42% in low solar radiation conditions and approximately 40% in high solar radiation conditions, but the new design is about 57% which ismore than 50%. The energy efficiency of new constructed system for all three kinds of PCMs is 36–54% on a clear sunny day, but increases to 47–58% on a cloudy/rainy day. This trend is reversed with the standard system. Overall, the proposed system improves efficiency by 10% to 58% for three PCMs as compared to standard system.

The aforementioned studies have concluded thatthe SWH system with PCM performed significantly better than the SWH system without PCM. Most studies focused on types of PCM and tank design that influence the performance of SWHs. And the PCM is placed in the water storage tank at different locations. As per the literature availability and best of the author's knowledge, there are very few studies in which PCM is filled inside the evacuated tubes of the SWH system.Moreover, in most studies paraffin wax as PCM has been used. In this study, palmitic acid has been usedas PCMwhich is filled inside the evacuated tube as a thermal energy booster. The objective of this workis to analyze the effect of clear and cloudy weather conditions onthe performance of HP-ETC based SWH system filled with PCM. The experimental results show the practical applicability of palmitic acid as PCM with the SWH system.

2.Experimental setup and Methodology

The experimental study was completed in two phases. In Phase-I, an appropriate selection ofPCM for an evacuated tube collector wasdone which is very critical. In Phase-II, implementation of selected PCM in designed solar collector system and analyzed the performance of PCM integrated SWH system for clear and cloudy weather conditions have been carried out.

2.1 Selection of PCM (Phase-I)

Paraffin wax and fatty acid based PCMs are primarily utilized for low/medium temperature range heating applications because of their stable physical and chemical properties, lack of toxicity and fire hazard, and are relatively inexpensive and readily available[17].These characteristics make them ideal heat storage material in evacuated tube solar collectors.In this study, the high heat storage capacity and favorable thermophysical properties of palmitic acid areutilized. Palmitic acid exhibits a wide range of latent heat capacities varies from 204.93 to 205.52 kJ/kg, melting point temperature between 61.10°C to64.70°C, specific heat at different temperature rangesfrom 2.20 to 2.48 kJ/kg°C, and heat conductivity (K) of 0.25 W/m K. Thus, palmitic acid for heat storage can be chosen based on their melting/solidification and SWH's operating temperatures. The density of palmitic acid for (liquid-solid) and (solid-state) are 0.85 g/cm^3 at 25°C and 0.89 g/cm^3 at 70°C. The melting point temperature, capacity of latent heat, specific heat, and other thermophysical parameters were assessed by DSC analysis. The manufacturer provides the remaining attributes[18].

2.2 Description of the experimental setup

Fig. 1 depicts the schematic view, and an experimental setup of the HP-ETC based SWH system filledwith palmitic acidas PCM.The developed SWH system was tested under outdoor conditions on the rooftop of School of Energy Management, Shri MataVaishno Devi University, Jammu, India (32.9418°N, 74.9541°E). The designed system was placed at an angle of 45° to the south. The palmitic acid was used as latent heat storage (LHS) material, filled in annulus space between the absorber side of theET and aluminium finned of HP.Then, with the help of a beaker, liquified PCM is directly filled with 75% of that total volume. As per the liquified density, 1.9 kg of selected palmitic acid is filled in each tube.

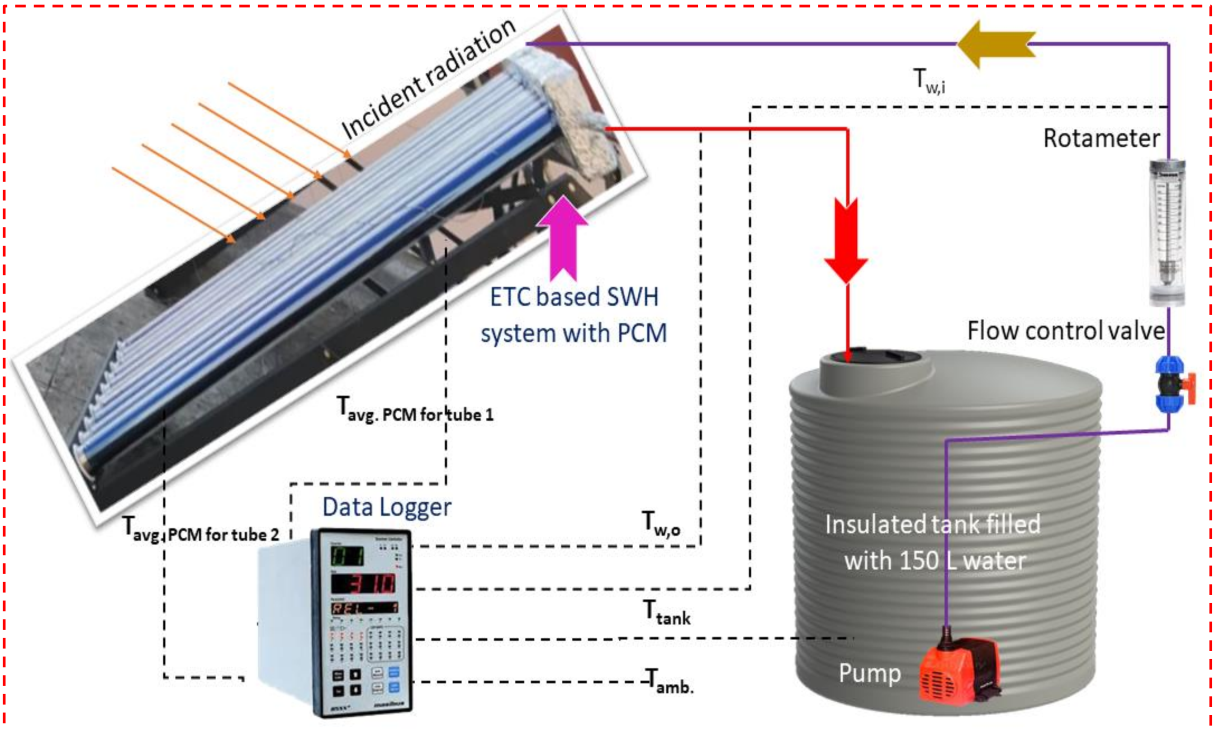

Figure 1: The image view of the experimental test arrangement.

The proposed SWH system was made of nine thermosyphon heat pipes with ETs. EachHP ishaving analuminum fin to increase the effective heat movesfrom absorber tube to HP and increase the conductivity of the used PCM duringcharging/dischargingprocess. Experimental investigation was conducted at a fixed flow rate of 20 LPH for clear and cloudy weather conditions. The working fluid i.e. water is circulated through a pump and itsmass flow rate was measuredusing ahigly calibrated rotameter. The hot water is collected inside the insulated tank and recirculated to achieve high degree of hot water.Six calibrated thermocouples were arranged throughout the proposed system to observe the temperatures of various places.

The thermocouples are arranged from T_1-$T_6$and presented in Table 1 with their suitable locations. Also, the detailed technical information onthe test setup and its measuring instruments are presented in Table 2.

Table 1: Description of the several thermocouples locations on the SWH system

S.No.	Notation of temperature	Temperature with their respective position (°C)
1	T_1	The average temperature of PCM inside the tube 1
2	T_2	Average PCM temperature inside the tube 2
3	T_3	The inlet temperature of the water
4	T_4	The outlet temperature of the water
5	T_5	The temperature of water storage tank
6	T_6	Temperature of ambient

Table 2: Specification of the experimental setup

S.No.	Specifications	Value/material
1	Evacuated tube length	1800 mm
2	Glass material	Borosilicate glass
3	Thickness of glass	2-3 mm
4	Absorptivity of absorber tube	>92%
5	Emissivity of absorber tube	<8%
6	Heat pipe material	Copper
7	Condenser section length	63.5 mm

8	Evaporator section length	1600 mm
9	Temperature range ofRTDs	-50°C to 550°C
10	Submersible pump flow range	0-2.6 LPM
11	Rotameter flow rate range	0-1.6 LPM

2.3 Experimental methodology

This study investigated the energetic and exergeticefficiency of a HP-ETC based SWH system with PCM(palmitic acid)at a fixed flow rate of 20 LPH for clear and cloudy weather conditionsinKatra (J&K), India. A part of incoming solar radiation falling on area of collector is captured by PCM. The remaining portionof solar radiation is collected by the moving fluid (water), flowing through the manifold.There are two test conditions: *Run-I* at 20 LPH for clear weather conditions and *Run-II* at 20 LPH for cloudy weather conditions. For better accuracy of results, the experimental setup was operated twice for the same environmental conditions

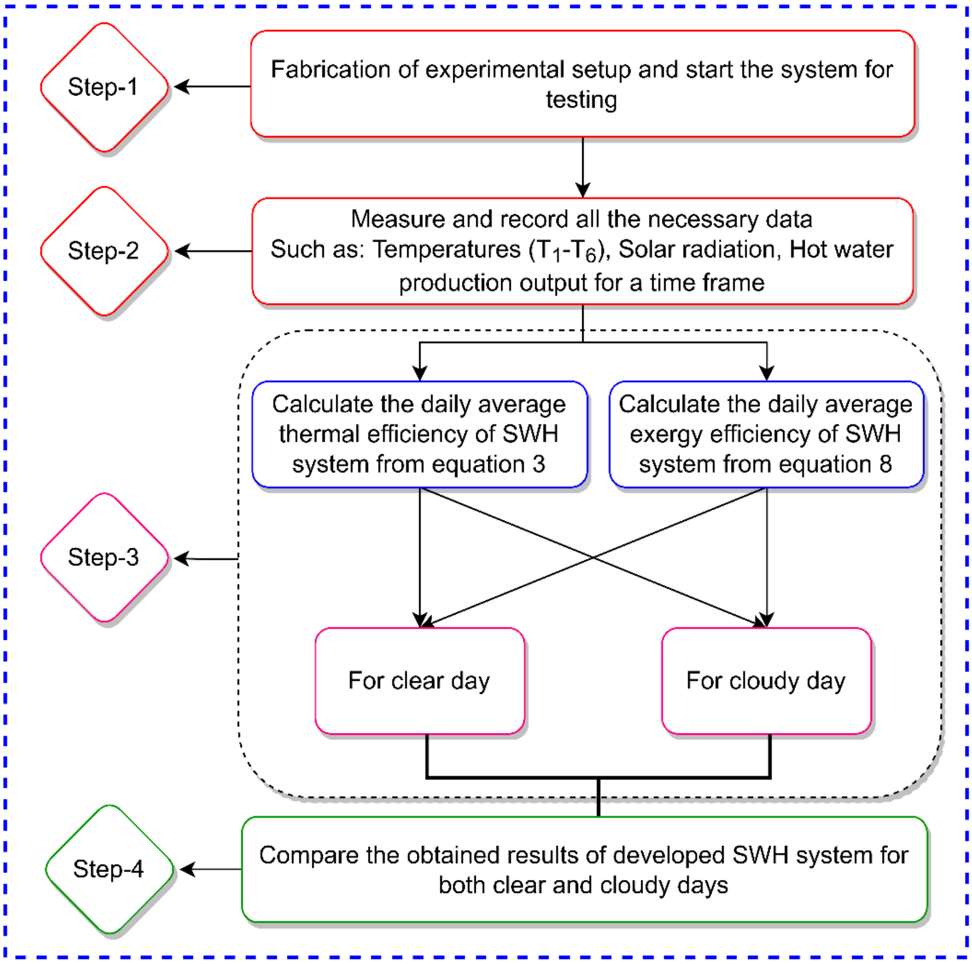

Fig. 2: Steps to be followed for experimental investigation

Initially, the setup is covered with a black sheet, at 8:00 a.m. the cover is removed to operate the experimental setup. The experiment was conducted from 8:00 a.m. to 6:00 a.m. the morningof the next day for almost 22 hours. In addition, the flow diagram depicts the methodologyadopted to assess various outputparameters of the developed SWH system.

3. Performance analysis

This section discusses the performance analysis of the designed SWH system.Section 3.1 and Section 3.2 were dedicated to energetic and exergeticstudy of the developed system and determined the amount of useable energy and exergy provided by solarthermal collectors when solar energy incident on the collector areaas an input.

3.1 Energy analysis

The energy analysis (EA)is used to interpret and analyze the performance of thermal systems that have been developed. Daily thermal efficiency (DTE) is calculated by dividing the average daily useful energy gain (Q_{useful}) by the average daily solar energy ($Q_{absorbed}$) fall on aET solar collector. The mathematical expression can be written as equation (3)[19].

$$Q_{useful} = \dot{m}_w \times C_{p,w} \times (T_{wo} - T_{wi}) \tag{1}$$

$$Q_{absorbed} = I_T \times A_{aperture} \tag{2}$$

$$\eta_{DTE} = \frac{\sum Q_{useful}}{\sum Q_{absorbed}} \tag{3}$$

3.2 Exergy analysis

Although theI^{st}law of thermodynamics talks about EA, there is no indication of how much the efficiency of the thermal system has deteriorated. Using 2^{nd} law of thermodynamics, exergy analysis provides evidence about the system's actual losses. The use of exergy analysis in system design, optimization, and study of thermal performance are all important considerations to keep in mind. To conduct an exergy analysis of the produced systems, the following set of equations from 4 to 8 is used[20].

The average exergy gain can be calculated by taking average net exergy over manifold of SWH system and dividing it by the number of developed systems[21].

$$\sum Ex_{gain} = \sum Ex_{out} - \sum Ex_{in} \tag{4}$$

The exergy at outlet sectionof the manifold can be written as

$$\sum Ex_{out} = \dot{m}_w \times C_{p,w} \times \left[T_{wo} - T_{amb}\left(1 + T_{amb} ln\left(\frac{T_{wo}}{T_{amb}}\right)\right)\right] \quad (5)$$

The exergy at inlet of the manifold can be written as

$$\sum Ex_{in} = \dot{m}_w \times C_{p,w} \times \left[T_{wi} - T_{amb}\left(1 + T_{amb}\ ln\left(\frac{T_{wi}}{T_{amb}}\right)\right)\right] \quad (6)$$

For the developed systems, the average incident exergy can be calculated as

$$\sum Ex_{solar} = I_T \times A_{aperture} \times \left[1 - \frac{4}{3}\left(\frac{T_{amb}}{T_{sun}}\right) + \frac{1}{3}\left(\frac{T_{amb}}{T_{sun}}\right)^4\right] \quad (7)$$

Thus, daily exergy efficiency should be obtained by dividing the average of the system's exergy gain by the average of incident exergy on developed system[22].

$$\eta_{DEX} = \frac{\sum Ex_{out} - \sum Ex_{in}}{\sum Ex_{solar}} \quad (8)$$

3.3 Uncertainty study

The uncertainty analysis of the measurements is examined to obtain the precision of recorded data. Generally, a significant quantity cannot be expressed clearly but relies on components that can be evaluated directly,e.g.Y= f (X_1; X_2; X_3; X_4……). The observed parameters X_1; X_2; X_3; X_4; and so, on have a randomly varying value, referred to as uncertainty[23]. This analysis identifies how the uncertainties associated with each calculated variable propagate into the measured amount value. The uncertainty analysis equation can be written as:

$$U_z = \sqrt{\sum_i \left(\frac{\delta Y}{\delta X_i}\right)^2 U_{xi}^{\ 2}} \quad (9)$$

For example, temperature sensors uncertainty is $\pm$0.5°C, whereas the uncertainty in a pyranometer is $\pm$1.5%, and the uncertainty in a rotameter is $\pm$2% of the standard deviation.As per the above equation, the uncertainty in exergy and energy efficiencies varies from $\pm$0.45-0.9% and $\pm$1.5-2.5%, respectively.

4. Results and discussions

The discussion started with solar radiation changeswith respect to time. Then a variation of useful thermal energy gain for the developed system is discussed on time basis. Also, the effect of PCM temperature inside the ET with respect to time for both clear and cloudy days is comprehensively explained. The next segment discussed the differencebetween outlet water temperature, inlet water temperature, storage tank temperature, and ambient temperature with reference to the time for both clear and cloudy days. Finally, the energetic and exergeticoutputs of the developed SWH system are explained and compared with each other in this study.

4.1 Solar radiation variation forclear and cloudy days

Fig. 3 depicts the solar radiation variation in W/m^2 for a clear and cloudy day incident on the developed SWH system. The solar radiation data was measured usinga Solarimeter (TM-207) at regular intervals of 30 minutes. The overall solar radiation data trend for a clear sunny day is ascending in nature with respect to time and touched its maximumvalue at 12:45 p.m.After that, it decreased gradually.On a cloudy day, solar radiation fluctuates repetitively during the day whenever clouds hide the sun. The maximum fluctuation happenedbetween 9:00 a.m. and 2:00 p.m. due to an overcast sky with dense clouds.

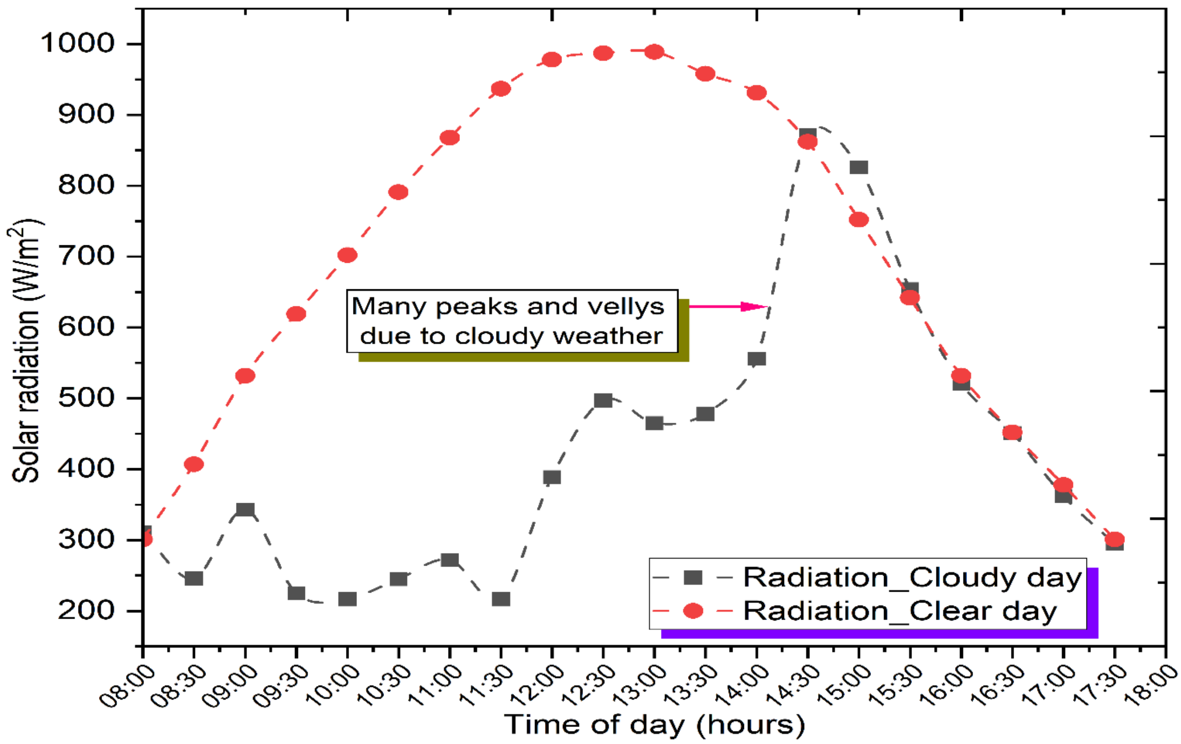

Fig. 3: Solar radiation variation for cloudy and clear days.

4.2 Thermal energy gain variation for a clear and cloudy day

The variation of instantaneous useful thermal energy gain with time for both clear and cloudy weather conditions at a fixed flow rate (20 LPH)is shown in Fig. 4.The variation of useful thermal energy transferred to water can be calculatedby using Eq. (1).

It is detected from Fig. 4 that whenever solar radiation intensity is high, the excess thermal energy is absorbed and collected in form of latent heat within.Furthermore, the trends of useful energy gain by water for both climate conditions are quite similar. The stored heat in PCM is released into the water during cloudy weather conditions, causing the increased outlet water temperature. Fig.4 revealed that the stored amount of energy in water on a clear sky day is more thanon a cloudy day. The daily stored energy of water for the developed SWH system is higher than the heat energy collected by the PCM in the first half of the operating session. The most useful energy peak is achieved around 3:00 p.m. on both clear and cloudy days. The maximum daily energy for the developed HP-ETC based SWH system collected was 10.65 MJ and 8.52 MJ for clear and cloudy days. It can be evident that the developed system can be operated at low-intensity solar radiation at sunrise and sunset and during intermittent cloudy conditions.

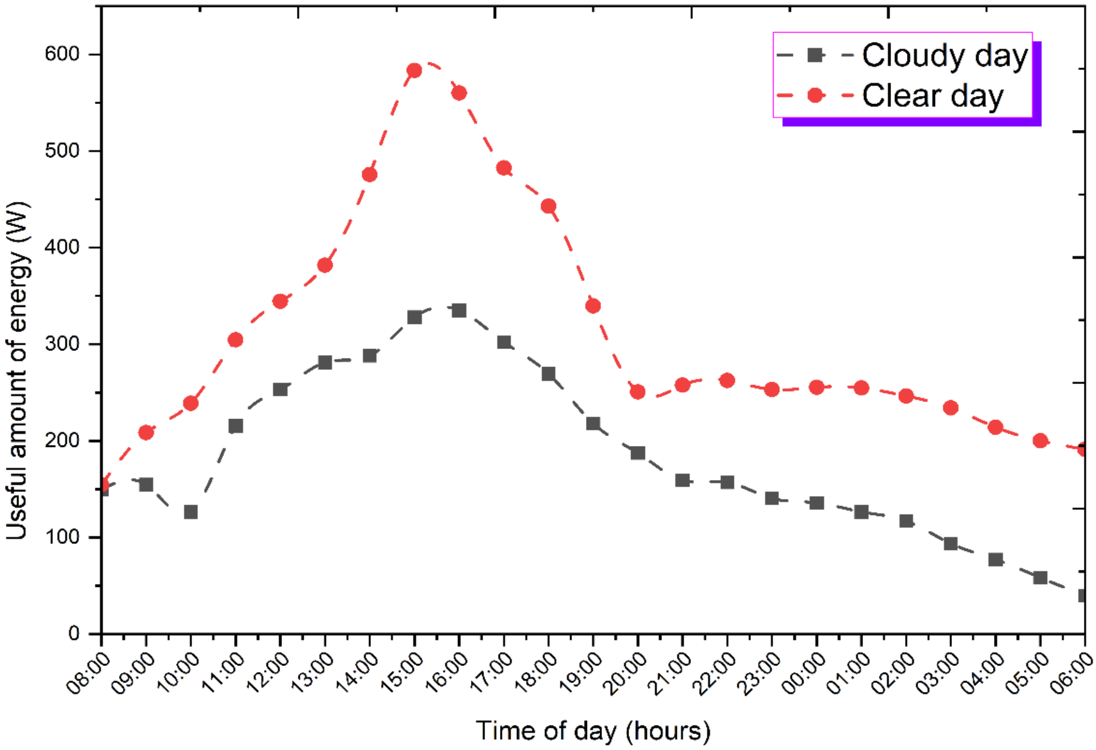

Fig. 4: Useful thermal energy gain for clear and cloudy weather conditions

4.3 Average PCM temperature variation for clear and cloudy days

Fig. 5 depicts the changes in PCM temperature inside the ET for both clear and cloudy days. It can be observed that the amount of latent heatstored by PCM fluctuates due toworking fluid’s flow rate. When flow rate of moving water increases, the heat transferred to the water rises due to convection and vice versa. The trends of average PCM temperature inside the ET for both clear and cloudy weather conditions are similar.

The maximum PCM temperatureswere 112°C(Tube-1) and 108°C (Tube-2)at somewhere around 3:00 p.m. for the developed finned heat pipe based ETC-SWH system on a clear day. In contrast, the maximum temperature of PCM ona cloudy day was 97°C (Tube-1) and 90°C (Tube-2). It observed that the best thermal output was achieved on a cloudy day during the simultaneous mode of operation. Moreover, it was found that throughthe charging cycle,inthe first half, the highest temperature in the evacuated tube was obtained in the upper portion, while the lowest temperature was achieved inthe bottom part of the ET. On the other hand, during the discharging process,the reverse happened. The sudden variation in temperature during the discharging process shows liquid PCM's start into a solid form. It gives latent heat release, which occurs at a specific temperature range. The discharging trend of PCM for both days is identical. It indicates the uniform temperature variation inside the tube. The temperature variation of PCM throughout the day shows that the developed system has aextended phase change period than the standard SWH system.

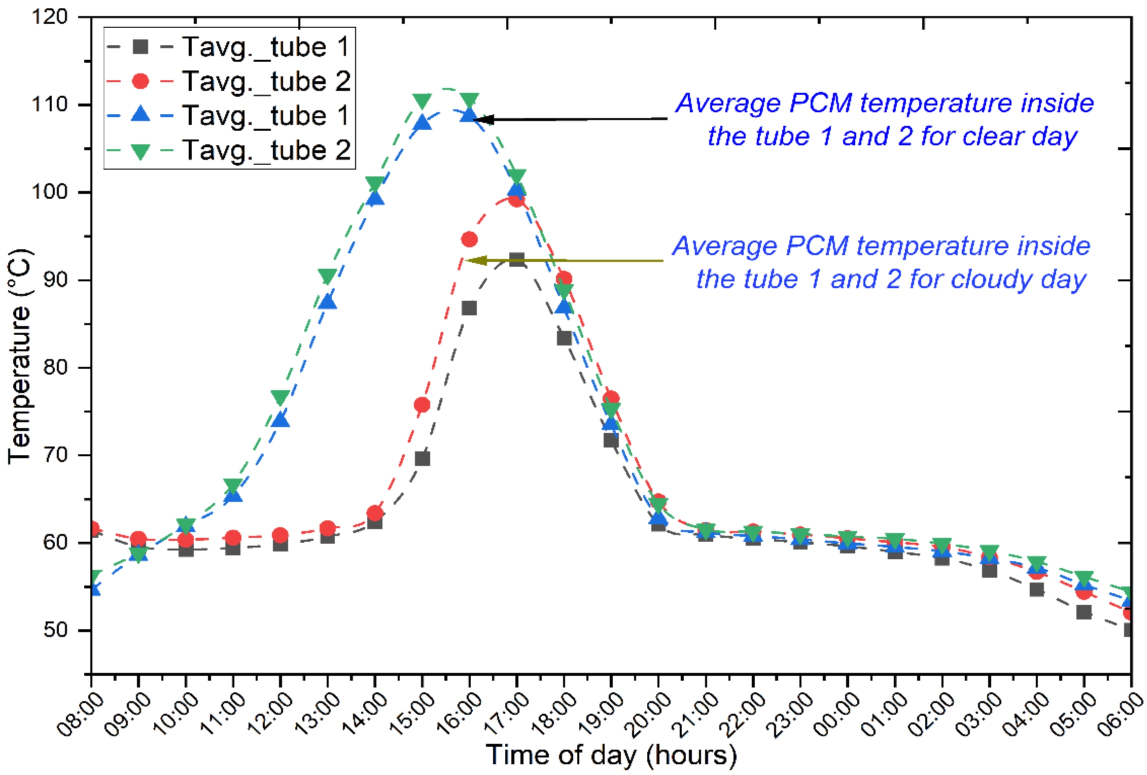

Fig. 5: Temperature distribution of PCM inside the evacuated tube.

4.4 Variation in outlet and inlet water temperature for a clear and cloudy day

The variation of heat transfer fluid (water) inlet ($T_{w,i}$) and outlet($T_{w,o}$) temperature, water storage tank temperature (T_{tank}) and ambient temperature (T_{amb}) throughout the day from 8:00 a.m. to 6 a.m. is discussed in this section for both clear and cloudy days.

For the 20 LPH, water outlet and inlet, and ambient temperature distribution arepresented in Fig. 6 and Fig. 7. It was observed from figures that outlet temperature of the water ona clear day is higher than on a cloudy day during the charging phase and discharging phase. However, as the PCM’s average temperature inside the tube for a clear day is higher, it will transfer more heat to the working fluid, causing a higher outlet temperature of the water. The changes in ambient temperature on a cloudy day fluctuate with outside environmental conditions. Whereas the ambient temperature variation with respect to time is uniform,it first increases and then gradually decreasesafter 5:00 p.m. For cloudy day conditions, the heat energy absorbedby PCM as latent heat throughout the day (charging process)and in the evening at off sunshine hours (discharging process) the stored energy is transferred to circulating working fluid (water). It is seen that the energy stored in PCM delayed the increase in outlet water temperatureduring late-night hours.

For a fixed mass flow rate of 20 LPH, the max. outlet temperatures of water were 62.2°C and 50.4°C(around 3:00 p.m.) for clear and cloudy days,respectively.Here, the maximum difference between the water's outlet temperature and inlet temperatureswas25.5°Cand 14.4°Cfor clear and cloudy day conditions. The water is circulated in a closed path for the developed SWH system. Moreover, at a particular instant inlet and outletof water and storage tank temperature are the same because the PCM becomes solid after releasing all the latent heat stored within it.The water storage tank temperature for the designed system was 46.2°C and 41.4°Cat 6:00 a.m. of the next morning for both climate conditions after 22 hours of start. It is a pretty high-water temperaturethat can be used for household applications like bathing, washing, clothing, etc.

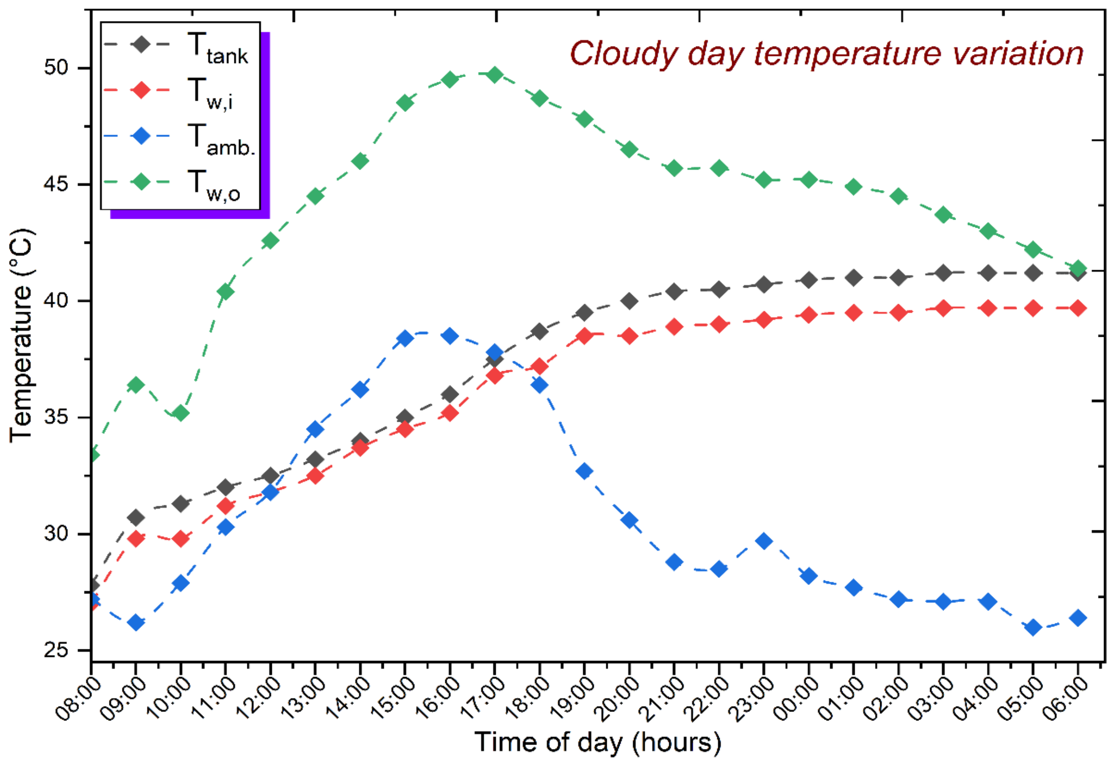

Fig.6: Variation of outlet, inlet, tank temperature, and ambient temperature for cloudy day condition

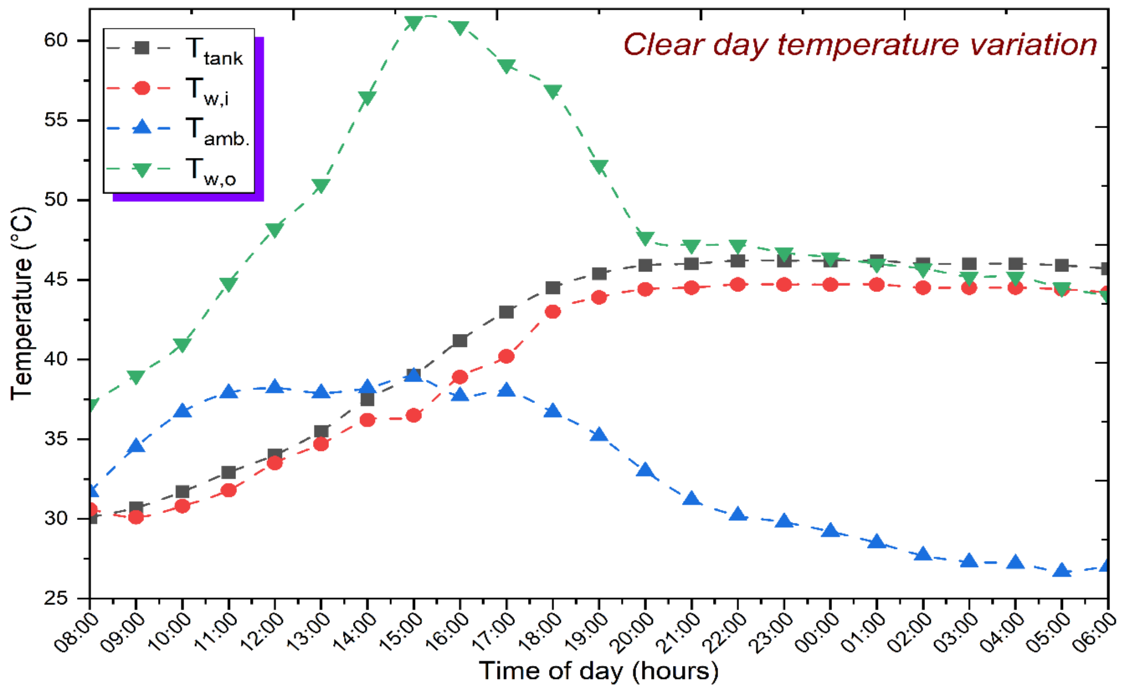

Fig. 7: Changes of outlet, inlet, tank temperature, and ambient temperature for clear day condition.

4.5 Daily energetic and exergetic efficiencies of HP-ETC based SWH system

In this section, daily average energetic and exergetic efficiencies of the developed finned HP-ETC based SWH system calculated using solar radiation data and other observed parameters are shown in Fig. 8. The average daily energeticand exergeticoutpus of developed SWH systemsis 76.57% and 79.64%, and 2.37% and 1.38%, respectively, for clear and cloudy day conditions. A cloudy day's daily average energy efficiency is higher than a clear day due to the minimum heat loss to the surroundings. It was found that energy efficiency increased with respect to time till 05:30 p.m. for both weather conditions. After that system's energy efficiency is not taken into account due to the unavailability of solar radiation. The designed system's energy efficiency was much higher than the conventional system (54.10% @24 LPH designed by Chopra et *al.,*[24]). The resultsof a few studies were compared with the present study, as shown in Table 3.

Table 3: Various experimental results comparison with the present study

Researcher	**Mass flow rate**	**Daily average energy efficiency**
Chopra et al. [18]	*16 LPH*	*75.44%*
Essa et al. [25]	*20LPH*	*52.20%*
Present study	*20 LPH*	*76.57% (Clear day)*
		79.64% (Cloudy day)

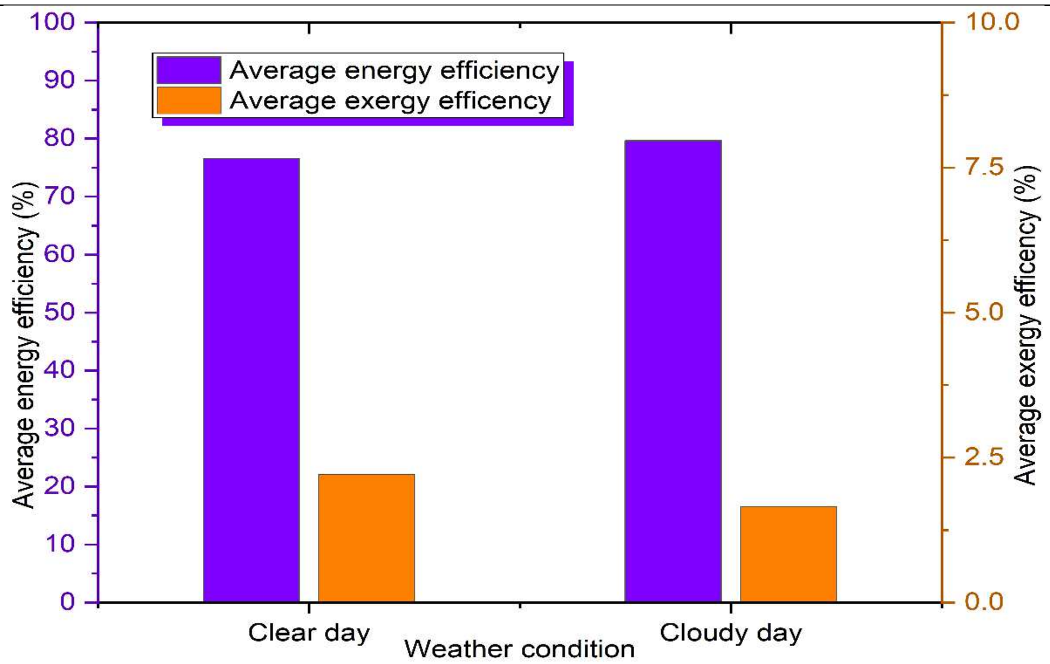

Fig. 8: Daily energetic and exergetic efficiencies of the SWH system for both clear and cloudy days.

Finally, it was discovered that daily average exergetic efficiency is always less for all flow rates than daily energy efficiencybecause exergy cannot be restored once it has been destroyed (See Fig. 8).But the exergy analysis of proposed system considers all of the system's losses and things that could not be changed. Thus, exergy study shows quality rather than quantity of energy.The experimental results obtained from the present study also highlight the various advantages of finned heat pipe-based ETC-SWH system over conventional systems, including (i) Due to aluminium fin outside the heat pipe, the rate of heat transfer from HP to PCM during the simultaneous mode of operation (ii) Avoid overheating problem of heat pipes inside the evacuated tube. (iii) minimize the instant fluctuations of solar radiation data on the energy output of SWH system.Overall, the results showed that PCM integration inside the finned heat pipe-based evacuated tube for TES and increased rate of heat transfer has an extra edge over the convention SWH systems through the simultaneous mode and continuous operation load of hot water demand. However, the designed SWH system integrated with PCM needs more studies regarding the restricted energy recovery at night hours/off sunshine hours.

5. Conclusions

The applications of PCM in SWHs are discussed in this work, and it was discovered that the optimum phase change temperature is 40-70°C. A few studies have shown that including PCM in SWH can retain heat throughthe day and release it to heat the working fluid (water) during the off sunshine hours. Furthermore, PCM has a larger storage capacity than sensible heat storage. This study designed and fabricated a finned heat pipe-based ETC-SWH system with PCM for household applications. The experiments are conducted under the Indian climate conditions of Jammu on a clear and cloudy day at 20 LPH. The following conclusions are given as follows

- The proposed finned heat pipe based ETC-SWH system obtained better performance as compared to conventional systems (validated from other studies). It happened because of the storage of excess heat energy in PCM compared to conventional SWH system.
- The daily useful amount of energy collected by water was10.65 MJ and 8.52 MJ for clear and cloudy climatic conditions respectively. The max. water outlet temperatures were 62.2°C and 50.4°C, and storage tank temperatures were 45°C and 41°C, respectivelyfor clear and cloudy day conditions.

- The daily average energetic and exergetic efficiencies of developed SWH system for clear were found to be 76.57% and 2.37%, whereas corresponding values for cloudy day conditions were 79.64%, and and 1.38%, respectively.
- On a cloudy day (intermittent nature of solar radiation) daily thermal energy efficiency of system is higher than on a clear day. So, the current system can be seen as a viable option for the on-demand operation of hot water and fluctuation of solar radiation or overcast weather conditions.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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CRediT author statement

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