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Performance enhancement of evacuated tube solar collectors: A review

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H I G H L I G H T S

- ETSCs enhance solar thermal efficiency using advanced heat transfer techniques.
- This study integrates nanofluids and PCMs to boost ETSC performance, ensuring stable heat output.
- Novelty lies in optimizing nanofluid concentration for maximum efficiency in diverse applications.
- Results highlight improved thermal conductivity and sustained heat supply post-sunset.

Keywords:

Heat transfer

Evacuated Tube collector

Heat pipe

PCM

Nanofluids

A B S T R A C T

Solar thermal energy is essential for industrial and home applications, such as solar drying, space heating, water heating, and water desalination. Solar collectors are essential elements in these systems, as they transform solar irradiance into thermal energy. Evacuated heat pipes (EHPs) have emerged as efficient thermal transfer devices among sophisticated solar thermal technologies, capable of handling heat with low losses. These pipes function by employing a vacuum-sealed environment that markedly diminishes thermal resistance and convective heat loss. The heat transfer process is facilitated by the phase change of a working fluid, which evaporates at the heat source and condenses at the cooler end, so permitting efficient thermal management. This research study provides a thorough examination of developments in heat pipe-evacuated tube solar collectors (ETSCs), emphasizing diverse techniques for improving their efficiency. The initial section underscores the significance of ETSCs in solar residential hot water systems, outlining the particular applications and benefits of various collector types. The second section addresses the application of nanofluids to enhance heat transfer efficiency and the incorporation of phase change materials (PCMs) to guarantee a continuous heat supply, even post-sunset. Moreover, the work proposes the ideal concentration of nanofluids for diverse applications, offering significant insights for the next research.

1. Introduction

Solar energy, geothermal energy, wind energy, hydropower, marine power, and bioenergy are the six main types of renewable energy sources [1]. Figure 1 shows the relationship between renewable energy sources and energy consumption/demand in the form of transportation, heating/cooling, and electricity [2]. Solar power is the most important renewable energy source because it has no negative impact on the environment. In order to ensure a reliable and environmentally friendly energy supply in the future, numerous solar energy harvesting systems have been developed. Semiconductors accomplish direct electrical generation from solar energy, whereas indirect electrical generation and direct heat generation are accomplished by solar collectors [3]. Given that solar radiation is accessible solely during daylight, energy must be harvested efficiently to optimize the utilization of daylight hours, followed by appropriate storage Greetings [4]. Solar water heaters and solar air heaters are two types of collector devices that use insolation to power flat plates, thus increasing the thermal energy of water or air. In order to reduce their reliance on fossil fuels and the environmental damage they do, many developing countries' industrial and manufacturing sectors are turning to solar power as a crucial alternative [5]. Solar collectors are extensively utilized for diverse applications, including solar water heaters, solar cookers, steam generators, air warmers, and solar water treatment systems. There are two fundamental categories of collectors: stationary and tracking [6]. Due to their extensive acceptance angle range and absence of sun-tracking mechanisms, non-imaging collectors are commonly utilized in residential and commercial applications at temperatures ranging from 60 to 300 °C. It directly harnesses solar energy, primarily for power generation and heating purposes [7]. Evacuated tube collectors surpass flat plate collectors in both technique and design. At midday, the sun is perpendicular to a flat plate; however, due to the tubular design of the evacuated tube, all glass surfaces are oriented towards the

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sun for much of the day [8]. Nonetheless, the flat plate collector possesses two significant disadvantages [9]: Convection heat loss via the glass cover from the collection plate and Lack of solar tracking.

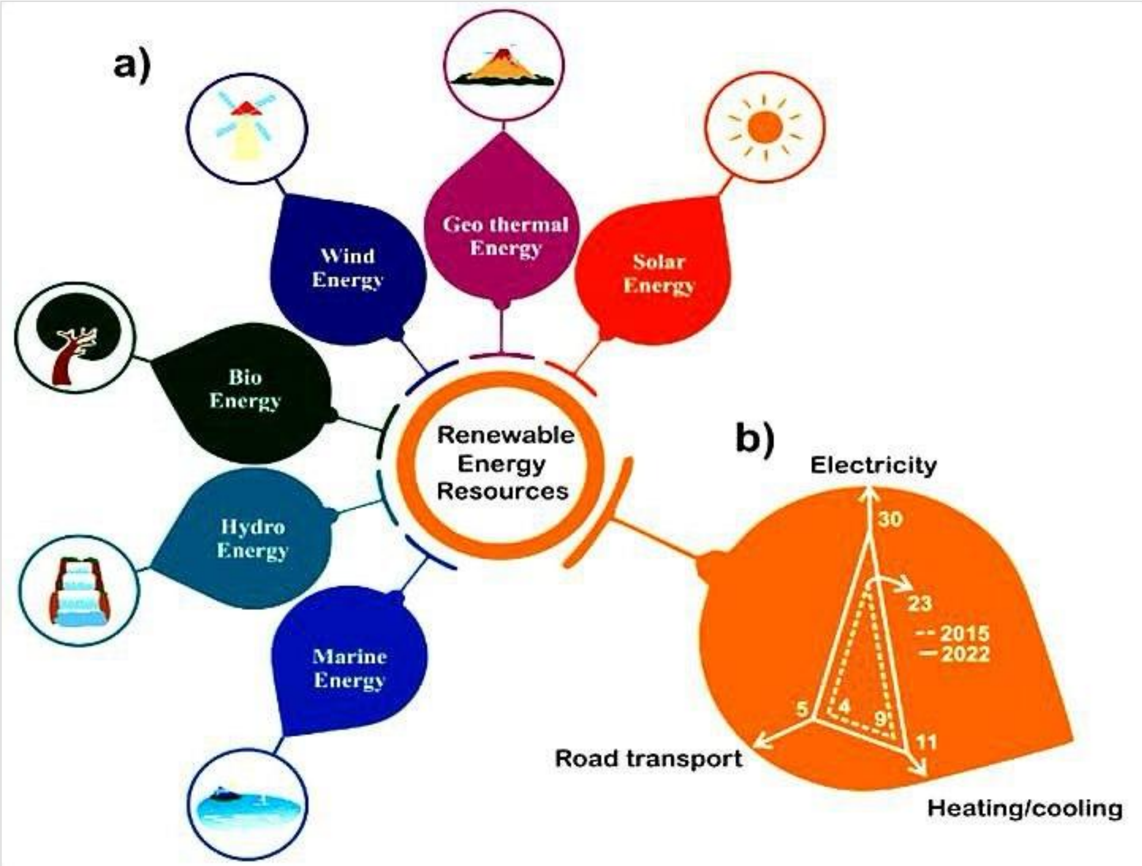


Figure 1: (a) various sources of renewable energy, and (b) contribution of renewable energy sources to electricity generation, heating/cooling, and road transport [2]

ETSCs have significantly reduced costs and thermal losses compared to traditional FPCs [10]. Employing a CPC design, which directs solar rays to a singular focal line according to the "Edge Ray Principle," the solar collector concentrates the incident sunlight. A highly reflective substance reflects the laser beams incident on the CPC, directing the light to the evacuated tube that functions as the receiver. There exist two types of evacuated tubes: direct and indirect [11]. The evacuated tube is employed to establish a vacuum between concentric borosilicate glass tubes. Al-N/Al, a distinctive coating, is utilized on the inner layer to augment its capacity for solar radiation absorption, although the outer layer remains transparent with minimal reflection [12]. Heat pipes facilitate heat transfer between the evaporator and condenser with minimal temperature differentials, in alignment with the principles of thermal conductivity, phase transition, and latent heat theory. Heat pipes are very efficient due to the elevated heat transfer coefficients associated with condensation and boiling, hence improving the performance and thermal efficiency of solar collectors [13]. Heat exchangers, such as heat pipes, utilize two primary categories—passive and active—to enhance heat transfer. Active types require external forces, whereas passive types do not necessitate them [14]. A thermosyphon is a heat transfer apparatus that utilizes gravitational forces to facilitate the evaporation or condensation of a working fluid. These devices can transport substantial quantities of heat with minimal temperature fluctuation. Boopathy [15] conceived the thermosyphon concept for the first time in 1942. The heat pipe is occasionally analogous to the thermosyphon, as illustrated in Figure 2. The latent heat of vaporization is absorbed by a heat transfer fluid with a low boiling point through a heat pipe in an evacuated tube solar collector. When a fluid comes into touch with a heat pipe, the energy from the vaporized heat transfer fluid is transferred to the fluid at the tip of the pipe. After cooling, the heat transfer fluid returns to the heat pipe's base, where it begins the recirculation process [16]. Figure 3 shows how a heat pipe can be enhanced with phase change material and fins for maximum efficiency [17].

In this work, multiple types of nanomaterials were combined at different concentrations. Nanomaterials were used in different proportions, along with varying filling ratios of phase change materials. The PCM was placed at the bottom of the heat pipe in a way that did not obstruct the flow of the working fluid inside the pipe. This design aims to enhance the efficiency of thermal energy storage and compensate for the heat loss during the absence of sunlight.

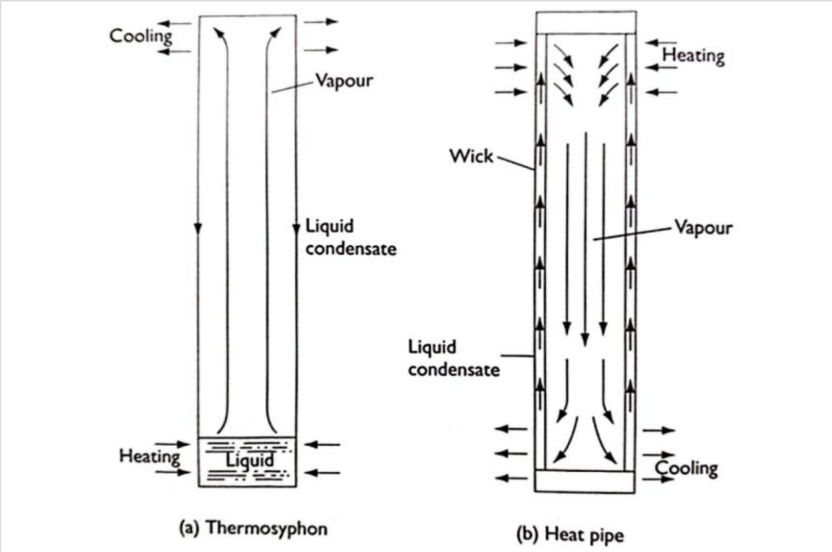


Figure 2: The heat pipe and thermosiphon [18]

1.1 Evacuated heat pipe

Olcha et al. [19], presented experimental tests that have been done over two months on the energy performance of a heat pipe-type evacuated solar collector comprising 24 tubes. In July, the solar collector attained superior thermal efficiency despite adverse weather conditions. The mean thermal gain was calculated to be 163 W/m² in July and 145 W/m² in August. In July and August, the solar collector exhibited average monthly energy efficiencies of 45.3% and 32.9%, respectively, alongside average monthly energy efficiencies of 2.62% and 2.15%, respectively. The thermal efficiency and exergy efficiency decrease by 67% and 41%, respectively, as the wind speed rises to 0.86 m/s. With an accepted half angle of 20 and a truncated geometrical concentration ratio of 1.95 rather than 2.92, the ICETHP solar collector was designed by Nkwetta et al., [20]. Reflector truncation decreases the average number of ray reflections before the absorber, reduces the amount of radiation that does reach the absorber, and increases the amount of radiation that is absorbed by the material by reducing its height. Lessens the amount of heat lost through each open window. A white borosilicate glass tube with an outside diameter of 100 mm and an inner diameter of 93 mm could encircle a 15 mm tubular absorber when the reflector was reduced to 1.95. Optical efficiency of 79.13% and total ray acceptance of 93.72% from 0 to 20 degrees of transverse angle were anticipated by a comprehensive two-dimensional ray tracing approach that relied only on the direct insolation component. After constructing and analyzing a heat pipe evacuated tube solar collector out of borosilicate glass, Kumar et al. [16], found an impressive efficiency curve. Temperature and sunlight are two of the most significant environmental variables that might affect the efficiency of heat pipe collectors. How far the condenser portion is from the evaporator is an important consideration in the design, as it controls the fluid in the heat pipe and essentially keeps the same efficiency as before, up to 80 °C. Ong and Tong [21], constructed an experimental apparatus to conduct experiments using water as the working fluid, with inclination angles ranging from 30° to 90° relative to the horizontal and filling ratios between 0.25% and 1.0%. The power input of the evaporator varied between 304 and 830 W. The researchers concluded that, within the boundaries of the experimental investigation, both the fill charge ratio and the inclination angles did not affect the thermosyphon's thermal performance. Thermosyphon heat transfer correlation with operating condenser and evaporator temperature differential and mean heat transfer coefficients were determined. All of these studies have been summarized in Table 1.

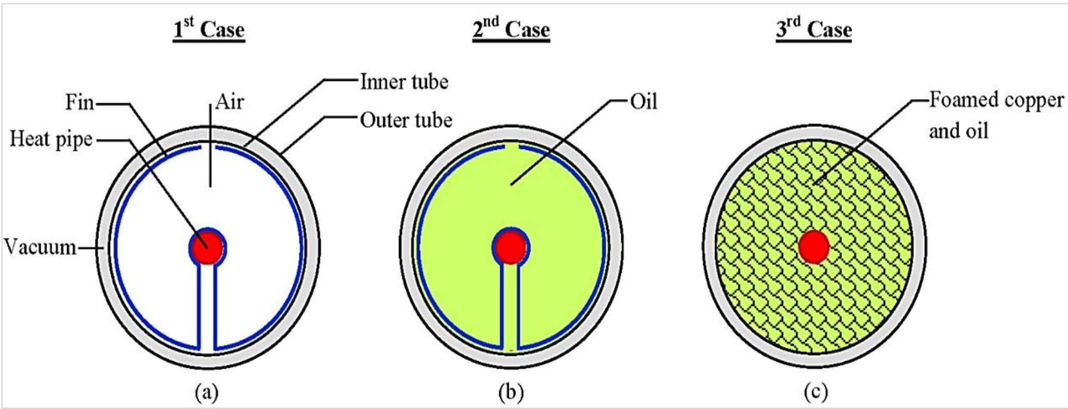


Figure 3: Cross-section of the evacuated tube heat pipe in case of inserting (a) finned surface, (b) finned surface and oil, and (c) foamed copper and oil [17]

1.2 Performance enhancement of ETSC using nanofluids

The aim of Çimen et al. [22], was to avoid the problem of overheating. On the warmest, most radiation-filled summer days, a decline in efficiency above 80 °C is employed to keep the temperature at 95 °C. As soon as the water temperature in the tank rises, any glass evacuated tube will stop transferring heat to the water. The natural cooling of the tank water during the night is another important factor in keeping everything in balance. The investigations use a variety of liquids as heat pipe fluids, including the current fluid, acetone, methanol, and ethanol. From 80 °C onwards, the newly constructed all-glass evacuated tube with ethanol had a daily conversion efficiency of 77.5% according to the collector aperture area. Consistency is shown in the experimental results. For example, Kabeel et al. [23], investigated how coaxial heat pipes were modified to improve the thermal efficiency of glass-evacuated solar collectors. Refrigerant was charged in the annulus volume region between two concentric copper tubes that made up a heat pipe. Researchers looked at how different tilt angles affected the thermal performance of the evacuated solar tube collector to find the sweet spot for the experiment. The effect of filling ratios ranging from 30% to 60% on the thermal efficiency of the coaxial heat pipe solar collector was investigated experimentally for the two refrigerant kinds, R22 and R134a. With heat pipes removed and a mass flow rate of 0.009 kg/s, the results showed a 67% improvement in thermal efficiency. By simulating a two-phase flow vertical thermosyphon with varying heat inputs, Alizadehdakhel et al. [24], examined the efficiency. A variety of fill ratios (0.3, 0.5, and 0.8) and input energies applied to the evaporation were tested to determine the thermosyphon's output. Using computational fluid dynamics (CFD) modeling, the Navier-Stokes equations were solved all at once. Based on the results, computational fluid dynamics (CFD) is the way to go when discussing and modeling the complex flow and heat transmission in thermosyphons. In their study, Chougule et al. [25], examined the thermal performance of three separate wickless solar heat pipes. The pipes were tested with different types of working fluids, including pure water, water surfactant, and CNT-water nanofluid, and at inclination angles of 20, 31, 5, 40, 50, and 60 degrees. The second collection made use of nanoparticles, while the first one employed water as its working fluid. However, the third set of data used 2-ethylhexanol in water at a concentration of 150 ppm as a cooling agent. According to the results of the experiments, the 2-ethyl-hexanol solar collector outperforms the traditional water and CNT/water nanofluid solar collectors. In order to solve engineering equations, Ziapour and Shaker [26], linked a FORTRAN code with a program. Several other working fluids were tested, such as water, ammonia, R-22, R-11, and R-134a. We show that compared to the standard fourth-order Runge-Kutta approach, the proposed time integration strategy has a broader stability range. Regardless of whether convective effects are considered inside the TPCT, an interesting result of the present model indicates that the steady-state solutions of the condenser surface temperatures are equal. Verification findings indicate that the present model is a simple and efficient tool for building TPCTs in stable and transient regimes. It has been examined how inclination angles and fill ratio impact the thermal efficiency of a two-phase closed thermosyphon at temperatures lower than 65 °C. Scientists Ozsoy and Corumlu [27], conducted studies to study the thermal performance of an ETSC utilizing silver water nanofluid for commercial purposes. Four sets of two-weekly heat tube tests using a silver-water nanofluid were performed to monitor improvements in THP efficiency. It has been noted that the enhanced heat transfer performance of the THP that was tested with the silver-water nanofluid was maintained. Using nanofluid working liquid instead of pure water improves the solar collector's performance by 20.7% to 40%. When employing silver-water nanofluid, the THP evacuated tube heat receiver significantly outperforms the control group in the laboratory testing. In their study on thermal efficiency evaluation and ETSC entropy analysis, Tang et al. [28], used titanium dioxide (TiO_2) nanofluid as the working fluid. A nanofluid of titanium dioxide (TiO_2) is created by dispersing a very small amount of TiO_2 nanoparticles into purified water. The efficiency of the evacuated tube solar thermal collector (ETSC) can be enhanced with the increased thermal conductivity of TiO_2 nanofluids. To sum up, the thermal conductivity of TiO_2 nanofluids is significantly enhanced as the volumetric concentration of nanoparticles increases. In a study conducted by Iranmanesh et al. [29], the effect of graphene nanoplatelets (GNP) in a nanofluid containing distilled water was studied experimentally. Graphene nanoplatelets nanofluids have had their thermal and physical properties studied, including their stability, specific heat capacity, viscosity, and thermal conductivity. To test the effectiveness of the collector, the ASHRAE standard 93-2003 has been utilized. The results indicated that utilizing GNP nanofluid as an absorption medium enhanced the solar panel's thermal efficiency by as much as 90.7% at a fluid velocity of 1.5 L/min. The results indicated that increasing the mass fraction of nanoparticles enhanced thermal energy gain, resulting in a higher fluid outlet temperature when utilizing graphene nanosheets. Al-Mashat and Hasan [30], examined the efficacy and enhancement of heat transmission in evacuated-tube solar collectors. The experiment was done in Baghdad from April 2011 until March 2012. Two varieties of reflectors were utilized, one flat and one curved, and Nanofluid (DW + Al_2O_3) was incorporated into the working fluid to improve the collector's thermal properties. The results indicate that the maximum temperature of the collector in winter was 79 °C and 99 °C in summer, while the application of nanofluid allowed the temperature to reach 99 °C in winter. In order to reduce heat loss, Huang et al. [31], developed heat shields between the absorber plate and the glass tube, thermal protection (if installed). In order to absorb energy from the absorber plate, the heat pipe is mechanically linked to the bottom surface of the plate within the glass tube. Experimental results showed that at inlet water temperatures ranging from around 20 to 150 °C, heat shields increased thermal efficiency, and solar collector performance improved with increasing inlet water temperatures. Simulated findings demonstrated that, for all input water temperatures, the new collector outperformed the conventional one in terms of thermal efficiency, and this advantage was even more pronounced when solar radiation was weaker and ambient temperature was lower. The goal of the study performed by Siritan et al. [32], is to create the best possible closed-loop pulsing heat pipe for use in commercial solar water heater systems that use evacuated tubes instead of thermosyphons. According to the Net Saving Method and economic analysis, it is rated based on its high thermal performance and greatest net saving. According to the findings of the experiments, the ideal CLPHP configuration has an inner diameter of 1.50 mm, an evaporator length of 1.25 m, and four settings. With an expenditure of 482.4 USD and a simple payback period of 3.3 years, the total heat rate of water obtained was 518 W, and the net saving was 901.4 USD over 10 years. The effectiveness of the nanoparticles was tested at various milligram-for-residue (mfr) concentrations, which ranged from 0.015 to 0.035 by volume. Researchers found that a maximum boost of 37.3% in temperature difference was achieved utilizing a volume fraction of nanoparticles of 0.035% and a mass flow rate of 0.017 kg/s. In comparison to water, the maximum increase in heat gain was 42.3% higher. Eidan et al. [33], studied how nanofluids based on Al_2O_3 and CuO nanoparticles affected the efficiency of ETSC heat pipes. The authors investigated the optimal fill ratio (40, 50, 60, 70, and 80%) and angle for the heat pipe ETSC in order to determine its optimal output. The results show that the collector works best when the ratio is 70% and the angle of tilt is 45 degrees. It was also determined how the collector's thermal performance was affected by two nanofluids: acetone and CuO/Al_2O_3. After conducting experiments with two different concentrations of nanofluids (0.25% and 0.5% by volume), it was found that the maximum percentage improvement in performance might be around 34%, 74%, 32%, and 73%, respectively. Under the same circumstances, the collector worked far better with nanofluids than with acetone. Both nanofluids showed an efficiency boost as the concentration was raised. Sharafeldin et al. [34], examined the effect of employing copper nanoparticles on the ηth of ETSC. A variety of nanoparticle concentrations and mole fractions were tested in the experiments. The use of 0.03% nanoparticle resulted in a temperature difference rise of 17%-51.5 percent, a reduction of 34% in collector area, and an all-time high of 0.83 for the absorbed energy parameter. Using the same nanoparticle composition resulted in a reduction of 312.533 kg of CO_2 emissions and an increase of the removal energy parameter to 21.66. Using both experimental and analytical methods, Sadeghi et al. [35], investigated the thermal performance of ETSCs that contained coils and were integrated with nanofluids. The thermal performance of ETSC was evaluated using three different models. A nanofluid (Cu_2O/deionized water) volume fraction of 0.08 and mfr of 50 l/h produced the best results for an ETSC tank size of 25L, with an energy efficiency of 60% and an exergy efficiency of 6%. All of these studies have been summarized in Table 2.

1.3 Performance enhancement of ETSC using PCM

Solar water heaters, such as those studied by Elarem et al. [36], can be efficiently linked with PCMs to increase thermal energy saving and decrease heat loss during the night. In their investigation of ETSCs with Nano-PCMs as Latent Heat Storage Systems, Elarem et al. [37], focused on such systems. Computational analysis was performed on the fin parameters, which include the fin thickness and the fin spacing. Their results show that the inclusion of fins has a major effect on the phase change heat transfer of paraffin in the ETSC. They found that the PCM melts faster as the fins' thickness decreases. In addition, it was found that adding 1% Cu to the PCM produced the optimal mass concentration for a 2K rise in the HTF output temperature. In addition, their research showed that incorporating a Solar Parabolic Trough Reflector and a PCM into the ETSC improved the system's efficiency. A water heater system with an independent storage tank containing a layer of PCMs was investigated in a study carried out by Prakash et al., [38]. In a study conducted by Abokersh et al. [39], the effects of PCM were examined in a sealed water heater (SWH) with a direct pass U-pipe. Each evacuated tube contained 0.8 kg of paraffin wax. During charging, most heat transfer occurs by convection; the collector's efficiency is 14% greater in the fin-less configuration compared to the other. However, when discharging energy, the fin-type evacuated tube achieves a higher total success rate. When it comes to ETSCs, Felinski and Sekret [40], broke down the results of using PCM. During peak load, the water temperature inside the tank is improved because of the use of PCM in an ETSC, which enables the storage of more excellent heat for a longer period. Additionally, a solar fraction increase of 20.5% was seen when PCM was used in an evacuated tube collector. Using forced circulation in two configurations one with and one without a fin, Abokersh et al. [41], investigated U-pipe ETSC by combining paraffin wax with these. The results show that the designed system outperforms the usual system and enhances the heat transfer characteristics of PCM. According to the simulation results, on that specific day, the finned system discharges 47.7 percent more energy than a typical system, whereas the finless system discharges 35.8 percent more energy. Within the same meteorological conditions, Chopra et al. [42], detailed an experimental investigation of heat pipe evacuated tube solar collectors containing and lacking phase change material for use in water heating applications. Figure 4 shows that one system, evacuated tube collector-A, did not use any phase change material in its evacuated tubes, while the second system, evacuated tube collector-B, used SA-67. As a thermal storage material, SA-67 (2.25 kg/tube) makes up 75% of the total volume of each evacuated ETC-B tube. The results showed that evacuated tube solar collectors had a daily thermal efficiency of 42-55% and 79-87%, respectively, regardless of the phase change material. There was a daily improvement in energy efficiency for water flow rates of 8, 12, 16, 20, and 24 L per hour when using the integrated evacuated tube collector with phase change material compared to the one without. At a flow rate of 20 L/h, the two systems reached their maximum daily thermal efficiency.

A heat pipe ETC (HPETC) can be modeled using computational fluid dynamics (CFD), as demonstrated by Pawar and Sobhansarbandi [43]. In order to cross-validate the results obtained from the current experimental analysis and CFD, the boundary conditions are set using the field testing data. An arrangement of six cell layers encircles the PCM and heat pipe surfaces on the way to the fluid domain's core. In Phase II, the PCM and HPETC are developed, whereas in Phase I, the commercially available HPETC is modeled in 3D. Phase I involves simulating the 3D model of commercially available HPETC, while Phase II involves developing the HPETC that is integrated with the PCM. Tritriacontane paraffin (C33H68), with a melting point of 72 °C, is the chosen type of PCM. The experimental data and the modeling findings are in good agreement, with an average variance of 2.04% for Phase I and 4.80% for Phase II, respectively. Dhaou et al. [44] investigated the thermal improvement of an Evacuated Tube Solar Collector by adding Phase Change Material (PCM) to copper and nickel metal foams and equipping it with plate fins. Four cases were numerically simulated to obtain the results: case 1 with pure PCM, case 2 with metal foam, case 3 with fins, and case 4 with metal foam plus fins. The results demonstrated that the thermal performance of ETSC is significantly enhanced when fins and metal foam are inserted simultaneously. Completely replacing pure PCM with this mixture reduces processing time by around 9% and using just plate fins shortens it by about 2%. The findings indicated that the ETSC/PCM system's dynamic heat storage/release mechanism is marginally affected by the pore size of the metal foams. For solar water heaters (SWHs), Papadimitratos et al. [45], introduced a new way to incorporate phase change materials (PCMs) into evacuated solar tube collectors. This technique involves completely submerging the heat pipe in the phase-changing substance. Two separate phase change materials (dual-PCM)—Tritriacontane and Erythritol—with melting points of 72 and 118 °C, respectively—make up the solar collector that has been suggested (see Figure 5). Both continuous and intermittent use of the solar water heater in conjunction with the suggested solar collector are examined. Commercial solar water heaters on a large scale also test the practicality of this technology. Additionally, the study found that compared to conventional solar water heaters without phase change materials, there was a 26% improvement in efficiency during normal operation and a 66% improvement during stagnation mode. These improvements extend beyond the enhanced functionality of solar water heater systems.

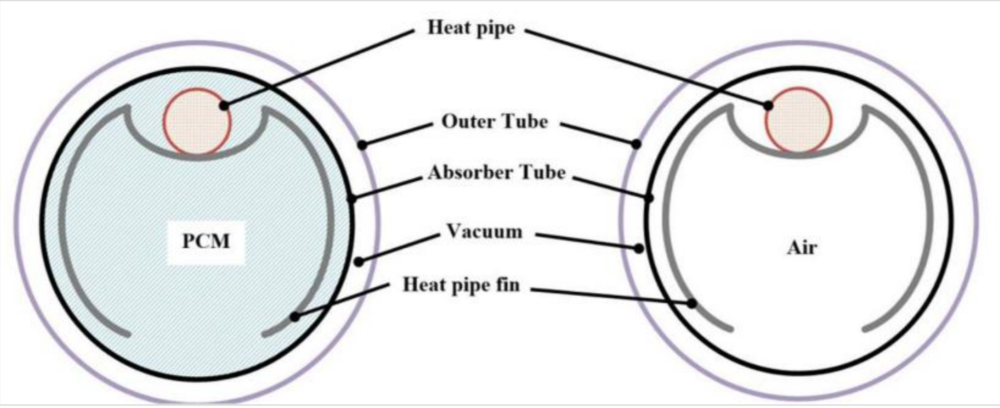


Figure 4: Cross-section of evacuated tube (a) with PCM (b) without PCM [42]

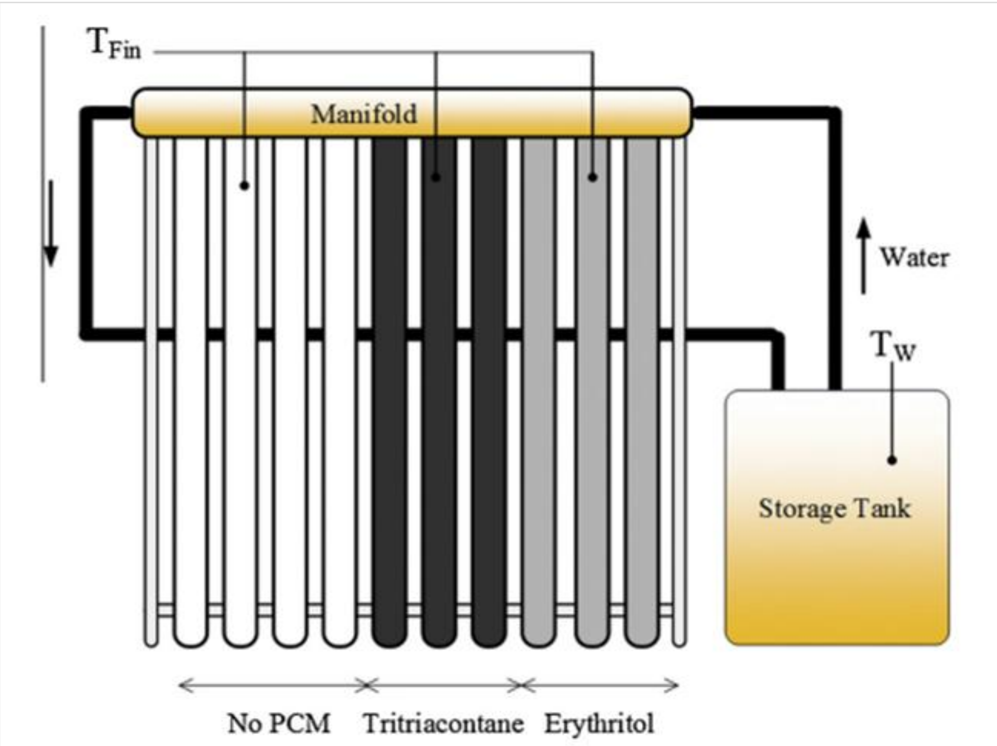


Figure 5: Schematic configuration of experimental setup [45]

For example, Xue [46], investigated the thermal performance of a residential solar water heater with solar collector coupled phase-change energy storage, which involves conducting tests of exposure and constant flow rate. Because PCM is thick and has poor thermal conductivity, heat cannot easily flow through the PCM module. At the same collector area, conventional water-in-glass evacuated tube solar water heaters perform better thermally under exposure than DSWHSCPHES. Additionally, DSWHSCPHES works better when the flow rate is steady as opposed to when exposed. There is a relationship between the ratio of diffuse to global radiation and the system's performance; when these two variables rise, the system's performance falls, and vice versa. Using a helicoperically finned heat pipe, Essa et al. [47], conducted experimental studies on an evacuated tube solar collector. During the test, two collectors were utilized. The typical fin type was part of the control system, which was the first. The results show that compared to conventional fins, helical fins archived higher temperature uniformity in Paraffin along the tube axis. The helical fin system had a maximum temperature difference of 4 °C and the traditional fin system a maximum of

12.25 °C, both measured under the same flow rate. When compared to the conventional one, the helical fins improved daily efficiency by 13.6 percent and 15.9 percent at 0.5 and 0.665 L/min, respectively. In addition, the helical fin system was 30–60 minutes behind the traditional one in initiating the solid–to–liquid phase shift. An oscillating heat pipe (ETSC) was created by Wu et al. [48], specifically for heating water. In order to improve the efficiency of the heat pipe ETSC system, paraffin wax was used as a latent heat storage material. When comparing daily efficiency fluctuations between collectors with and without PCM, they discovered that the former had a fluctuation of less than 30%. Even on summer nights, the collector's outlet temperature with PCM stayed over 50 °C, so this was necessary. During winter nights, they saw that the PCM-based system had a COP (coefficient of performance) greater than 3.0. Furthermore, it was noted that the PCM-based system reached 50 °C more quickly than the one without PCM. Two separate PCMs were employed by Zhai et al. [49] to enhance the heat pipe ETSC's thermal performance. During times of low solar radiation or high energy demand, the evacuated tubes used in this study were filled with erythritol and tritriacontane, which act as PCMs and provide hot water. In comparison to the control group, the PCM-enhanced system performed 66% better in stagnation mode and 26% better in normal mode, according to the trial data. Desalination units with PCM (paraffin wax) integrated heat pipes (ETSCs) allowed for continuous desalination even when sunlight was not available, according to research by Faegh and Shafii [50]. Additionally, it was noted that the distillation output of the system with PCM is 86% higher than that of the system without PCM. The system's yield increased to 6.555 kg/m^2 when PCM was used. According to Essa et al. [51], when the mass flow rate of the heat transfer fluid was set at 0.25 LPM, the reference collector's efficiency was 21.9% lower than that of the PCM (parafbaifin wax) integrated ETSC. By studying the charging and discharging processes, they discovered that the enhanced efficiency of ETSC was caused by the complete phase change of the phase change material that was chosen. In their study, Olfian et al. [52], examined how spirally corrugated U-pipe affected the delivery of ETSC paired with PCM. Results showed that compared to conventional smooth tubes, corrugated tubes resulted in a 21.55% improvement in collector efficiency. Additionally, the four-lobe corrugated tube played a role in keeping the operational temperature at 40 °C right up until 8:00 p.m. Analytical studies on PCM's heat storage and release processes were conducted by Bazri et al. [53], in a storage tank. When exposed to low levels of sunshine throughout the day, the results showed that the standard system, when combined with the best PCM, was only 32–42% effective. However, when exposed to greater levels of radiation, its performance rose to about 37–43%. Instead, there was a 57% and 50% improvement with the new small design. While the effectiveness ranged from 36% to 54% on sunny days, it increased from 47% to 58% on overcast days. With all three PCMs tested, the new little design achieved an overall efficiency ranging from 10 to 58%. With the goal of developing a more efficient heat pipe evacuated tube solar water heater collector, Alshukri et al. [54], studied a novel approach to integrating phase change materials (PCMs) into either the ET or one of two independent tanks located next to the water tank. Using this technique, medical grade paraffin wax was used to fill the evacuated tube and store thermal heat; grade A paraffin wax was used to fill the two separate tanks. An ET and two PCM storage tanks, respectively, integrated the second and third HP/ETCs with PCM. The fourth HP/ETC served as a point of comparison because it was demonstrated in Figure 6 to be devoid of PCM. Based on the data, it can be concluded that incorporating PCM into the ET and the separated tanks improves efficiency by 55.7%, whereas incorporating it into the ET alone increases efficiency by 49.9%. However, compared to the reference collector that did not contain PCM, the efficiency was 36.5% higher after PCM was integrated into the separated tanks.

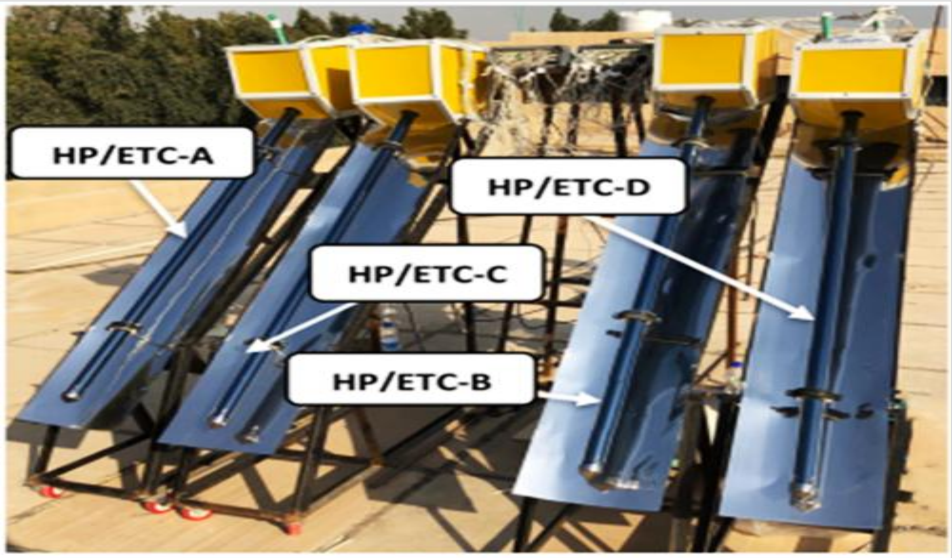


Figure 6: A photograph of four studied HP/ETCs with the instrumentation [53]

By combining conventional solar thermal storage with heat storage units filled with PCM and incorporating a finned heat pipe to increase heat dispersion, Bai et al. [5], conducted an experimental evaluation of an unconventional solar thermal storage heating system (see Figure 7).

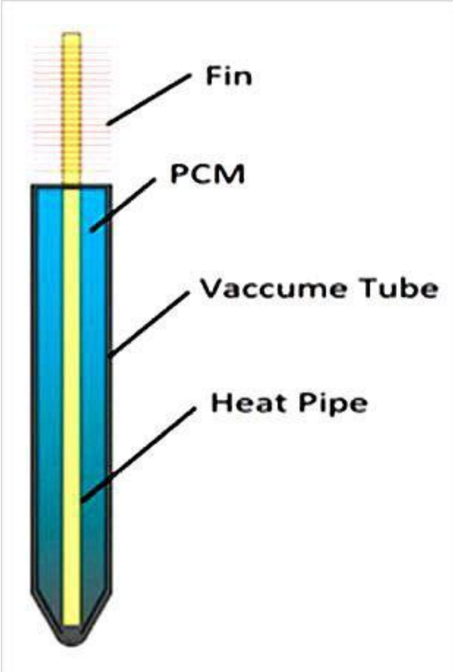


Figure 7: Finned heat pipe and filled with PCM [5]

A numerical analysis was conducted by Jalil and Mahdi [55], to determine the impact of changing the paraffin wax's thermal characteristics on the efficiency of a double-glazed window that was doped. The results demonstrate that the unit's performance can be enhanced by increasing the density, latent heat, and thickness of the paraffin wax PCM. This will lead to an increase in the temperature-time lag and a decrease in the temperature decrement factor of the double-glazed window. To the contrary, modifying the paraffin wax's specific heat capacity is an ineffective and unproductive method for improving the unit's performance. Additionally, under Baghdad's ambient conditions, a window thickness of 20 mm or greater is recommended (PCM thickness). Because of their thermal qualities, such as low thermal conductivity and high latent heat, phase change materials (PCM) show great promise as superior insulation materials. Nsaif et al. [56], began using PCM in the walls and windows to lower the room's interior temperature and internal surface temperature. Two distinct PCM melting points lower the maximum internal and surface temperatures by 6 °C. The built-in PCM blind system shielded the room's inhabitants from the sun's rays. All of these studies have been summarized in Table 3.

Table 1: Evacuated Tube Heat Pipe

Type of Solar Collector	Key Characteristics	Environmental Conditions	Thermal Efficiency	Exergy Efficiency	Key Findings	Ref.
Heat pipe-type evacuated tube collector	24 tubes,	July and August, wind speed 0.86 m/s	45.3% in July, 32.9% in August	2.62% in July, 2.15% in August	Efficiency decreases with increasing wind speed, with an average thermal gain of 163 W/m² in July.	[19]
Solar collector with truncated reflector	Geometrical concentration ratio 1.95	Half angle of 20°	79.13% (optical efficiency)	93.72% (ray acceptance)	Reducing reflector height decreases heat loss and increases radiation absorption.	[20]
Heat pipe evacuated tube collector	Borosilicate glass	Temperatures up to 80°C	High-efficiency curve	---	Temperature and sunlight significantly affect efficiency; efficiency remained stable up to 80°C.	[16]
Thermosyphon heat pipe collector	Inclination angles from 30° to 90°	Filling ratios between 0.25% and 1.0, input power 304–830 W	---	---	The fill ratio and inclination angle did not affect the thermal performance of the thermosiphon.	[21]

Table 2: ETSCs with Nanofluid and working fluids

Working Fluid	Nanofluid Type	Main Enhancement	Performance Improvement	Temperature Range (°C) Fluid Flow Rate (kg/s)	Additional Findings	Ref.
Acetone, Methanol Ethanol	---	Evacuated tubes with natural cooling at night	77.5% efficiency	> 80°C	Ethanol-enhanced heat pipe fluid shows 77.5% efficiency after 80 °C for the daily conversion.	[22]
R22, R134a	---	Modified coaxial heat pipes with refrigerant in copper tubes	67% improvement in thermal efficiency	0.009 kg/s	Coaxial heat pipes show significant improvement at different tilt angles.	[23]
---	---	Two-phase flow vertical thermosyphon simulation	---	---	CFD simulations for thermosyphon flow show complex heat transfer behavior.	[24]
Water, CNT-water, 2-ethyl hexanol,	CNT-water nanofluid, 2ethylhexanol ,	Wickless solar heat pipes with different fluids	2-ethyl hexanol outperforms CNT-water	Various inclinations (20°–60°)	2ethylhexanol fluid improves thermal performance over CNT and water.	[25]
Water, Ammonia, R-22, R-11, R-134a	---	Time integration method for TPCT modeling	---	---	Stability improvement for steady-state TPCT condenser surface temperature solutions.	[26]
Silver-water nanofluid	Silver nanoparticles in water	Commercial ETSC with nanofluid	20.7%–40% improvement	---	Silver nanofluid significantly enhances thermal efficiency.	[27]
TiO_2 nanofluid,	TiO_2 nanoparticles in water	Increased thermal conductivity with TiO2 nanofluid	---	---	TiO2 nanofluid improves thermal conductivity, enhancing efficiency.	[28]
Water, GNP nanofluid	Graphene nanoplatelets in water	Thermal properties of GNP nanofluids	90.7% improvement in thermal efficiency	1.5 L/min fluid velocity	GNP nanofluids significantly increase thermal efficiency with higher nanoparticle mass.	[29]
DW + Al_2O_3 nanofluid	Al_2O_3 nanoparticles in water	Use of flat and curved reflectors	Winter 79 °C, Summer 99 °C	99 °C (summer)	Nanofluid use improves collector temperature performance in both winter and summer.	[30]
---	---	Heat shields to reduce heat loss	Improved thermal efficiency	20–150 °C	Heat shields enhance collector performance under varying temperatures.	[31]
---	---	Closed-loop pulsing heat pipes in ETSC	37.3% temperature difference increase and enhancement 518 W	0.017 kg/s	Ideal configuration with 37.3% improvement in temperature difference and net savings.	[32]
Acetone, CuO/Al_2O_3 nanofluids	CuO/Al_2O_3 nanoparticles	Nanofluids with varied fill ratios	32%–74% improvement in performance	---	Nanofluids with acetone show higher efficiency than without it at optimized ratios.	[33]
---	Copper nanoparticles	Nanoparticles tested for ETSC thermal efficiency	17%–51.5% improvement	---	Copper nanoparticles improve energy absorption and reduce CO_2 emissions.	[34]
Cu_2O/deionized water	Cu_2O nanoparticles	Integration of nanofluids in ETSC with coils	60% energy efficiency	50 l/h	Cu_2O nanofluid at 0.08 volume fraction and 50 l/h flow rate yields the highest efficiency.	[35]

Table 3: ETSCs with PCM

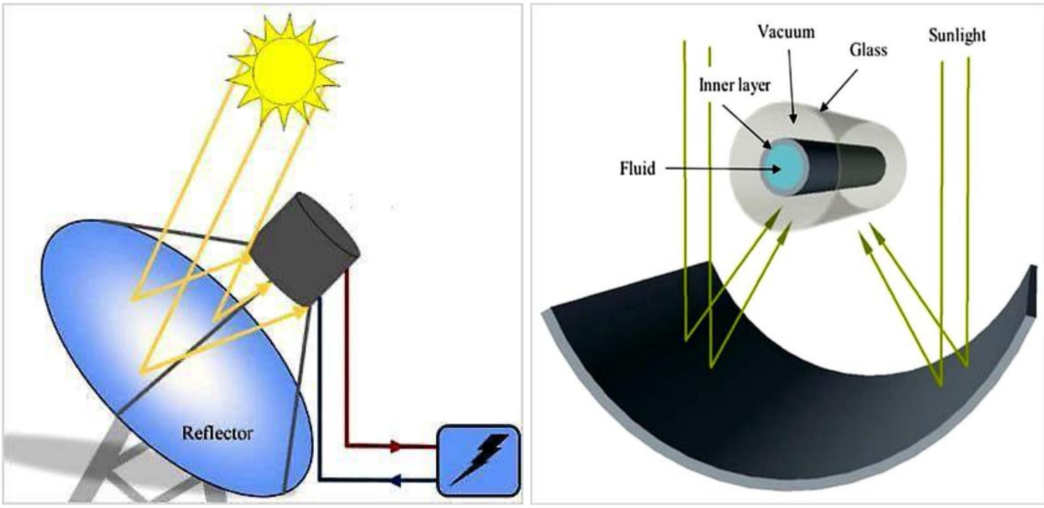
Solar Heating System	Type of PCM	Efficiency Improvement	Main Findings	Ref.
ETSC (Evacuated Tube Solar Collector)	Paraffin	Faster melting of PCM and increased HTF output temperature	Adding fins accelerates PCM melting. 1% Copper addition increases the HTF output temperature by 2 °C. PCM combined with a Parabolic Trough Reflector increases system efficiency.	[37]
Independent Solar Water Heater	---	Increased efficiency with PCM in the independent tank	PCM in an independent storage tank improves heat retention overnight.	[38]
Sealed Water Heater (SWH)	Paraffin Wax	Higher thermal transfer efficiency with fins	Finless configuration showed 14% better efficiency during charging. The finned system performed better during the discharging.	[39]
ETSC (Evacuated Tube Solar Collector)	Not specified,	20.5% increase in solar fraction with PCM	PCM improves tank temperature during peak load, storing heat for longer and increasing system efficiency.	[40]
ETSC (Evacuated Tube Solar Collector)	SA-67	42-55% improvement in daily thermal efficiency	Adding PCM (SA-67) improved performance at all water flow rates, with maximum efficiency achieved at 20 L/h flow rate.	[42]
HPETC (Heat Pipe Evacuated Tube Collector)	Paraffin	2.04% improvement in performance	CFD analysis developed a 3D model of HPETC with PCM. Experimental data showed good agreement with simulation results.	[43]
ETSC (Evacuated Tube Solar Collector)	PCM + Metal Foam	9% reduction in processing time, 2% with fins	Adding metal foam and fins to PCM significantly improved thermal performance.	[44]
Solar Water Heater (SWH)	Erythritol, Tritriacontane	26% improvement in normal operation, 66% in stagnation mode	PCM embedded in evacuated tubes increased efficiency in both normal and stagnation modes.	[45]
ETSC (Evacuated Tube Solar Collector)	Paraffin	< 30% fluctuation in efficiency	PCM kept outlet temperature above 50°C during winter nights, maintaining high efficiency.	[48]
HPETC (Heat Pipe Evacuated Tube Collector)	Erythritol, Tritriacontane	66% improvement in stagnation, 26% in normal operation	PCM-enhanced systems performed 66% better in stagnation and 26% better in normal operation compared to the control.	[49]
ETSC (Evacuated Tube Solar Collector)	Paraffin	86% higher desalination yield	PCM in desalination systems allowed continuous operation even without sunlight, increasing yield to 6.555 kg/m².	[50]
ETSC (Evacuated Tube Solar Collector)	Paraffin	13.6%-15.9% improvement in daily efficiency	Helical fins improved daily efficiency compared to traditional fins, and the helical fin system showed higher uniformity in paraffin temperature.	[47]
Double-glazed window	Paraffin	Improved performance with increased PCM thickness and latent heat	Increasing PCM density and latent heat improved temperature lag and reduced temperature drop.	[55]
Walls and windows for insulation,	PCM with two different melting points,	Reduced internal temperature by 6 °C	PCM in walls and windows effectively reduced internal temperature, with a difference of 6 °C between the maximum surface and internal temperatures.	[56]

2. Classification of solar thermal collectors

Solar thermal collectors convert the sun's radiation into thermal energy to heat a heat transfer fluid. This makes them a practical answer to the issue of energy conservation. The precise temperature and magnitude of this conversion are dictated by the technology employed by the collector [57]. STCs are classified as concentrating and non-concentrating based on their concentration level.

2.1 Concentrating collectors

The receiver and concentrator are the two main components of a concentrating collector, which allows the receiver to absorb a concentrated beam of sunlight. It is feasible to operate at high temperatures because of the concentration, and thermal losses are reduced because of the tiny receiver area [58]. Common high-temperature uses for these collectors include producing steam for use in power generation or other processes [5]. Figure 8 (a and b) shows two more ways these can be categorized: parabolic trough collectors (PTCs) and parabolic dish reflectors (PDRs).



(A) **(B)**

Figure 8: (a) PDR (b) PTC [5]

2.2 Non-concentrating collectors

Collectors that do not concentrate are employed for uses involving medium temperatures. As shown in Figure 9 (a and b), respectively, these are further categorized as ETSCs and FPSCs. Because of their large volume output and suitable temperature range requirements, non-concentrating collectors are the go-to choice for most commercial and residential applications. For non-concentrating solar power applications, evacuated tube collectors are becoming more popular as an alternative to flat plate STC due to their reduced heat losses and increased efficiency [5]. The solar absorber can reduce its radiative heat loss with the help of selective coatings, and its convective and conductive heat losses can be reduced even further with the help of an evacuated glass enclosure. A type of thermal diode, heat pipes can withstand subzero temperatures, don't contain any moving parts, and don't need any additional pumping power [59].

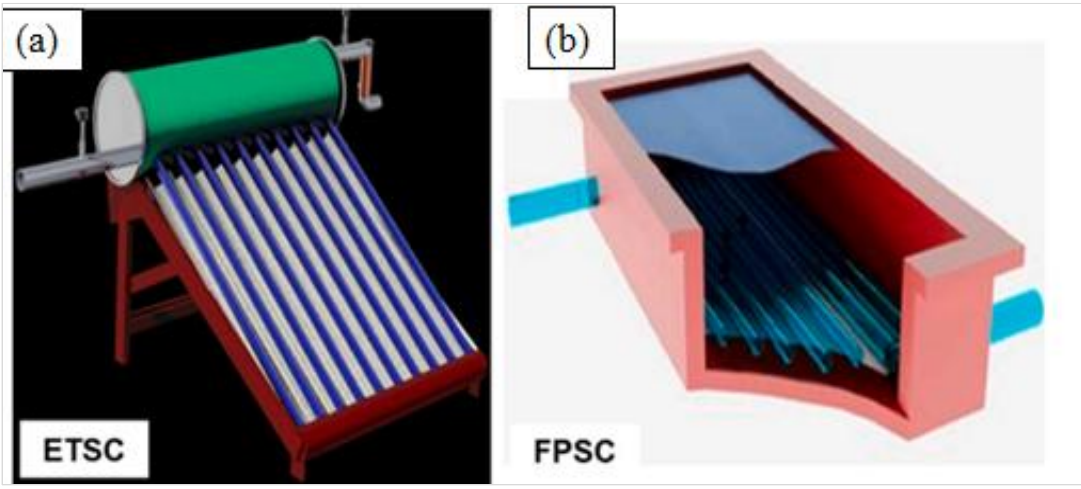


Figure 9: (a) Evacuated tube (b) Flat plate [5]

2.2.1 Heat Pipe - Evacuated tube collector (HP-ETC)

A heat pipe is an additional component of vacuum tube collectors that use thermosyphons inside their cores instead of conveying liquid straight through them. Figure 10 shows an evacuated tube collector with a heat pipe, which is composed of a heat pipe placed inside a glass tube that has been vacuum-sealed. Collectors may operate at greater temperatures than flat plate collectors due to the vacuum container's reduction of conduction and convection losses. Heat pipe-evacuated tube collectors outperform flat plate collectors at short incidence angles, which is a major benefit [60]. They put the heat pipe's fins to good use by making the most of its thermal advantages. The primary distinction between the traditional heat pipe mechanism and the heat pipe with an evacuated tube collector is in the heat transfer process that happens between the absorber wall of the tube and the fluid [61].

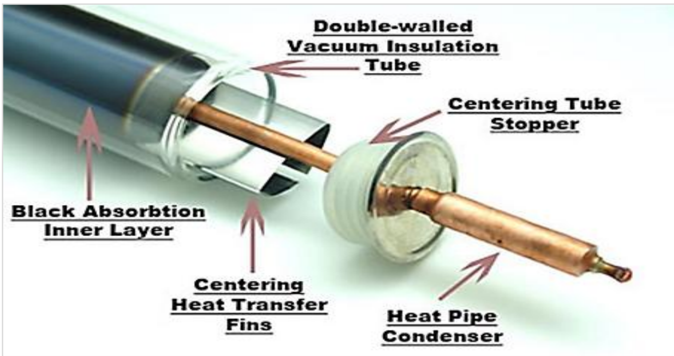


Figure 10: Heat Pipe - evacuated tube collector (HP-ETC) [60]

3. Introduction to nanofluids

A nanofluid is a type of fluid in which there is a very small concentration of particles with a size smaller than 100 nm, distributed evenly throughout the fluid. An example of a base fluid is a nanofluid, which is created by adding a small amount of nanoparticles to the original fluid and increasing its thermal conductivity. Researchers will increasingly use nanofluids in the future for heat transfer applications, particularly those involving renewable energy sources. The utilization of nanofluids enhances the efficiency of solar collectors. Since more heat is being collected by the sun, the demand for fossil fuels is decreasing [2]. Among the many novel qualities of nanofluids that make them a promising candidate for uses requiring improved heat transfer are their high thermal properties, enormous surface area, and robust optical characteristics. The heat transfer coefficient, conductivity, density, and low specific heat of nanoparticles in nanofluids make them ideal for thermal devices. When compared to pure fluids, nanofluids have much larger absorption and extinction coefficients. A number of solar applications benefit from nanofluids because they are less likely to clog pumps and pipes or sediment than suspensions of micro or millimeter-sized particles and because they lower the total charge and the critical surface area of heat transfer in thermal systems [62]. As a result of their superior thermal characteristics, nanofluids find widespread application as coolants in heat transfer devices, including heat exchangers and electronic cooling systems [63] (such as flat plates) and radiators. On the other hand, their regulated optical qualities make them valuable as well [64]. Enhancement of polymerase chain reaction efficiency by graphene-based nanofluids [65]. Nanofluids in solar collectors are another application where nanofluids are employed for their tunable optical and thermal properties and in solar ponds [66].

4. Phase change materials (PCMs)

Eutectic PCMs include organic-inorganic, organic-organic, and inorganic-inorganic components, as well as inorganic (salt hydrate, metallic), paraffinic, and non-paraffinic components. As shown in Figure 11, PCMs have a variety of characteristics, including thermal, chemical, kinetic, and economic ones [67]. The performance of the collector was evaluated using a PCM-filled U-tube ETSC. During the day, when the sun is shining, energy can be stored in photovoltaic modules (PCMs). By nightfall, this stored energy can be used. Three steps make up the process of energy storage and transmission within PCM: first, solar energy absorption; second, the PCM charging procedure (liquefying); and finally, the PCM discharge process into cold source water (solidification) [5].

The advantage of compactness is provided by latent heat storage by PCMs since their fusion heat is greater than their specific heat. When a substance goes through a phase change, it changes from one state to another. For example, when a solid turns into a liquid or a liquid turns into a solid. Figure 12 shows a variety of thermal storage material types. At fusion temperatures within the required range, a number of PCMs are known to melt. However, in order to store latent heat, these materials need to have certain chemical, kinetic, and thermodynamic characteristics. The low cost and high accessibility of these materials should also be taken into account [69].

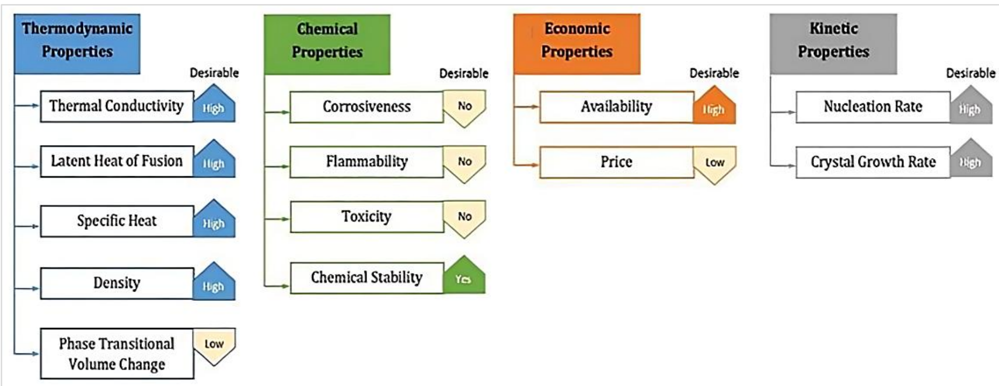


Figure 11: Properties of PCMs [68]

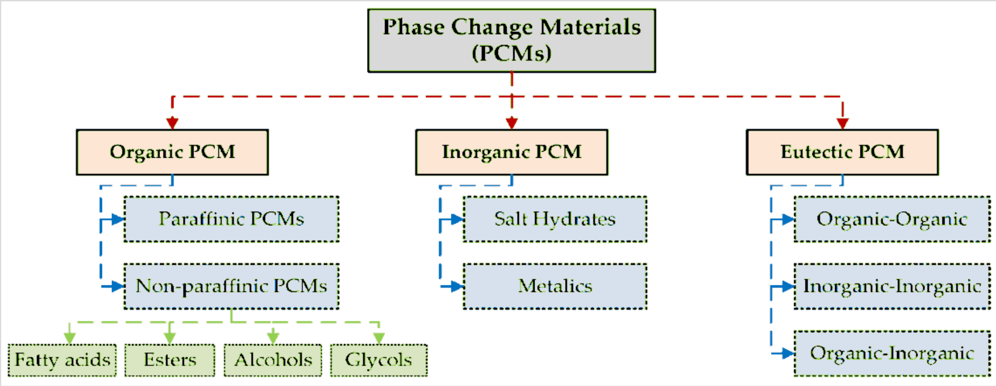


Figure 12: The classification of phase change material [69]

4.1 Thermal energy storage methods

Materials that can absorb heat when heated and release it when cooled are the building blocks of energy storage systems, which seek to convert energy into a form that can be stored and accessed when needed. Sustainable energy storage options include thermal energy storage devices. At this time, three methods for thermal energy storage are under active investigation [70]: Sensible Heat Storage (SHS), Latent Heat Storage (LHS), and Thermo-chemical energy storage.

4.1.1 Sensible heat storage (SHS)

TES systems can store both sensible and latent heat. Energy can be stored by means of Sensible Heat Storage (SHS) devices, which use the material's heat capacity, which increases as its temperature increases. The energy storage capacity of SHS systems is affected by the material's specific heat capacity, material amount, and temperature change gradient [71].

4.1.2 Latent heat storage (LHS)

The principle of latent heat storage (LHS) involves a material's phase transition. Phase change, the transformation of a solid into a liquid, happens at a certain temperature. Until the substance changes from solid to liquid, the temperature will remain constant. In this process, the material is heated until it undergoes a phase transition. The latent heat of vaporization or fusion is the amount of energy that gets trapped inside a substance when it undergoes a phase shift. Phase transition materials release their stored heat in their solid state first when subjected to a rise in temperature. The material takes in a lot of heat during this transformation. Liquid materials are able to store energy effectively when the transition is complete because their temperature rises once more [72].

4.1.3 Thermochemical energy storage

It is the amount of chemical material and endothermic heat of a perfectly reversible chemical reaction that defines the amount of heat storage in thermochemical energy storage systems, which release the stored energy when the bonds between molecules are broken or rebuilt [73]. An important material, paraffin wax could undergo a phase shift and store energy. Their exceptional stability is in stark contrast to the many degradation-free cycles of latent TES operation. This meant that paraffin waxes might be used as PCMs [64]. Paraffin wax has many desirable qualities that make it an ideal material for latent heat thermal energy storage. These include being safe, not interacting with other materials, being compatible with container materials, having a high latent heat, having little to no supper cooling, being chemically stable, and having a range of phase change temperatures [74].

5. Economic and environmental impact

Emissions of toxic gases like carbon dioxide are a direct outcome of the use of fossil fuels to heat water [75,76]. An effective solution to this issue is to install a solar water heating system, which will decrease emissions of carbon dioxide [77,78]. There are no embedded emissions of any kind other than energy and CO_2 in the solar water heating system [79], adhered to the "Cradle to Gate" macro method, which details the carbon dioxide emissions and embodied energy. The energy that goes into making the solar collector is known as its embodied energy, and the amount of carbon dioxide gas that was produced by making each material is called its embodied CO_2 emission. The solar collector's production process consumes the most energy. There will be no need to worry about the amount of energy needed for operations or the release of carbon dioxide because the solar collector is a renewable energy-based technology [80]. Figure 13 shows that the embodied energy of the collector is 2011.45 MJ, and Figure 14 shows that 252.55 kg of CO_2 is emitted during production. When compared to water heating systems that rely on fossil fuels, these values are incredibly low. Michael et al. [81], investigated the solar collector's impact on the environment and the economy. Solar collectors using various nanofluids were cost-effectively compared by Faizal et al., [82]. A comparison to the electric solar water heating system allowed them to determine the payback period as well. About 2.5 to 3 years was the estimated payback time.

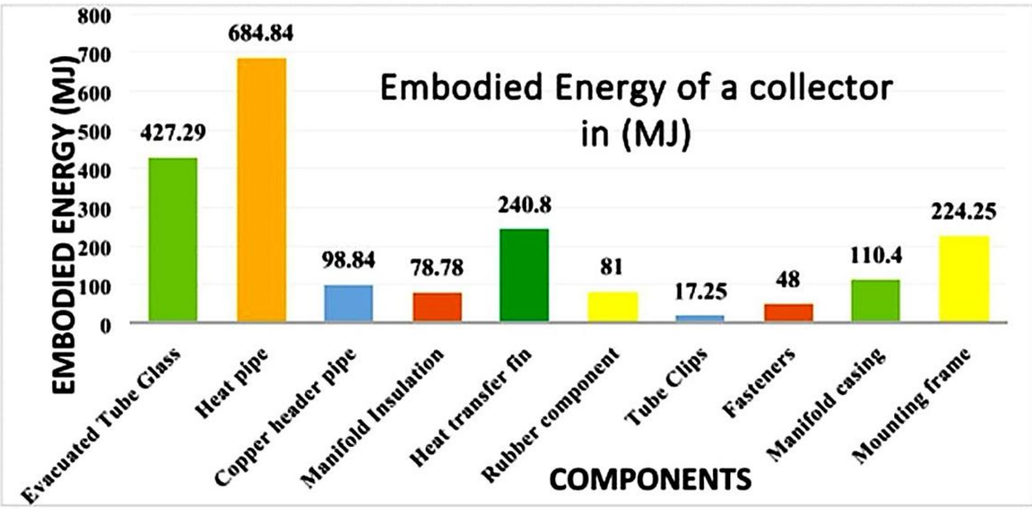


Figure 13: Embodied Energy of the collector [80]

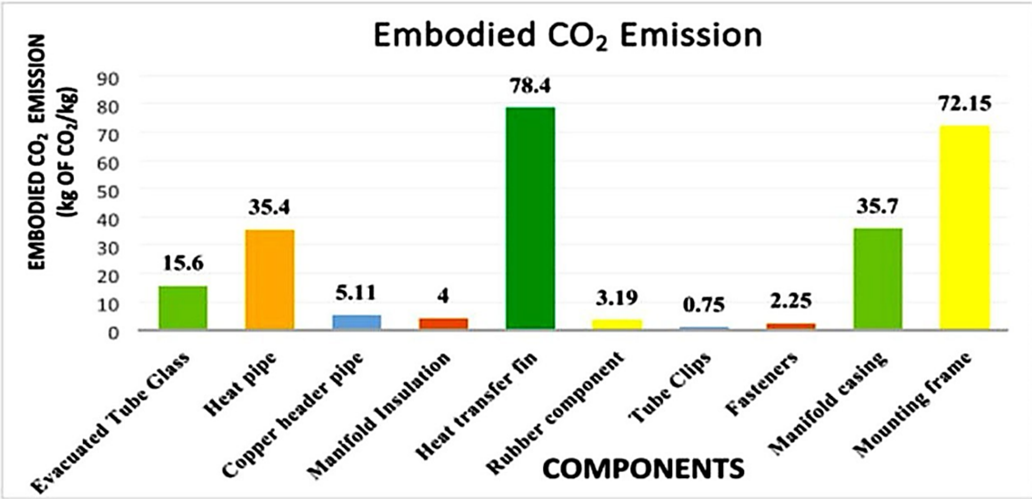


Figure 14: Embodied CO_2 Emission of a solar collector [80]

6. Cogeneration and trigeneration applications of an ETSC

The simultaneous creation of two energy is known as cogeneration. Commonly referred to as "CPH," this process generates both heat and electricity. All the ideas and methods that go into making heat and power are part of it [83]. As a byproduct of generating energy, waste heat enhances the system's efficiency in this process. Trigeneration, also known as combined cooling, heating, and power (CCHP), is the process of going a step further by incorporating the production of cooling energy from waste heat. Using a thermoelectric module and an HP-ETSC, Wei He et al. [30], created a working prototype. They determine the electrical and thermal efficiency within the 25 °C to 55 °C temperature range. Thermal and electrical efficiency are also negatively affected by rising water temperatures, according to the data. Around 20% to 25% of the heat energy became electrical energy at 25 °C. Electric and thermal energy can be produced via a solar thermoelectric cogeneration system (STEC) that Miao et al. [84], created. This system includes an ETSC, a parabolic concentrator, and thermoelectric modules (TEMs). Among their results was an efficiency of 3.87% in converting solar energy into electricity and 69% in converting solar energy into thermal energy. A novel solar cogeneration system, described by Faraji et al. [85], is comprised of eight ETSCs linked in series-parallel and a thermoelectric (ELEGANT-24) apparatus for producing electricity. A DC voltage of 57 V was the highest open-circuit voltage that could be measured. In their experimental study, Zhang et al. [86], focused on solar cogeneration technology. An organic Rankine cycle and solar collectors operating in series and parallel make up the system. According to their research, the efficiency of ETSC is temperature-dependent. In order to produce two powerful thermal and electrical components all at once, Song et al. [87], devised an STEC system. The testing results showed that the thermal efficiency was 57% and the electrical efficiency was 3% when the water temperature was 130 °C and the sun irradiation was 700 W/m^2. A solar trigeneration system with an evacuated tube collector was developed by Marrasso et al., [88]. Office heating, electrical, and cooling needs were the basis for the system's design. Their experimental results show that in heating mode, ETSC achieves an average efficiency of 44.2%, whereas micro-CHP achieves an electrical efficiency of 25.5% and a thermal efficiency of 63.2%. Theoretically, Meng et al. [89], examined a combined heat and power (CHP) system that uses metal hydrides to generate electricity and cool buildings using solar energy and industrial waste heat. Compared to the conventional one, their proposed solar CCHP performed better. In their study, Mohan et al. [90] examined a solar thermal poly-generation system that included an ETSC, absorption chiller, heat exchanger, and membrane distillation unit. This system can be used to meet the cooling, desalination, heating, and electrical needs. A comparative experimental investigation was carried out by Kegel et al. [91], employing various combinations of solar thermal cogeneration and trigeneration integration. We analyzed the system using TRNSYS software. Annual utility costs were reduced by 21%, and greenhouse gas (GHG) emissions were reduced by 16%, according to their analysis.

7. Future work

To enhance the efficiency and performance of evacuated tube solar collectors (ETSCs), various research avenues may be investigated:

1) Optimization of nanofluids: Subsequent research should concentrate on determining the ideal concentration and variety of nanofluids for various operational conditions to improve thermal conductivity and heat transfer efficacy.
2) Integration of Phase Change Materials (PCMs): Further investigation is required to identify optimal PCM compositions and configurations to guarantee dependable heat storage and release during intervals of diminished or absent solar irradiance, such as on overcast days or at night.
3) Resilience and vacuum preservation: Exploring advanced materials and sealing methodologies to augment the long-term vacuum retention of heat pipes and tubes will enhance the durability and dependability of ETSCs.
4) Anti-Scaling and Self-Cleaning coatings: Creating coatings to inhibit scaling and minimize maintenance needs is a crucial focus for future advancement, particularly for systems utilizing hard water.
5) Hybrid systems: Investigating hybrid systems that integrate ETSCs with additional renewable energy sources, such as photovoltaic panels, may yield a more stable and continuous energy supply for residential and industrial applications.
6) Expense Minimization.
   Future research may focus on creating more economical manufacturing techniques and materials to lower the total cost of ETSCs while preserving high efficiency.

8. Conclusion

The evacuated tube collector (ETC) is an advanced method for capturing solar heat for various practical applications, particularly in food processing. ETCs with and without heat pipes are commonly used. Most research has focused on utilizing ETCs in drying processes for fruits and vegetables. This study presents key findings from a detailed analysis of ETC-based systems for air heating and food processing:

1) Effect of altitude angle: The altitude angle of solar beams has minimal impact on the efficiency of the collectors due to the cylindrical shape of the absorber, which allows for better solar energy absorption at different angles.
2) Comparison with flat plate collectors: Evacuated tube collectors outperform flat plate collectors under similar operating conditions. Among ETCs, those with heat pipes show better performance than direct-flow ETCs.
3) Heat pipe ETC for food drying: Heat pipe ETCs have been extensively adopted for various food drying applications due to their higher thermal efficiency and better heat transfer capabilities compared to direct flow ETCs.
4) Temperature and weather dependency: ETSC-based drying systems can achieve high drying temperatures, but their efficiency is highly dependent on local weather conditions and environmental factors such as solar radiation, ambient temperature, and wind speed.
5) Key factors for efficiency: Solar radiation intensity and the mass flow rate of the heat transfer fluid are critical parameters affecting the energy and exergy efficiencies of ETSCs. Adjusting the mass flow rate in response to variations in solar intensity is important to optimize drying performance and ensure high-quality dried products.
6) Enhancements through nanofluids and PCM: The use of nanofluids and phase change materials (PCMs) significantly improves the thermal performance of solar air heaters (SAH) and ETSC dryers. Integrating thermal energy storage systems and auxiliary heat sources allows the drying process to continue even after sunset.
7) Primary applications and performance improvement: ETSCs' primary application has been air heating rather than food drying. However, various design enhancements, such as using different fin geometries, reflectors, metal foam inside the ETC tubes, nanofluids, nano-PCMs, and synthetic oils, have been shown to significantly improve the performance of ETSC-based drying systems and solar air heaters.

Author contributions

Conceptualization, **S. Ali, J. Jalil,** and **A. Shuraiji.**; data curation, **S. Ali.**; formal analysis, **S. Ali.**; investigation, **S. Ali.**; methodology, **S. Ali.**; project administration **J. Jalil.**; resources, **S. Ali.**; software **J. Jalil.**; supervision, **J. Jalil,** and **A. Shuraiji.**; validation, **J. Jalil, A. Shuraiji,** and **S. Ali.**; visualization, **S. Ali.**; writing—original draft preparation, **S. Ali.**; writing—review and editing, **S. Ali**. All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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