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Research Article

Performance Improvement in Thermal Efficiency of Solar Evacuated Glass Tube Collector Using Latent Heat Storage Materials

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ABSTRACT

In the present review paper, the existing evacuated tube solar water heating systems are studied. Solar energy is available in abandonment free, environmentally clean, and therefore it is one of the most promising alternative energy sources. The effective utilization of solar energy is hindered by the intermittent in nature and its availability, limiting use of solar energy effectiveness in domestic and industrial applications especially in water heating. Now a day, plenty of solar water heater is used for domestic, commercial and industrial purposes. These review focuses of the development of research confined the techniques and technologies for the improvement in evacuated solar water heating system. In the project the main aim is to conserve the energy by using renewable energy sources like solar energy, but to overcome the major drawback of water heating system is the continuous drop of temperature, that will be consider here with the help of using PCM. The efficiency of the collector increases by 5-6 % when considering PCM with thermal energy storage tank. The proposed work that has been done mainly on the basis of energy conservation using latent heat storage Material.

Keywords: Solar waterheating collector, solar water heating systems, Phase Change Material, Energy storage Tank, etc.

Introduction

Through solar energy is widely distributed it is dispersed and available only at the rate 500-1000 w/m^2.Looking at the industrial and commercial 2/3 of the final energy consume for heating applications. At present solar thermal systems are mainly used for domestic hot water heating. In this project utilizing the Evacuated glass tube solar collector which is capable for producing temperature up to 80^{o}C. PCM thermal energy storage is based on the energy absorbed/generated when a material under goes a phase change from solid to liquid, liquid to gas, or vice versa. To reduce the energy consumption cost of conventional electrical heaters in heating and DHW systems, PCM thermal energy is stored during the off-peak load period. This energy is then discharged during the peak period.

Literature Review

Evacuated tube solar collectors, especially water-in-glass types, outperform flat-plate collectors at high temperatures. Performance tests using ISO 9459-2 and numerical studies revealed an inactive region near the sealed end of the tube, potentially affecting performance (G.L Morisson 2004). In this paper work is carried out to study the feasibility of storing solar energy using Phase Change Materials (PCMs) and utilizing this energy to heat water for domestic purposes during nighttime It is concluded that LHTES systems are a commercially viable option for solar heat energy storage with further research in this area. (Vikram, Kaushik, 2006), PCMs in latent heat storage systems provide high-energy density and isothermal storage, used in various applications like heat pumps, solar engineering, spacecraft, and building climate control. The paper reviews and analyzes these systems. (Atul Sharma 2007). The new PCM-graphite compounds with optimized thermal properties were used, such as 80:20 weight percent ratio mixtures of paraffin and stearic acid (PS), stearic acid and myristic acid (SM), and paraffin and palmitic acid (PP). It can be concluded that PS gave the best results for increasing the thermal performance enhancement of the SDHW tank. (Muhsin Mazmana, *et al*, 2009). Latent heat storage with PCM improves solar

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water heater performance due to high latent heat and large surface area.(Anant Shukla 2009) In this paper work carried out on experimental investigation on the use of water-phase change material storage in conventional Flat plate solar water heating systems. The PCM storage advantage is firstly demonstrated under controlled energy input experiments with the aid of an electrical heater on an insulated storage tank, with and without the PCM containers. It was found that the use of the advice configuration can result in a 13–14 °C advantageous in the stored hot water temperature over extended periods of time. (Al-Hinti, *et al,* 2010). Evacuated tube collectors are designed, analyzed, and compared with commercial brands to assess their ability to power a 1 KW absorption chiller using hot water from the collectors. (Siddarth Aorora 2011). In this paper a detailed thermal model of a parabolic trough collector is presented. The thermal analysis of the collector receiver takes into consideration all modes of heat transfer;(Soteris A. Kalogirou, 2012). In this paper a detailed thermal model of a parabolic trough collector is presented. The thermal analysis of the collector receiver takes into consideration all modes of heat transfer; (Soteris A. Kalogirou, 2012).

In this work, a storage solar collector that consists of six 80-mm diameter copper pipes connected in series is integrated with a back container of paraffin wax as a PCM thermal storage media. (Abdul Jabbar, 2013). Using paraffin wax PCM in solar water heaters increased energy storage density by 39%, energy efficiency by 16%, and extended hot water supply by 25%, improving thermal stratification. (mohammad Ali 2013). LHTES using PCMs can store solar energy efficiently. PCMs are ideal for various applications due to their high energy density and small temperature change during melting/solidifying. They help reduce fuel dependency and environmental impact. (Abhay Lingayat 2013). Performance investigation of thermal energy storage system with Phase Change Material (PCM) for solar water heating application. Energy and energy including their cost analyses for the TES system were performed. Accordingly, total life cycle cost was calculated for different flow rates of the Heat Transfer Fluid (HTF). Therefore it can be summarized that total life cycle cost decreases with the increase of flow rate. In this study, a shell and tube thermal energy storage for solar water heater system has been examined experimentally. (M.H. Mahfuz, *et al,* 2014). Solar energy is free and clean but has intermittent availability, limiting its use in water heating. Thermal conversion is more efficient (70%) than electrical (17%). Solar water heating systems are easy to maintain and improve thermal efficiency through enhanced convection heat transfer. This review covers various enhancement techniques and optimization methods for solar water heating systems. (S. Sadish kumar 2014). An analysis of various Phase Change Materials and its application for flat plate Solar Water Thermal Storage System is aimed at analyzing the behavior of a four phase change materials as a part of thermal energy storage system. (Ganesh Patil, *et al*, 2015). The storage of PCM thermal energy is more beneficial than sensible energy storage because of its high density of storage energy per unit volume/mass. This review presents previous works on thermal energy storage as applied to DHW and heating systems. PCM has been used in different parts of heating networks and DHW systems, including solar collectors, storage tanks, packed beds, and duct networks.(M.K. Anuar Sharif, *et al*, 2015). The new ETC/S system with paraffin PCM inside evacuated tubes extended operating time, reduced heat loss, achieved useful heating medium temperature (~45°C), and increased useful heat by 45-79% during the discharge cycle. (P Felinksi 2016).

The study investigates a solar water heater system with 12 evacuated tube heat pipe solar collectors and a latent heat storage tank. Efficiency ranges from 38%-42% on sunny days and 34%-36% on cloudy-rainy days. Flow-rate directly impacts efficiency, and the combination of heat pipes and PCM eliminates thermal stratification. (M S Naghvi 2017). The study analyzes integrating PCM in a direct flow evacuated tube solar water heater with a U-tube heat ex-changer. Paraffin wax stores solar energy, and water flows through a U-shape copper tube inside the PCM. Un-finned collectors are 14% more efficient due to higher average temperature. (Mohammad Hany 2017). Low flow rates enabled complete phase change in evacuated tube solar collectors with paraffin PCM, maximizing energy storage. High flow rates hindered thermal energy storage benefits. The study proposes a correlation to estimate hot water supply based on discharge temperature.(Mohammad a Essa 2018). Evacuated tube collectors, enhanced with heat pipes and phase change materials (PCMs), improve efficiency, reliability, and user-friendliness for solar thermal applications like water heating, space heating, and cooling. This review covers recent research, theoretical analysis, financial benefits, and future recommendations.(k.Chopra 2018). The study modifies evacuated tube solar collectors (ETSCs) by removing the stagnant region with a bypass tube, improving efficiency by up to 11% and useful gain by 25%. The modification ensures uniform temperature distribution and enhances the average water

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temperature by 1.5°C.(Mohammad Jowzi 2019). Using R134a as the working fluid in a heat pipe solar collector (HPSC) increases its efficiency compared to using distilled water.(N. Jayanthi 2019). This study investigates a solar collector with stearic acid PCM, enhancing efficiency up to 72.52% and solving heat pipe overheating and low PCM conductivity issues. Annual costs are lower, with a 6-year payback period. The design eliminates thermal stratification.(K. chopra 2019). The study analyzes a modified evacuated tube solar water heating system using a vertical shell and tube heat ex-changer. It evaluates energy, energy, and economic performance with nano-fluid and de-mineralized water, showing efficiency and practical suitability in areas with hard underground water. The system is designed for fouling-free operation.(Gaurav Saxena 2020). A new ETSC with Nano-PCM and fins enhances performance. Adding copper nanoparticles to paraffin wax improves heat transfer. Thinner fins speed up PCM melting. The optimal 1% Cu in PCM increases HTF outlet temperature by 2 K. The best flow rate for full PCM melting is 0.003 kg/s. (Raja Elram 2021). A PCM-filled U-type ETC with fins reduces energy fluctuations, extends hot water supply, and lowers peak HTF outlet temperature. Optimal conditions achieve 50.72% thermal efficiency and 19.20% thermal storage efficiency, with hot water supply extended by 160 minutes. Higher HTF flow rates shorten supply time, and larger glass tubes improve efficiency.(young Li 2022)

PCM's –latent heat storage materials:

PCM absorbs and deliver heat at a nearly constant temperature. They store 5–13 times more heat per unit volume than sensible storage materials such as water, masonry, or rock.

$Q = M \times LH$ ……….(1)

Q is the amount of thermal energy stored or released in form of latent heat (KJ), M is the mass of material used to store the thermal energy (kg), and LH is the latent heat of fusion or vaporization (KJ/Kg).

It's clear from equation that the amount of thermal energy store as latent heat depend on the mass &the value of latent heat of used material. Material used to store the thermal energy in the form of latent heat are called phase change material.

Assumptions:

1) The solar radiation intensity along the axial and circumferential directions of the evacuated vacuum tube (collector unit) is uniform.
2) The wind speed is in the normal direction of the vacuum tube glass cover axis.
3) The working fluid in the tube is uniform and the flow is stable.
4) The temperature, pressure, and other state parameters in the same section are uniform.

Experimental Setup:

Experimental setup consist of Evacuated glass tube collector containing eleven number of tubes, completely insulated hot water tank, Insulated thermal energy storage tank, cold water tank, reflector, Insulating box etc. Here TES tank utilize to increase the performance of the system with the help of paraffin wax used as a phase change material for storing large amount of latent heat during its fusion. Here TES tank & Hot water tank are connected in such way that, they are utilizing in both way separately or together.

A schematic diagram of the experimental setup is shown in Fig. 1. The setup is essentially similar to conventional, commercially available, solar water heating systems with a few differences. It consists of eleven evacuated tubes with an area of 860 mm X 1560 mm, with a tilt angle of 30°C.The collectors which have black painted reflector plates placed at back of the evacuated tubes. The galvanized steel storage tank is cylindrical in shape having a length of 750 mm, an inner diameter of 500 mm and a volume of 140 lit. It is insulated with 25-mm thick layer of glass wool insulation.

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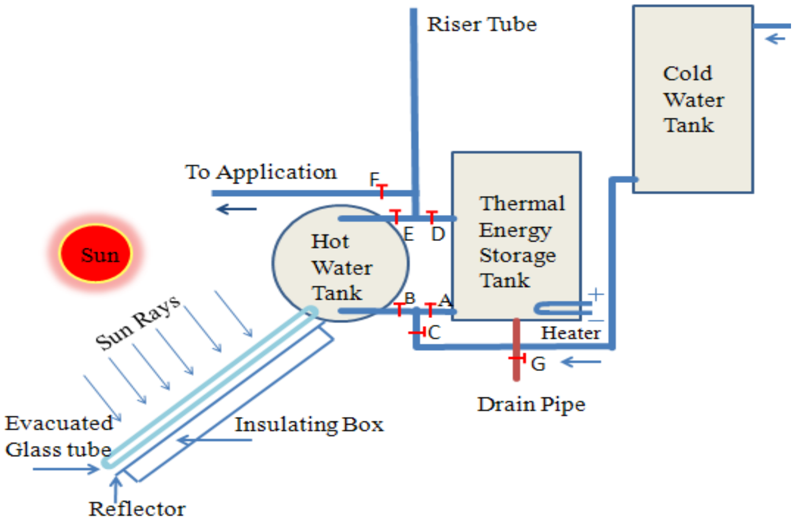

Fig. 1 Experimental setup

When the valve A & D closed normal circuit run without thermal energy storage tank, similarly when the valve E & B closed the circuit run without solar water heating system, when valve A B C D open then heat transfer from hot water tank to TES tank through natural convection, near about same temperature obtain in both the tank. [10,12,14]

Fig. 2 Actual Experimental Setup

Figure 2 shows the actual experimental setup consist of TES tank coupled with hot water tank , through natural convection heat transfer from HWT to TES tank.[10,12,14]

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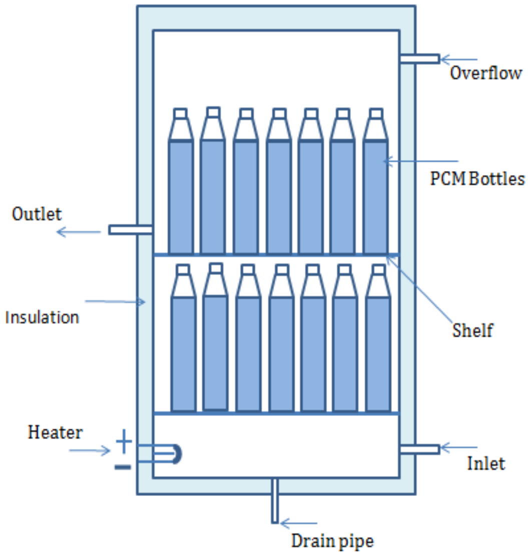

Fig. 3 Geometry of TES Tank

Fig. 3shows a detailed cross-sectional view of the storage tank. The tank contains a total of 40 thin walled, cylindrical, polypropylene (plastic) containers. Each container has a volume of 1.0 lit, and contains 0.95 kg of paraffin wax which was used in this investigation as the PCM. The thermos-physical properties of the paraffin wax are given in Table 1. [3 ,5,6,24]

Table1. Thermo-physical properties of the paraffin wax.

Sr. No.	Property name	Values
1	Melting point	58-60 ^oC
2	Latent heat of fusion	190 KJ/Kg K
3	Density (Solid Phase)	820 Kg/m^3
4	Density (Liquid Phase)	780 Kg/m^3
5	Specific Heat	2.4 KJ/Kg K
6	Thermal Conductivity	0.24 w/mk

The PCM containers are arranged in the tank on two levels, each containing 20 containers, with the aid of two perforated sheet metal separators. The choice of these containers was meant to reach a relatively large heat transfer surface area in comparison with the volume of the PCM, and to minimize the thermal resistance between water and the PCM. The total volume of the PCM containers is 40 lit, with water occupying the remaining 100 lit, in the storage tank. The bottom section of the storage tank also contains an auxiliary 1.5 kW electrical heater, in order to enable controlled conditions investigations.

Thermal Analysis of system

5.1 Thermal Analysis of Reflector

In the analysis of reflector try to reduce the heat loss through the space between the two tubes we are providing the reflector to improve the performance of the system. The reflector made by the mild steel sheet having thickness 1 mm, below which insulating material glass wool filled up to thickness of 50 mm, to reduce the heat loss and at the back side providing wooden sheet having thickness 6 mm.

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Fig. 4 Geometry of reflector

The heat loss from the reflector is calculated by using following equation,

$$Q = \frac{T_i - T_o}{\frac{X_1}{K_1 A} + \frac{X_2}{K_2 A} + \frac{X_3}{K_3 A} + \frac{1}{h_i A_i} + \frac{1}{h_0 A_o}} \quad \ldots\ldots\ldots (2)$$

Table 2 Properties of Air

Sr. No,	Properties	Values
1	Temperature, T (°C)	33
2	Dendity, ρ (kg/m³)	1.156
3	Specific Heat, C_p (J/kgK)	107
4	Thermal Conductivity K (W/m°C)	0.0260
5	Kinemetic viscosity ν (m²/s)	1.6268x10⁻³
6	Prandelt No. Pr	0.7272
7	Thermal Diffusivity α (m²/s)	2.2356x10⁻³

5.2 Thermal Analysis of Energy Storage Tank.

TES tank consist of two steel drum having external diameter & internal diameter is 550 mm & 500 mm, as well as length is 800 mm, the space between external & internal drum filled with glass wool having thickness of 25 mm.

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Analysis of circular shell of TES tank.

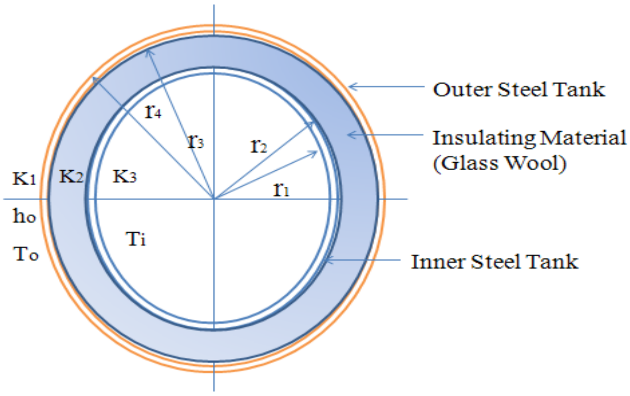

Fig. 5 Geometry of TES Tank

Where,

Q_1=Heat loss through cylindrical shell.

r_1=Internal radius of Inner steel tank.

r_2=External radius of Inner steel tank.

r_3=Internal radius of outer steel tank.

r_4=External radius of outer steel tank.

T_i= Temperature of water inside the tank

T_o=Temperature of air outside the tank.

h_o= Heat transfer coefficient of air.

In the analysis of thermal energy storage tank, find out rate of heat loss from TES tank to the surrounding.

By using relation,

$$Q_1 = \frac{\Delta T}{\in R} \ldots\ldots\ldots\ldots (3)$$

$$Q_1 = \frac{T_i - T_o}{R_1 + R_2 + R_3 + R_4 + R_5} \ldots\ldots\ldots\ldots (4)$$

Where,

R1=Conductive Resistance of outside tank.

R2=Conductive Resistance through glass wool

R3=Conductive Resistance of inside tank.

R4=Convective Resistance of inside tank.

R5=Convective Resistance of outside tank.

K1=Thermal Conductivity of outside tank.

K2= Thermal Conductivity of glass wool

K3= Thermal Conductivity of inside tank.

L= Length of TES tank.

$$Q_1 = \frac{T_i - T_o}{\frac{ln(r_4/r_3)}{2\pi L K_3} + \frac{ln(r_3/r_2)}{2\pi L K_2} + \frac{ln(r_2/r_1)}{2\pi L K_1} + \frac{1}{h_i A_i} + \frac{1}{h_o A_o}} \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Analysis of bottom sheet of TES tank.

In the analysis of bottom side of TES tank which is acts as composite wall having three layer , inside & outside made by mild steel & between which glass wool filled. [8]

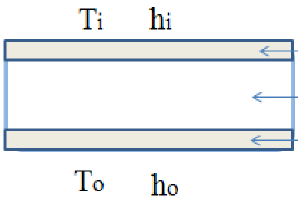

Fig. 6 Construction of bottom plate of TES tank.

Where,

Q_2=Heat loss through bottom side of TES tank. [20]

$$Q_2 = \frac{\Delta T}{\in R} \ldots\ldots\ldots (6)$$

$$Q_2 = \frac{T_i - T_o}{R_1 + R_2 + R_3 + R_4 + R_5} \ldots\ldots\ldots\ldots (7)$$

$$Q_2 = \frac{T_i - T_o}{\frac{X_1}{K_1 A} + \frac{X_2}{K_2 A} + \frac{X_3}{K_3 A} + \frac{1}{h_i A_i} + \frac{1}{h_0 A_o}} \ldots\ldots\ldots (8)$$

Where,

X1=Thickness of outside tank

X2= Thickness of glass wool insulation

X3= Thickness of inside tank

Hence total heat transfer rate from TES tank to surrounding is given by,

$$Q = Q_1 + Q_2 \ldots\ldots\ldots\ldots (9)$$

6. Results:

6.1 Hourly Efficiency – Comparison of Cases 1, 2, and 3: The fourth graph compares the hourly efficiencies of all three cases—Case 1, Case 2, and Case 3—on a single plot. Case 3 consistently outperforms the other two, especially during peak solar hours. Case 2 remains in the middle range, while Case 1 has the lowest performance throughout the day. This comparison clearly shows the incremental benefits gained by each design improvement, with Case 3 offering the highest efficiency.[

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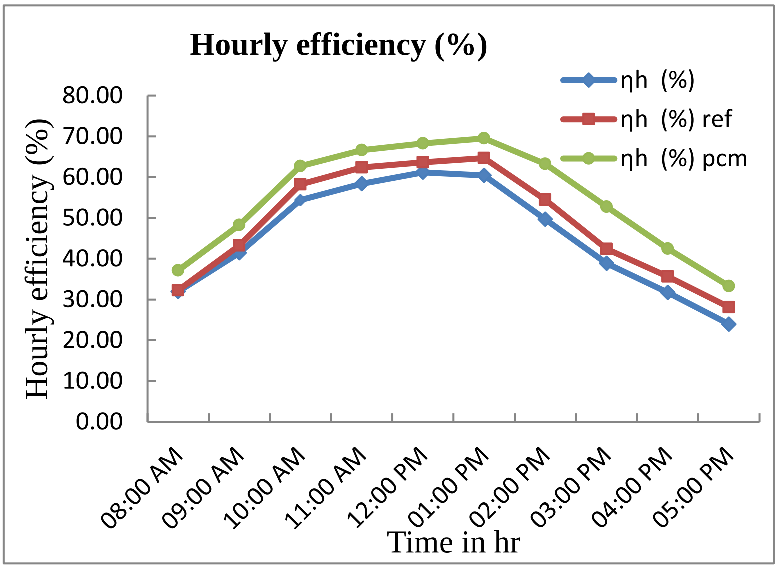

Fig. 7 Hourly Efficiency Comparasion

6.2 Heat Gain – Comparison of Cases 1, 2, and 3: The fourth graph compares the heat gains of Case 1, Case 2, and Case 3. The plot clearly shows a hierarchy in performance, with Case 3 at the top, followed by Case 2, and Case 1 at the bottom. During peak hours, Case 3 delivers significantly more heat than the others, highlighting the effectiveness of its thermal management enhancements. This comparison emphasizes how system upgrades impact heat collection efficiency throughout the day.

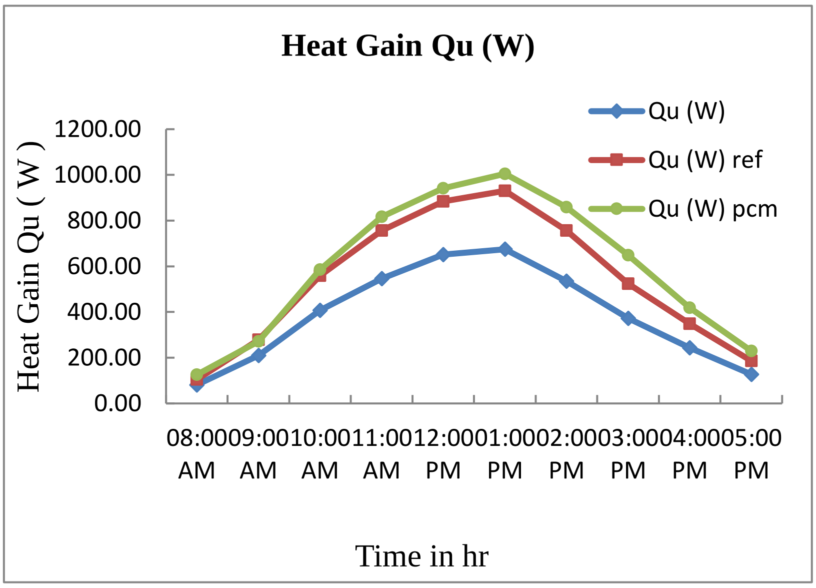

Fig. 8 Heat gain comparasion

6.3 Comparison of Radiation Intensity (IT) for Cases 1, 2, and 3: This comparative graph illustrates the solar radiation intensity received by each case over time. While the values are generally similar, small variations are seen due to environmental or positioning factors. All three cases peak around midday, with Case 1 receiving slightly higher intensity at some hours. However, differences in output efficiency imply that system design has a stronger impact on performance than radiation variation alone.[26]

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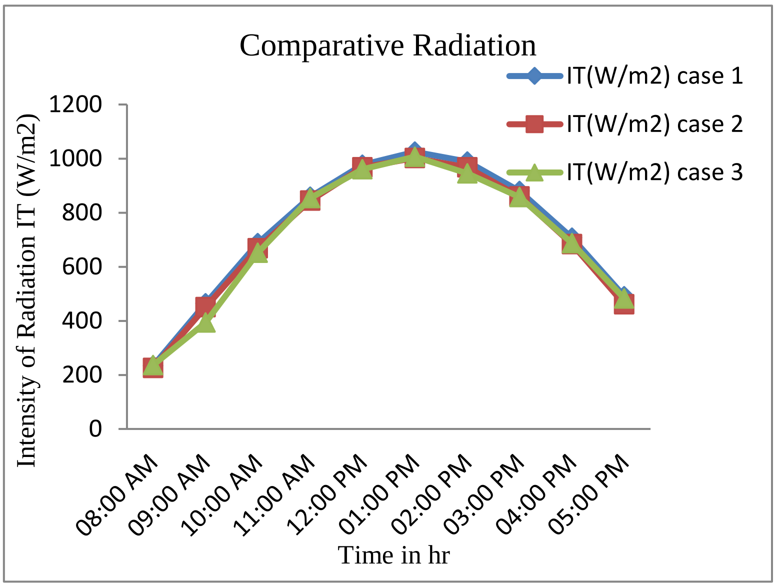

Fig. 9 Radiation comparasion

6.4 Comparative Outlet Temperature for Days 1, 2, and 3: This graph compares the outlet temperatures for all three days at 15-minute intervals. All curves begin above 70°C and show a steady decline. Day 3 consistently maintains slightly higher outlet temperatures than Days 1 and 2 after the first hour, demonstrating more stable thermal performance, potentially due to more effective PCM utilization or insulation efficiency. [2]

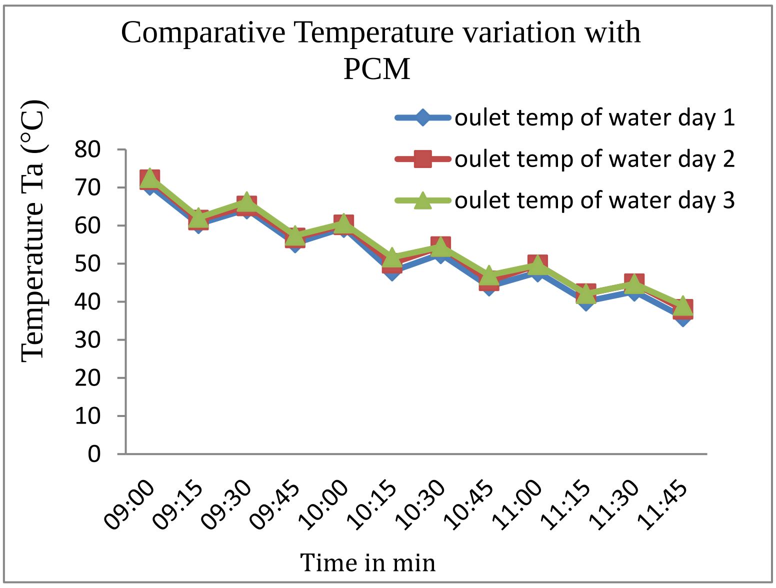

Fig. 10 Comparative Temperature variation with PCM

6.5 The graph "Comparative Heat Gain" illustrates the temperature variation and heat gain by water over three days at five time intervals (9:30 to 11:30 AM). Across all days, the temperature variation shows a consistent pattern, peaking around 10:30 AM and then gradually decreasing, with values ranging from approximately 3.0 to 5.0 units. In contrast, the heat gain by water remains significantly lower, varying between 1.0 to 1.8 units and following a similar rise-and-fall trend. The consistent peak at 10:30 AM suggests a daily heat absorption pattern, likely influenced by the presence of phase change material (PCM), as referenced in the figure title. This comparison highlights the effectiveness of PCM in moderating temperature by absorbing and storing heat.

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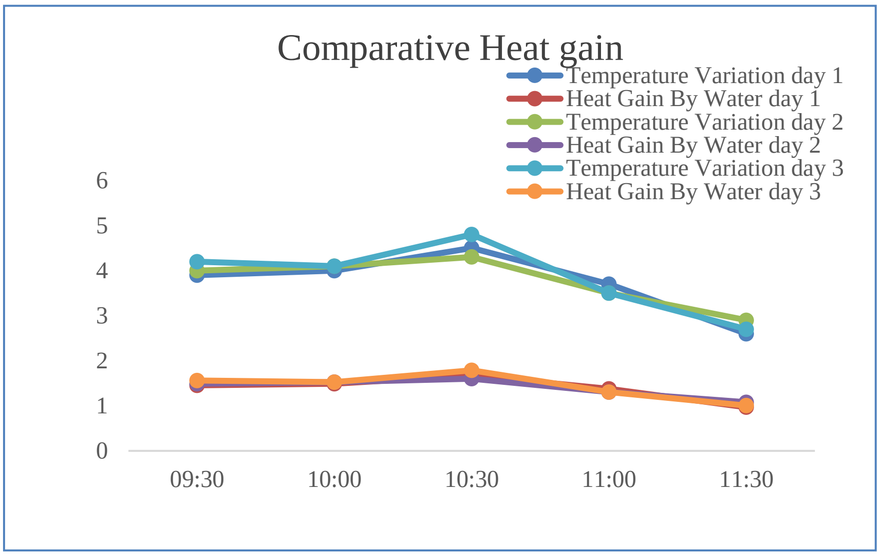

Fig. 11 Temperature Variation Vs Heat Gain By water on day 1

5. Conclusion: This paper reviews the application of PCM in domestic hot water and heating systems. These systems integrate PCM into Thermal Energy Storage tank. There have been several advantages for improving the thermal performance of the solar collector system. The following conclusions can be drawn as follow:

(1) Phase change material is viable option to increasing the efficiency of plant.

(2) The thermal performance of the PCM incorporation into storage tanks significantly enhanced in relation to energy capacity, operation time under a temperature range that is acceptable for application, and low DHW system.

(3) The average efficiency of the conventional solar collector is lower than that of the Evacuated Solar collector with reflector and energy storage tank.

(4) Output of system gives more satisfactory result with respect to time hot water can be made available for longer time.

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