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Review

Recent Advancements in Evacuated Tube Solar Water Heaters: A Critical Review of the Integration of Phase Change Materials and Nanofluids with ETCs

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Abstract: Evacuated tube solar water heaters are gaining more attention in the present market scenario as compared to conventional collectors. Such collectors are versatile because no solar tracking is required and the operating temperature range is also broad. Comparatively, it is cost-effective and may attain higher thermal efficiency. However, like other collectors, continuous energy supply is sometimes hampered by the intermittent nature of solar radiation. This problem can be partially resolved by using phase change materials (PCM) in the evacuated tube solar collector (ETC). PCMs can store the energy during the sunshine hours, which can be released when solar energy is not available. In the literature, several studies are available pertaining to the use of PCMs in ETC-based solar water heaters. The literature indicates that the integration of PCMs with ETCs has several merits. Nevertheless, systematic, and comprehensive review papers dedicated to such integrated energy storage systems with ETC solar water heaters are not available. Hence, the objective of this work is to compile the relevant experimental, numerical, and theoretical works reported in the literature. The present paper broadly reviews the recent design modifications, PCM integration with different kinds of ETC water heaters, and their life cycle assessment. Furthermore, studies in the literature pertaining to the application of nanoparticles in ETC systems are also discussed, and finally, a roadmap for this energy storage system is provided.

Keywords: evacuated tube collector; PCM; nanofluid; solar radiation; energy storage

1. Introduction

There is a significant transition of the net zero emission from the production of energy to its consumption as represented in Figure 1. It is estimated that the world GDP will approximately increase by 40% between 2020 and 2030 but supplied energy may decrease by 7%. Moreover, low-emission energy sources will grow up to 66.66% between 2020 and 2030. In the current scenario, merely one-fourth of the total supplied energy is from low-emission energy sources; however, it will increase to one-half by 2030. Primarily, solar, wind, modern bioenergy, and other renewable energy resources will dominate in achieving the net zero emission target [1].

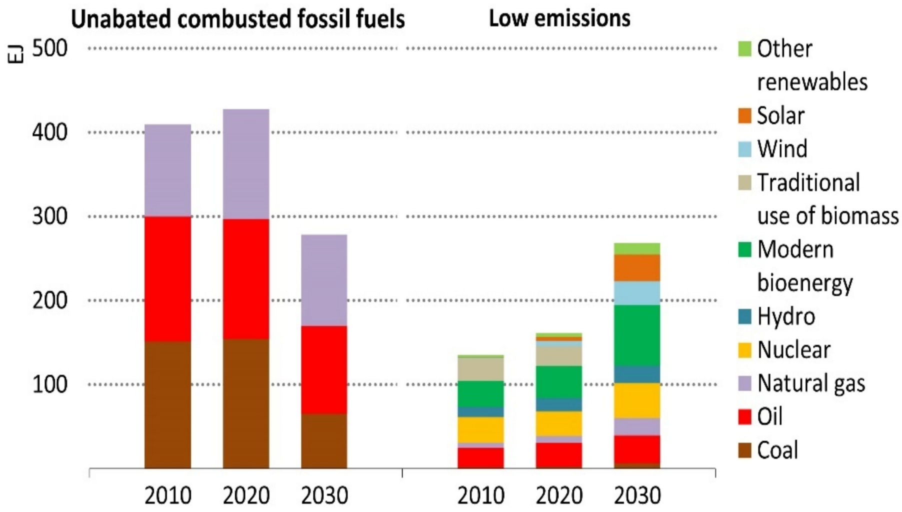


Figure 1. Transition in global total supplied energy by different sources (Energy and Iea, 2021 [1]).

Hence, in order to minimize the emissions and meet the increasing energy demands, a paradigm shift is required to utilize renewable energy efficiently and effectively without damaging the environment. It is well known that the Sun is the most inexhaustible source of energy, and solar energy has many applications, i.e., space heating and cooling, electricity generation, water heating, crop drying, desalination, etc. Out of these applications, solar water heating is one of the most environmentally friendly methods to utilize solar energy. Over time, there have been consistent efforts to develop and improve solar water heating technologies. Currently, several types of solar water heaters are utilized; nevertheless, their domestic use is still very limited. This may be due to their uncompact design, intermittent energy supply, and higher initial cost. Therefore, researchers in this field are trying hard to overcome these issues. Moreover, it is understood that hot water demand is continuously increasing for industrial as well as domestic applications. The Ministry of New and Renewable Energy (MNRE) in the Government of India reported that in the residential sector, the demand for hot water was about 129 million/day in 2017; however, it would be doubled by 2022.

It is worth mentioning that there are basically two types of solar water heaters that collect solar energy and convert it into a useful form of heat energy.

(a) Flat plate solar water heater
(b) Evacuated tube solar water heater

Flat plate solar water heaters are simple in construction, having less initial cost with low maintenance, but it has some demerits such as poor thermal performance and large amounts of heat loss, whereas ETCs overcome nearly all such drawbacks of flat plate collectors by simply changing their structure. An evacuated tube collector consists of two annular tubes in which there is a vacuum in between the annular space of the tubes. Due to its tube-like structure, it considerably minimizes heat loss; additionally, it does not require any tracking management. As shown in Figure 2, it has been predicted that ETCs cover a 68.8% market share, followed by 24.7% for flat plate collectors, and unglazed water collectors, which cover 6.3%.

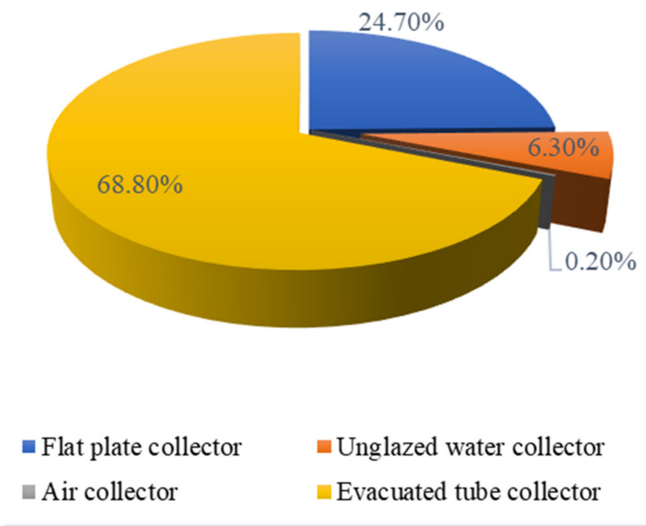


Figure 2. Distribution of the total installed capacity in operation by collector type in 2019—WORLD [1]).

1.1. Classification of ETC

Eberlein was the first to study the heat transfer phenomenon inside the evacuated tube collector (ETCs). He has developed a mathematical model in order to investigate the performance of ETCs using air as a working medium. The author noted that the heat loss was significantly less due to the annular shape of the ETC. Subsequently, enormous amounts of work have been carried out to further improve the performance of ETCs. Based on different designs and geometrical construction, ETCs are commonly classified as follows [2,3]:

i Water in glass tube-based collector
ii U-Tube-based solar collector
iii Heat pipe-based solar collector

1.1.1. Water in Glass Tube-Based Collector

It consists of a set of glass tubes that are connected to a water storage tank as shown in Figure 3. Each tube is concentric with another tube with a larger diameter. The vacuum is generated in the annular space in order to minimize the conduction and convection losses. The water flows from the storage tank to the glass tubes by the virtue of gravity. Glass tubes collect solar radiation and convert it into heat, which is transferred to the water. When water is heated up, its density decreases; hence, it moves in an upward direction in accordance with the thermosiphon principle. These tubes are usually simple in design and cheaper. It should be noted that the working pressure inside the ETCs is less; hence, a moderate temperature rise is achieved in such heaters. Moreover, the evacuated tubes are continuously in contact with hot- and cold-water streams, which may be responsible for the cracking of the tubes. These tubes are accompanied by such drawbacks and cannot perform well against the local demand of hot water consumption, i.e., taking more time to heat up the water, which leads to a slow response to hot water demand.

1.1.2. U-Tube-Based Solar Collector

This type of solar collector consists of similar evacuated glass tubes, and additionally, a U-shaped copper tube is inserted inside the hollow space available in the glass tube as shown in Figure 4. In this configuration, water flows through the copper tube and does not take heat directly from the evacuated tubes. In order to increase the heat transfer rate, sometimes extended surfaces, i.e., fins, may be used as an integral part of the U-tube. The efficiency of U-tube-type solar water heaters mainly depends on the contact between the extended surfaces and the absorber surfaces.

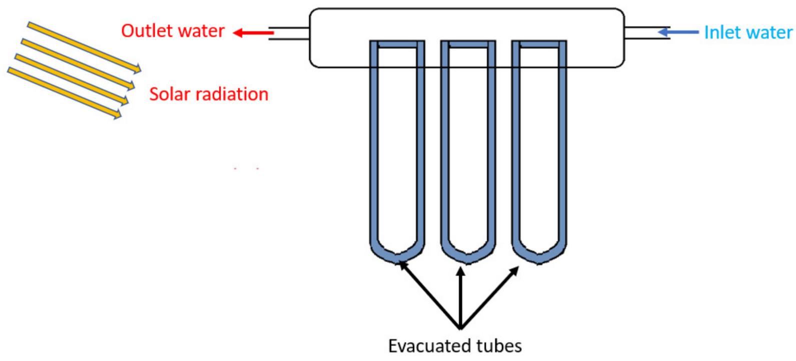


Figure 3. Schematic diagram of an all-glass evacuated tube solar water heater.

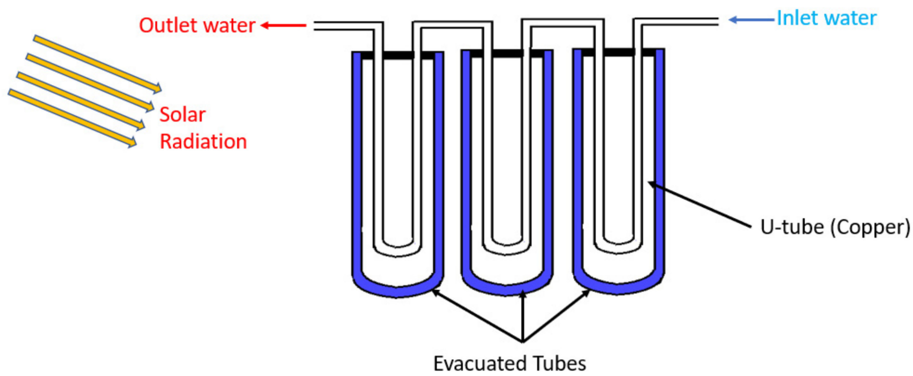


Figure 4. U-tube-type evacuated tube solar water heater.

These systems are particularly designed for high-pressure and temperature-based applications. Their anti-freezing, easy installation, and quick start-up characteristics make these tubes more attractive to heat pipe-based ETC water heaters. The inclusion of some additional components makes this configuration slightly cumbersome and costly as compared to the water in glass tube-based collectors.

1.1.3. Heat Pipe-Based Solar Collector

In conventional solar water heaters, tubes are used to carry the working fluid, i.e., water. The tubes are generally attached to the absorber plate, and the heat transfer mechanism is operated by means of natural or forced convection. Such systems need more space for natural circulation; moreover, high initial and operating costs are needed as a pump is required for the forced circulation system. Scaling and corrosion problems also occur as the tubes are in direct contact with water. Sometimes, it has been observed that a reverse flow of water happens at night, which may cause a decrease in the temperature of the stored water.

To overcome these problems, heat pipe-based solar collectors have evolved. A heat pipe-based solar water heater consists of sets of tubes attached to a tank as shown in Figure 5. Each tube contains a heat pipe, which is generally composed of copper. The heat pipe is surrounded by a glass tube, and the annular space is evacuated. It is worth mentioning that the heat pipe is a cylindrical-shaped tube which consists of a capillary wick and heat transfer fluid with a low melting point, usually alcohol fluid. It has three main regions (i) a working fluid section (ii) an evaporative section (iii) a condenser section. It works on an evaporating–condensing cycle. The working fluid takes the heat from the solar radiation and evaporates. It releases the heat from the condenser section to a heat sink located at the top of the tube. Hence, the heat transfer fluid flows by natural circulation between the two phases in order to transfer the heat as needed.

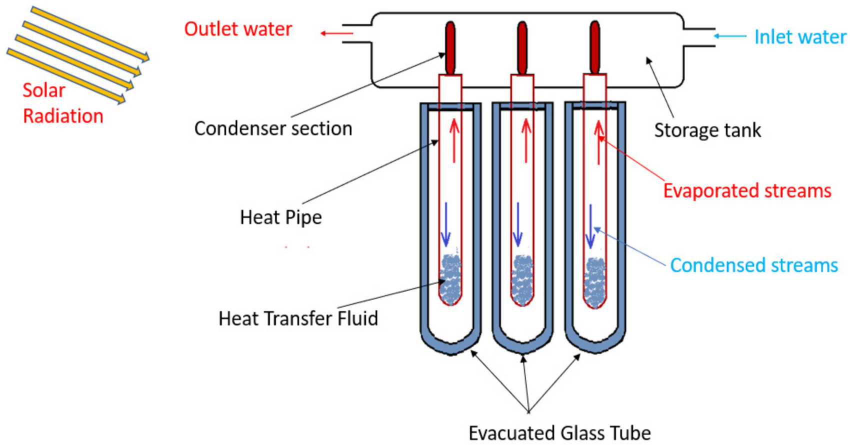


Figure 5. Schematic diagram of a heat pipe-based evacuated tube solar water heater.

The main problem associated with heat pipe-based solar water heaters is maintaining the vacuum environment. Thermal efficiency and operating life are mainly affected by these factors. These collectors also suffer overheating during operation, which may lead to unwanted rises in temperature and the cracking of the evacuated tubes.

This review article mainly covers the literature pertaining to the design modification of ETCs and the integration of phase change materials (PCM) and nanoparticle-enhanced PCMs, used in each type of evacuated tube collector. Furthermore, some other important innovations along with an economic and life cycle assessment of ETCs are included. The relevant directions required to carry forward future work in this field are presented.

2. Advancements in Water in Glass Tube-Based Collector

Various investigations have been undertaken in order to improve the overall thermal performance of all water in glass tube solar water heaters. Researchers have used different methods including an analytical approach, mathematical tools, and numerical simulations to find the various possible ways to enhance the performance of this configuration under numerous conditions. It has been commonly found that the overall efficiency lies in the range of 50 to 60%

2.1. Design Modifications

Glass tube-based collectors are the most widely used solar collectors due to their low initial cost, simple construction, easy installation, and high thermal efficiency. This leads to the wide appreciation of this collector in the market. However, researchers are consistently working to further enhance the performance and thermal efficiency of this configuration. Morrison [4] developed a heat extraction method and numerical model for all glass tube water heaters as shown in Figure 6. During the study, it was found that there was a stagnant region in the bottom of the glass tube which may influence its operation. Morrison [5] has numerically investigated the characteristics of water and the nature of the circulation of the flowing streams inside the hollow glass tube. During the study, it was found that there was a high impact of natural circulation currents on the temperature stratification of the storage tank, and this circulation rate is maximally influenced by solar radiation and the temperature of the storage tank.

Tang et al. [6] provided an assessment of the uncertainty of the mean overall heat transfer coefficient. The outcomes depict that inappropriate test procedures and measuring errors in temperature are the main factors for the uncertainty in the measurement of the overall heat loss coefficient. Budihardjo et al. [7] have experimentally and numerically developed the correlation for the natural circulation of the water inside the single-ended evacuated tubes. The numerical results showed the significant impact of circumferential heat flux distribution on the circulation. That is why the correlation could be used to predict the circulation flow rate at any time within a day. Shah et al. [8] investigated the flow patterns and heat transfer phenomenon in different lengths of ETC tubes using a propylene glycol-based water mixture. The highest efficiency was achieved for the shortest tube with an optimal flow rate of around 0.4–1 kg/min. Jaisanker et al. [9] investigated the effect of twist tape with rods and spacers on the performance of evacuated tube solar water heaters. They revealed that the Nusselt number (Nu) decreased by 11% and 19% for twist tape fitted with rods and spacers, respectively, as compared to a full-length twist. Tang et al. [10] developed the mathematical model in order to predict the collectible radiation on a single tube of the evacuated solar water heater and compared the performance of T-shaped collectors and H-shaped-type solar collectors. In the study, it was found that T-shaped solar collectors absorb more solar radiation as compared to H-shaped, and there is a significant impact of diffuse flat reflectors on the performance of T-shaped collectors, while they have a negligible effect on H-shaped solar collectors, as shown in Figure 7.

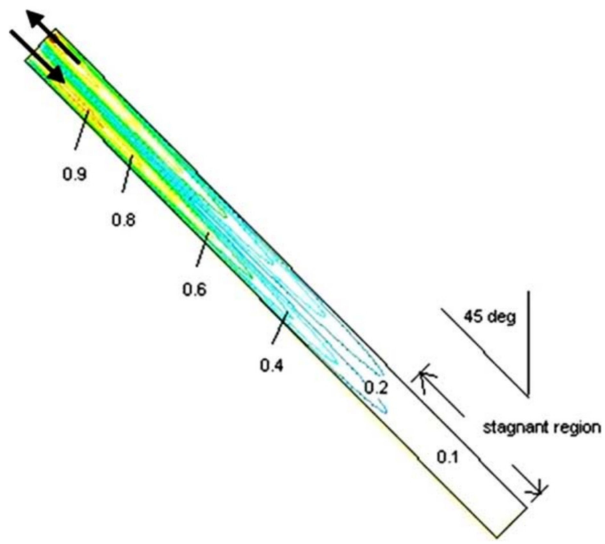


Figure 6. Velocity distribution in a single-ended tube and the presence of a stagnation region (Morrison et al., 2004).

(**a**) (**b**)

Figure 7. (**a**) H-shaped collectors (**b**) T-shaped collectors (Tang et al., 2009).

Budihardjo et al. [11] compared the performance of evacuated tube solar water heaters and flat plate solar water heaters experimentally as well as numerically. It was found that the flat plate solar water heater exhibited 8.6% more annual energy savings as compared to the evacuated solar water heater. Further, they noted that the amendments performed only to improve the collector performance could not be sufficient to overcome the increased heat loss from the bigger tank. Using a "hierarchical porous", "flexible-black TiO2/Carbon-Cloth (b-TiO2/CC)" as a "multifunctional air cathode", Ren et al. [12] have demonstrated a "photo-electric-thermal synergy (PETS)"-triggered "PSS Li-O2 battery" operating at "room temperatures". Chow et al. [13] performed a comparative study between single-phase open and two-phase closed thermosyphon systems. They revealed that two-phase ETC systems have more thermal efficiency as compared to single-phase ETCs, and the payback periods of both systems are nearly the same. Tang et al. [14] performed a comparative analysis of the thermal performance of evacuated tube solar water heaters under different collector tilt angles. In the experimental findings, it was observed that there is a negligible impact of the collector tilt angle on the heat removal, but both systems have different heat and solar gain. There is an insignificant impact of climatic conditions on daily thermal efficiency because small amounts of heat are lost from the collector to the surroundings. Chow et al. [15] suggested selecting the single-phase or two-phase evacuated tube collector under different climatic conditions. It was found that single-phase systems are more economical and have a shorter payback period as compared to two-phase systems, whereas two-phase systems were more efficient with a higher degree of adaptability to the climate. Tang et al. [16] performed an experimental investigation on the performance of the ETC water heater during nighttime. They reported reverse flow patterns inside the tubes at night, and this phenomenon has very little contribution to the total heat loss. Yao et al. [17] studied the effect of twisted inserts on the thermal performance of an evacuated tube solar water heater, as shown in Figure 8. It was observed that the twisted tape helps in maintaining temperature uniformity by reducing velocity magnitude. In addition, the Nu of the modified solar water heater was increased by 9.29% as compared to the conventional one. Bracamonte et al. [18] investigated the effect of tilt angle and thermal stratification on the performance of ETC water heaters. It was reported that a 10° tilt angle is crucial to having significantly high temperatures with some thermally inactive regions. Alfaro et al. [19] used two numerical techniques, namely, Boussinesq approximation (BA) and the variation of the properties with temperature (VPT). During their study, they found that the BA method is much closer to the experimental results of the low-temperature evacuated solar water heater.

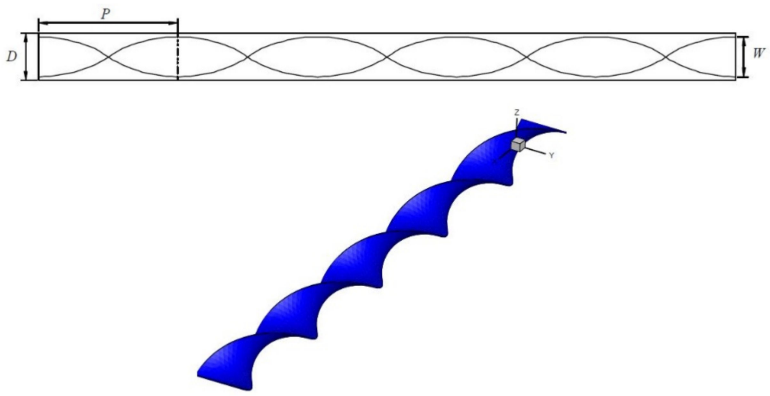


Figure 8. Twist tape inserts of solar water heaters (Yao et al., 2015).

Essa et al. [20] studied the temperature distribution and streamline variation inside the evacuated tubes by experimental and numerical methods. It was concluded that the flow structure inside the tubes is affected by the solar radiation intensity and incidence angle. There were two types of flow patterns formed inside the tube, out of which, one was linear in profile, whereas the second profile was helical in shape, which is generally observed during noontime. Gong et al. [21] performed a comparative study on straight-through glass solar water heaters and Dewar-type solar water heaters, particularly applicable for low- and medium-temperature range applications. The results revealed that the Nu of the straight-through glass tube was four times more than that of the Dewar tube water heater. It was due to the turbulent flow inside the straight-through tube, which leads to a high convective heat transfer coefficient and lower heat losses. Jowzi et al. [22] developed a modified evacuated tube solar collector in which a bypass tube at the bottom of the evacuated collector was introduced in order to remove the stagnant region, as shown in Figure 9. The results show that there is more uniformity in the temperature distribution inside the tube as well as in the tank with an enhancement of 11% efficiency. It was also found that the average water temperature inside the tank increased by 1.5 °C as compared to the conventional evacuated solar water heater operating under the same conditions. Li et al. [23] carried out experimental and numerical studies on double-row all-glass ETCs. The outcomes revealed that the declination angle had a noteworthy impact on the efficiency of the ETCs. It was also observed that more heat was stored with increases in the declination angle. Sadeghi et al. [24] used a gene expression technique in order to predict the performance of ETCs. It was revealed that the efficiency of the ETC system stays around 72%.

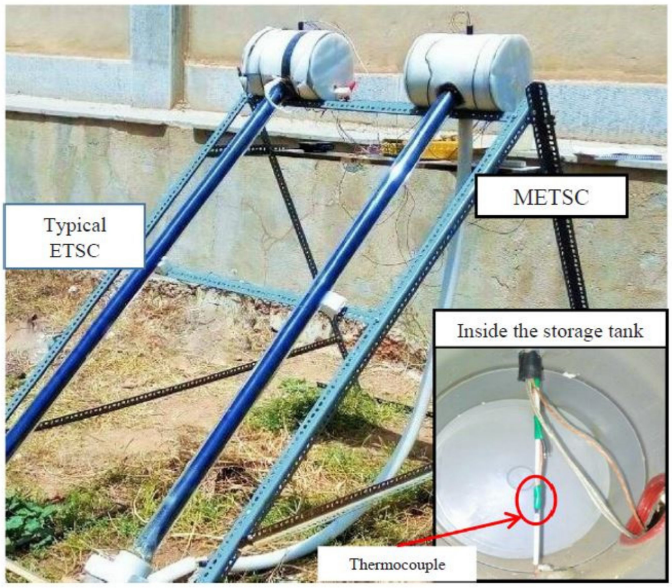


Figure 9. Comparative study of typical ETSC and modified ETS [22].

2.2. PCM Integration with ETC Systems

Solar collectors are the most effective equipment to obtain heat from solar energy. However, there are some problems associated with them, i.e., the intermittent nature of solar radiation, the uneven demand for domestic water, and fluctuating energy demands over the year. These problems can be solved up to a certain level with the help of energy storage materials. In the recent past, research in the domain of heat storage materials has generally dealt with sensible and latent heat storage materials. Time delays between energy demand in off-sunshine hours and the availability of energy have huge gaps. In order to fulfill the continuous energy demands, excess energy can be stored during the peak hours of sunshine and the same can be used at nighttime or during off-sunshine periods. Many researchers have used energy storage materials in their investigations; the most commonly used materials are latent heat storage materials due to their capacity for storing large amount of heat energy. Latent heat storage materials can be placed either inside the water storage tank or in a separate container.

Kumar et al. [25] investigated the performance of evacuated solar water integrated with a phase-change material (Paraffin wax). The PCM storage was mounted inside the water tank. In order to increase the energy storage capacity of the Paraffin wax, a nanocomposite PCM was introduced in which small amounts of silica nanoparticles were added at 0.1% of the mass. The results revealed that the energy efficiency of the evacuated solar water was 58.74% without PCMs, 69.62% with PCMs, and 74.79% with the nanocomposite PCM. The authors pointed out that by introducing the silica nanoparticle, the thermal conductivity of the Paraffin wax was increased by 22.78%.

2.3. Nano-Fluid as Working Medium

It has been observed that the efficiency of ETC-type solar collectors significantly depends on the heat extraction capacity of the working fluid. Hence, to improve the heat extraction characteristics of the working fluid, its thermal conductivity needs to be increased. Nanoparticles are one of the key substances that hold higher thermal conductivity. Therefore, adding the nanoparticles to the base fluid increases the overall thermal conductivity of the working fluid. Moreover, it also increases the specific area as well as the Brownian motion, which further supports increasing the thermal properties of the working fluid. Therefore, nanoparticles are added to the base fluid to achieve the desirable properties. Some authors have investigated the influence of adding nanoparticles on the performance of ETC-based solar water heaters. Sabiha et al. [26] investigated the impact of a water-based single-walled carbon nanotube nanofluid on the thermal performance of an ETC solar water heater. The experimental outcomes showed an immense increase in the thermal efficiency of the heater. Moreover, the maximum outlet temperature was obtained at the mass flow rate of 0.008 kg/s at a 0.2% volume of nanofluid. Ghaderian et al. [27] studied the effect of nanofluid (copper oxide as a nanoparticle with distilled water as a base fluid) on the efficiency of ETCs with an internal coil. The volume fraction of nanoparticles varied from 0.03–0.06%. It was observed that the efficiency of ETCs increased remarkably when nanofluid was taken as the working medium. There was a 14% increase in the average outlet temperature when the volume fraction varied from 0.03% to 0.06%. Ghaderian et al. [28] investigated the influence of an Al_2O_3/water nanofluid on the thermal performance of an ETC water heater with Triton X-100 as a surfactant. The outcomes revealed that the maximum efficiency was obtained as 57.63% for the flow rate of 60 L per h at a 0.06% volume of nanofluid. Mahbubul et al. [29] performed an experimental investigation for the enhancement of the thermal efficiency of an ETC water heater by using a single-walled carbon nanotube nanofluid (an integral part of the absorption cooling system). The results indicated that the efficiency was found to be 56.7% and 66%, respectively, when the systems were operated with pure water and a 0.2% volume of nanofluid. Manirathnam et al. [30] performed a study on improving the capacity of energy storage systems in ETC water heaters using nanocomposite phase change materials. In their study, 1 mass% of both Si and CuO was used in paraffin wax. It was revealed that the energy efficiency of the systems, i.e., without PCMs, with PCMs, and with a nanocomposite PCM were 33.8%, 38.3%, and 41.7%, respectively. Saxena et al. [31] used CuO nanoparticles in a base fluid of demineralized water integrated with a separate heat exchanger to investigate the thermal performance of an ETC water heater. It was observed that the maximum energy efficiency and maximum exergy efficiency were 45.12% and 9.51% using CuO as a nanoparticle in the demineralized water. Recently, Lopez et al. [32] analyzed the thermal performance of the ETC using a water-based nanofluid. The results showed that there were maximum reductions in the entropy generation rate of 87.5%, 65.5%, and 14.71% due to viscous effects, heat transfer, and heat loss by using nanofluid as the working medium. The collective and summarized information of ETCs, PCMs, and nanofiller-based all-glass tube collectors is tabulated in Table 1.

Table 1. Summary of selected investigations on all glass tube ETC-PCM/nanofluid-based systems.

S.N.	Author	Year	Experimental (E)/ Numerical (N)	Key Features	Outcome
1.	Yao et al. [17]	2015	E	Twisted inserts	There is a 9.29% increase in the Nusselt number of the modified ETC as compared with the conventional one.
2.	Essa et al. [20]	2017	E and N	Temperature and streamlined patterns	Solar radiation intensity and incidence angle have a great impact on the flow structure developed inside the tube.

Table 1. *Cont.*

S.N.	Author	Year	Experimental (E)/ Numerical (N)	Key Features	Outcome
3.	Ghardian et al. [27]	2017	E	Al_2O_3 as a nanofluid and Triton X-100 as a surfactant	The results revealed that the maximum efficiency was obtained as 57.63% for the flow rate of 60 L per h at 0.06% nanofluid by volume.
4.	Kumar et al. [25]	2018	E	Paraffin wax as a PCM and silica as a nanoparticle	The energy efficiency of ETCs is improved up to 74.79% with a nanocomposite and 69.63% with a PCM.
5.	Jowzi et al. [22]	2019	E	Bypass tube	More uniformity in temperature distribution has been observed by introducing the bypass tube, and the efficiency is increased by 11%.
6.	Gong et al. [21]	2020	E	Dewar-type collector	Nusselt number of the straight-through glass tube collector was four times higher than the Dewar tube collector.
7.	Li et al. [23]	2020	E and N	Double-row all-glass ETC	The declination angle has a great impact on the efficiency of ETCs, and a high amount of heat was stored with increases in the declination angle.
8.	Maniratanam et al. [30]	2020	E	Cu- and Si-based nanocomposite.	The energy efficiency of the systems, i.e., without PCMs, with PCMs, and with a nanocomposite PCM was 33.8%, 38.3%, and 41.7%, respectively.
9.	Du et al. [33]	2021	N	Different artificial neural network	For accurate prediction, the convolutional neural network model proved to be the best ANN model.
10.	Lopez et al. [32]	2022	E	CuO used as a nanoparticle	There are maximum reductions in the entropy generation rate of 87.5%, 65.5%, and 14.71% due to viscous effects, heat transfer, and heat loss by using nanofluid as the working fluid.

3. Advancements in U-Tube-Based ETC Collectors

3.1. Design Modifications

U-tube-type solar water heaters are suitable for high-pressure and temperature applications. It also has a simple structure as compared to the all-glass tube and heat-pipe evacuated tubes. Zhang et al. [34] used supercritical CO_2 as a working fluid in a U-tube-type solar collector. The results showed the significant impact of solar radiation on the CO_2 temperature and pressure. The daily time-weighted average collector efficiency was found to be more than 50%, and the annual collector efficiency was found to be nearly 60%, which was higher than those conventional collectors using water as a working fluid. Ma et al. [35] analytically studied the thermal performance of the U-tube type solar water heater using an energy balance equation to evaluate the heat loss coefficient and heat efficiency factor. They found a nonlinear agreement between the heat loss coefficient of an evacuated tube solar collector with a temperature gradient between the absorbing coating surface and the surrounding air. The heater efficiency factor is mainly affected by an ambient air layer between the absorber tube and the copper fins. If the synthetic conductance is increased from 5–40 W/m K, then the solar collector's efficiency and outlet fluid temperature are also increased by 10% and 16%, respectively. Liang et al. [36] proposed a filled-type U-tube-based evacuated solar collector. The authors used a highly conductive material, i.e., compressed graphite, as a filler material between the U-tube and the inner glass tube. During his study, a 12% increment was found in the thermal performance of the filled-type evacuated tube as compared to the copper fin-type evacuated tubes at a thermal conductivity of 100 $Wm^{-1}K^{-1}$. Liang et al. [37] presented a novel design of an ETC water heater in which a double U-tube was used inside the evacuated tube in order to eliminate the effects of thermal resistance between the absorber plate and the fins. The thermal efficiency was obtained to be 80% at a solar intensity of 900 W/m^2. Liang et al. [38] performed a study on a universal model of a filled-type evacuated tube collector as shown in Figure 10. The thermal performance of three different types of evacuated tube collectors was examined, in which a single U-tube was placed inside the first sample of the evacuated tube, while another two samples consist of two and three U-tubes, respectively. All the configurations were tested under the same operating conditions, as represented in Figure 11. The results revealed that an evacuated tube solar collector with three U-tubes exhibited a maximum efficiency of 82%.

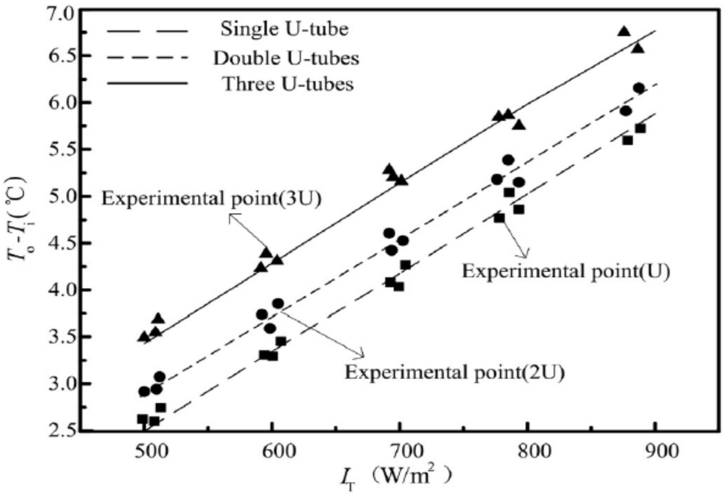
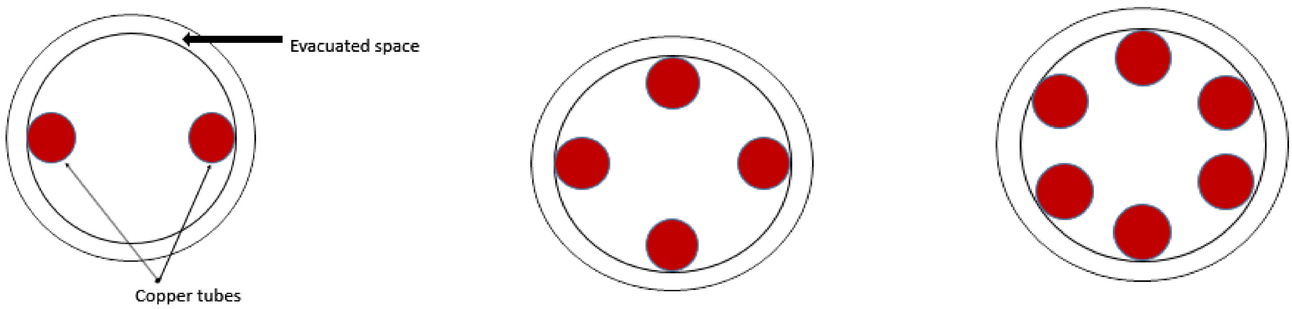


Figure 10. Variation of the temperature difference between outlet and inlet with the inclined solar irradiance [38].



(**a**) (**b**) (**c**)

Figure 11. Different configurations of U-tube-type solar collectors [38]. (**a**) Single U-tube. (**b**) Double U-tube. (**c**) Three U-tubes.

Gao et al. [39] carried out a parametric analysis of U-tube-type ETCs using mathematical modeling methods. The results deliberated that the thermal efficiency of the collector was not increased by increasing its length. It was suggested to use a low heat-loss coefficient-based solar collector in cold regions. Pandey et al. [40] investigated the thermal performance of U-tube-based ETCs using exergetic analysis. It was observed that U-tube-based ETC systems showed maximum and minimum efficiencies, respectively, at 15 L per h and 30 L per h of working fluid. In addition, the energy efficiency was found to be 66.57%, and the exergetic efficiency was found to be 13.38% at a mass flow rate of 15 LPH. Cui et al. [41] carried out mathematical modeling and performance analysis of a U-tube-type solar collector using different working mediums (water, air, and LiCl–H_2O). The results revealed that to increase the outlet temperature, a low mass flow rate of the coolant and an optimized collector length should be selected. Moreover, a significant impact of changing the ambient temperature on the net heat gain of the solar collector was found on days when the solar intensity was high. It was concluded that water exhibits the maximum amount of heat absorption capacity as compared to the other fluids used in this study. Nie et al. [42] investigated the thermal performance of a U-tube-type evacuated solar collector in which the working fluid was operating at a lower temperature than the ambient temperature. It was observed that the thermal efficiency improved with a decrease in temperature, whereas the thermal efficiency was higher at low solar irradiance. Korres et al. [43] examined the optical and thermal performance of mini-compound parabolic collector U-tube-type evacuated solar heaters. The authors reported that by changing the longitudinal incidence, the angle collector efficiency was not much affected, whereas the transverse incidence angle improved the optical efficiency. Naik et al. [44] performed experimental and numerical investigations on the performance of a U-tube-type evacuated solar water heater. The results showed that the solar intensity, mass flow rate, and inlet temperature of the working fluid had a significant effect on the useful heat absorbed by the working fluid moving inside the U-tube. The average overall efficiency was observed at around 51%. The average predicted energy efficiency was found to be 43%, and the exergy efficiency was 41% for humid subtropical conditions. Korres et al. [45] performed an analysis on an array of four U-tube-type evacuated solar collectors integrated with mini-compound parabolic collectors operating in the range of −80 °C to 35 °C. The results depict that the thermal efficiency decreased from the first module to the last module because of the higher heat losses due to the higher inlet temperature. Bhowmik et al. [46] developed a multi-layer perception approach in order to predict the performance of U-tube-based ETCs. The maximum efficiency was found to be 75% at a mass flow rate of 0.08 kg/s. Uniyal et al. [47] have also investigated the thermal performance of the U-tube-based ETC experimentally. The results revealed that the highest outlet temperature, i.e., 29.97 °C, of the water is achieved at a mass flow rate of 700 mL/min.

3.2. PCM Integration with the ETC System

It is worth mentioning that solar water heating systems with additional components like energy storage materials require a larger space; hence, they possess more weight. This problem becomes more severe when this system is applied to household applications. To overcome this problem, U-tube-type evacuated solar water heaters integrated with phase change materials (PCM) were introduced. In this system, energy storage materials are kept in the evacuated tube itself, resulting in reductions in the space requirements, overall weight, and cost of the system. As the thermal conductivity of the PCM is less, researchers have examined different methods, such as the inclusion of fins, ribs, and plates along with PCMs. Abokersh et al. [48] studied PCM-filled U-tube-type evacuated solar collectors. Paraffin wax was used as the PCM. In order to enhance the thermal conductivity of the paraffin wax, extended surfaces or fins were incorporated. During the experimental study, it was found that the U-tube solar collector filled with PCMs and mounted with fins depicts a better thermal performance as compared to unfinned PCMs and forced recirculation conventional solar collectors. By using a regression analysis tool, the forecasted average annual efficiency of unfinned and finned U-tube solar collectors and forced circulation solar water heaters was found to be 71.8%, 85.7%, and 40.5%, respectively. Further, Abokersh et al. [49] studied the performance of a U-tube-type ETC water heater integrated with a PCM (paraffin wax) and fins. It was observed that natural convection was the main factor for a better heat transfer phenomenon for the charging process. Essa et al. [50] investigated the effects of the charging and discharging processes of the PCM (paraffin wax) on the performance of ETC-based water heaters. It was found that the maximum efficiency of the collector could be achieved at a low mass flow rate of the working fluid and on the completion of the phase change process. There was a 21.9% increase in the efficiency of the PCM-based ETCs as compared to the conventional ETC at the flow rate of

0.25 L per minute. Xue [51] investigated the performance of a U-tube-based domestic solar water heater integrated with a phase change material, i.e., $Ba(OH)_{2.}$ $8H_2O$. The authors concluded that with an increase in the solar radiation or inlet water temperature, there was a decrement in the performance of the solar water heater system. However, the performance of the PCM-integrated system was inferior to the conventional one. Recently, Olfian et al. [52] used a corrugated spiral U-tube with paraffin wax in the ETC and reported that the corrugated tube increased the collector efficiency by 21.55% as compared to a smooth tube. Lim et al. [53] performed a CFD-based simulation of U-tube ETCs using different heat transfer fluids. The results concluded that there is an enhancement in the fin temperature by 45% in the PCM-based U-tube-based ETC compared to the conventional one. Feng et al. [54] studied the performance of ETC-PCMs by varying the properties of the PCM. It has been observed that the mass flow rate of HTF and the mass fraction of the nanoparticle of the MWCNT may increase the thermal performance of the ETC-PCM system. Olfian et al. [55] studied the impact of the diameter of the copper tube on the thermal performance of a U-tube evacuated tube collector. The results revealed that the optimal diameter of the copper tube is 6 mm, for which the thermal energy process is improved by 20%.

3.3. Nano Fluid Used

Tong et al. [56] performed experimental and analytical studies on the performance of U-tube-based ETCs using a multiwall carbon nanotube nanofluid. The results revealed that the heat transfer coefficient was increased by 8% when 0.24% nanofluid by volume was used as a working fluid. In addition to this, the collector efficiency was increased by 4% when water was filled in between the fins and the absorber surface. Kim et al. [57] theoretically investigated the performance of U-tube-based ETCs using different nanofluids. The authors used 20% propylene glycol-water as a working fluid. Different types of nanofluids such as multiwall carbon nanotubes, Al_2O_3, CuO, SiO_2, and TiO_2 were also used with the working fluid. It was observed that multiwall carbon nanotubes showed the maximum impact on the collector efficiency, whereas the least impact on the collector efficiency was observed in the case of SiO_2. There were reductions in CO_2 and SO_2 by 103.8–345.3 kg per year and 0.4–1.1 kg per year, respectively, when propylene glycol-based water was used as a working fluid. Kaya et al. [58] used ethylene glycol–pure water as a working fluid in a U-tube-type evacuated tube water heater and ZnO as a nanoparticle in it. It was found that the maximum collector efficiency was 62.87% at a 3% volume concentration and a 0.045 kg/s mass flow rate. Xie et al. [59] performed a study on a tankless solar water heater using stearic acid and a coconut shell charcoal-based phase change composite material. The results revealed that the thermal conductivity of the composite PCM was 2.88 times higher than pure stearic acid hence, it shows higher heat transfer rate than pure stearic acid. Algarni et al. [60] used a copper-paraffin-based composite PCM to improve the performance of the water heater. It has been observed that composite PCM-based ETC systems can provide hot water at 50 °C for 2 h longer than normal ETC systems. Collective and summarized information on PCM- and nanofiller-based U-tube evacuated tube collectors is tabulated in Table 2.

Table 2. Selected literature pertaining to U-tube ETC-PCM/nanofluid-based systems.

S.N.	Author	Year	E/N	Key Features	Outcome
1	Naik et al. [41]	2015	N	Different working mediums	Optimized selected length and low mass flow rate of the fluid favors in increasing the outlet temperature of the fluid.
2.	H. Shen Xue [51]	2016	E	$Ba(OH)_2{\cdot}8H_2O$ as a PCM and $BaCO_3$ used as a nucleant	Solar radiation and initial water temperature have impacts on system performance.

Table 2. *Cont.*

S.N.	Author	Year	E/N	Key Features	Outcome
3.	Abokersh et al. [48]	2017	E and N	Paraffin wax as a PCM	The simultaneous long-term predictions based on regression modeling show that the average annual efficiency is 71.8%, 85.7%, and 40.5% for the un-finned, finned, and FSWHS systems, respectively.
4.	Naik et al. [44]	2019	E and N	-	The solar intensity, inlet temperature, and mass flow rate of the fluid have a significant role on the useful heat absorbed by the fluid.
5.	Algarni et al. [60]	2020	E	Copper-based nano-enhanced PCM	Addition of 0.33 wt% of copper/PCM composite to the ETSC increases the efficiency by 32%. ETSC/Ne-PCM system can provide hot water up to 50 °C for about 2 h longer than typical ETC systems with a specific mass flow of 0.08 L/min.
6.	Olfian et al. [52]	2021	N	Paraffin wax as a PCM and a spirally corrugated tube	Corrugated tube increases the collector efficiency by 21.55% as compared to a smooth tube.
7.	Kabeel et al. [61]	2020	E	Hybrid storage materials	Daily thermal efficiency is improved by up to 72% in increasing the mass concentration of graphite in hybrid storage materials.
8.	Feng et al. [54]	2022	N	Multi-walled carbon nanotubes integrated with PCM	The mass flow rate of HTF and the mass fraction of the nanoparticle of MWCNT may increase the thermal performance of ETC-PCM systems.
9.	Olfian et al. [55]	2022	N	Paraffin wax	Thermal energy process is increased by 20%, and the optimal diameter for charging and discharging is 6 mm.

4. Advancements in Heat Pipe-Based ETC Collectors

4.1. Design Modifications

Heat pipe-based ETCs are used for several purposes such as domestic, solar space heating, and swimming pool heating. They are also preferred for extremely cold areas and for those places where water quality is not so good.

Riffat et al. [62] developed a theoretical model to predict the performance of heat pipe-based ETCs. The efficiency was found to be between 40% to 70%. Azad [63] performed experimental and NTU-based theoretical studies to evaluate the performance of heat pipe-based ETCs water heaters. It has been observed that the optimum ratio of the evaporator length to the condenser length was 8.25 for the maximum useful heat gain. Redpath et al. [64] explored the convective heat transfer mechanism inside the heat pipe integrated with an evacuated solar collector. A manifold collector containing 10-pin fin arrays was constructed over the heat pipe. There was a decrement in the normalized temperature at a few points of the array of pin fins, particularly at the pin diameter-to-pitch ratio of 3.2 due to the buoyancy phenomenon. Arab et al. [65] studied the effect of a long-pulsating heat pipe on the heat transfer mechanism inside the solar water heater system. The results revealed that the pulsating heat pipe showed a maximum heat transfer at a filling ratio of 70% with stable and long-lasting performance. It depicted a 53.79% efficiency, which was higher than the conventional thermosiphon efficiency, whose range varied from 31–36%. Ayompe et al. [66] analyzed the performance of an ETC water heater using field trial data. They revealed that the annual collector efficiency and system efficiencies were 63.2% and 52%, respectively. Positively, the maximum outlet temperature was found to be 70.3 °C. Beer et al. [67] carried out a comparative study between two distinct types of heat pipe-based ETCs. They performed modifications in the design of the manifold by introducing a parallel flow manifold with a metal form structure. It was observed that the modified manifold-based heat pipe had 25% higher thermal performance as compared to the conventional one. Gill et al. [68] investigated the yearly performance of domestic-type evacuated tube water heaters. It was found that the annual efficiency of heat pipe-based ETC systems was 63%. Kumar et al. [69] investigated the performance of heat pipe ETC water heaters. They noted that solar radiation and ambient temperature significantly affected the performance of the ETCs. Daghigh et al. [70] performed mathematical and experimental analyses on the performance of heat pipe-based ETC water heaters. The authors observed that the temperature distribution trend had a significant impact up to a number of 15 tubes, and the maximum outlet temperature is found around 64 °C. Joboory [71] performed a comparative study between the two evacuated solar water heaters, particularly for domestic applications, out of which, one worked on the principle of the natural circulation of water in a glass tube-type collector and the other system was equipped with a heat pipe-based evacuated solar collector. Experiments were performed with no load, intermittent load, and continuous load conditions. It was observed that the overall efficiency of the heat pipe-based solar water heater was increased by 22.5%, 42.5%, and 32.4% in the no-load, intermittent load, and continuous load conditions, respectively, as compared to the thermosiphon-based solar water heater. Elsheniti et al. [72] provided the optimization charts to select the optimum number and arrangement of the large array of ETC water heaters. The results revealed that by using optimization charts, one can reduce nearly 41% of the tubes used, which may save large amounts of the initial cost. Huang et al. [73] studied the impact of heat shields on the performance of heat pipe-based ETC solar water heaters. The results revealed that heat shields improved the thermal efficiency when the inlet water temperature varied from 20 °C to 150 °C. The efficiency of the solar collector was improved by 11.2% when the inlet temperature was 150 °C. Elsheniti et al. [74] developed a mathematical model in order to predict the performance of heat pipe-based solar collectors, particularly for high inlet fluid temperatures. It was found that the exit water temperature decreased and the efficiency improved by either reducing the inlet temperature or increasing the flow rate of the water. Shafieian et al. [75] developed a mathematical model in order to evaluate the performance of a heat pipe-based ETC for the cold season. They found that the hot water consumption pattern had a remarkable impact on the optimum design of the ETC-based solar water heater system. Decreasing the flow rate of the fluid had a positive impact on the outlet temperature of the fluid. Tamuli et al. [76] investigated the performance of the dual array-based ETC water heater. The results revealed that for most of the day, the average efficiency varies between 70–80%, and there is an enhancement in the heat extraction by 15–20% using an additional heat pipe.

4.2. PCM Integration with ETC Systems

As mentioned in the previous sections, latent heat storage materials are perhaps more popular and efficient due to their capacity for storing high amounts of heat energy. Therefore, researchers have also examined the performance of heat pipe configurations with PCMs. Naghavi et al. [77] presented a mathematical model in order to determine the performance of a finned-attached heat pipe-based evacuated tube solar water heater equipped with a PCM (paraffin wax). In his study, the PCM was filled into the manifold. It was found that the developed system had higher thermal efficiency than the conventional heat pipe-based ETC at a flow rate of more than 55 L per h. In addition, a comparatively lesser impact was observed on the fluctuation of efficiency with variations in the mass flow rate of the water as compared to the conventional one. Papadimmitratos et al. [78] investigated the performance of a heat pipe-based solar water heater integrated with a dual-phase change material (Tritriacontane and erythritol). It was found that there was a 26% increment in the efficiency of the dual-PCM ETC water heater under normal conditions compared to without PCM-based ETCs. Sekret et al. [79] developed an energy storage system integrated with ETCs, for which they used paraffin wax as an energy storage material. The results showed that there was an increase in the operating time of the developed system, as it continuously took the heat from the storage material during the off-sunshine hours. It was also found that there was a decrement in heat loss as there was a decrement in the average temperature of the heating medium. The total useful heat obtained was increased by 45% to 79%, depending on the mass flow rate for the PCM-integrated evacuated solar collector. Wu et al. [80] developed oscillating heat pipe-based ETCs integrated with phase change materials. It was observed that there was 30% less fluctuation in the collection efficiency using PCMs as compared to without PCMs, irrespective of the season. It was found that the COP of the PCM-integrated solar collector was three on winter nights, which kept the water temperature near about 50 °C, which was not possible in conventional solar water collectors. Bazri et al. [81] performed an analytical study of the charging and discharging characteristics of the phase change materials used in solar water heating systems. A comparative study using different phase change materials was performed. The results revealed that the system exhibited efficiency from 32% to 42% in winter and 37% to 43% in summer. They also found that the PCM-based system also had higher efficiency in rainy or cloudy conditions as compared to a conventional one. Pawar et al. [82] carried out a numerical investigation on the thermal performance of heat pipe-based ETCs integrated with phase change materials. During the study, tritriacontane paraffin as an energy storage material was used in the study. It was observed that there was more fast cooling without a PCM (stearic acid) system as compared to with a PCM material. Chopra et al. [83] investigated the thermal performance of a heat pipe-based evacuated solar water heater integrated with a phase change material. They also performed a 1500 thermal cycling test on stearic acid in order to check its thermal and chemical stability. It was found that evacuated tube collectors without PCMs showed maximum daily thermal efficiency of around 55.46%, whereas ETCs with PCMs showed 87.8% at a flow rate of 20 L per h. Chopra et al. [84] performed thermodynamic and economic analyses of evacuated tube collectors with and without phase change materials (stearic acid). At a flow rate of 24 L per h, for ETCs with PCMs, the maximum average energy efficiency was found to be around 78.36%, whereas ETCs without PCMs showed 54.1%. This showed the efficacy of PCMs in ETCs. Moreover, upon using stearic acid with ETCs, the cost of producing hot water is significantly reduced as compared to ETCs without PCMs and geysers. Li et al. [85] studied the experimental and analytical performance of composite PCM (erythritol and expanded graphite)-integrated heat pipe-based evacuated solar water heaters for mid-temperature applications. It was observed that a composite PCM with 3% weight expanded graphene was found to be the most suitable energy-storing material, with an increase of 40% in its energy-storing efficiency. Sobhansarbandi et al. [86] studied PCM (octadecane paraffin wax)-integrated ETC with a multifunction absorber surface. In order to improve the solar absorption capacity, carbon nanotube-based sheets were used. The results revealed that carbon-based nanotubes enhanced the performance of the PCM as well as the overall performance of the system. Naghavi et al. [87] investigated the performance of the PCM (paraffin wax filled inside the manifold) integrated heat pipe based evacuated tube solar water heater. The thermal efficiency of the proposed system was found to be 38–42% on sunny days and 34–36% in the rainy or cloudy seasons. This system removed not only the drawbacks of the heat pipe ETC water heater but also eliminated the stratification problem by incorporating a new latent energy storage system. Azad [88] studied the effects of the number of tubes and the types of flow through the collector on the performance of a heat pipe-based ETC solar collector. It was found that by increasing the number of tubes and absorber area, the efficiency of the ETCs enhanced remarkably. Chopra et al. [89] carried out an investigation in order to evaluate the performance of heat pipe-based ETC water heaters integrated with phase change materials in two different modes, i.e., the midday charging mode and the full-day charging mode. It was observed that the maximum thermal efficiency was 72.52% at a mass flow rate of 24 L per h and the efficiency of the PCMs for both modes varied between 61–64%.

4.3. Nano Fluid Used

Noie et al. [90] studied the effect of nanofluid (aqueous Al_2O_3 nanoparticle) on the efficiency of a two-phase thermosiphon-based evacuated solar collector. The results revealed that there was a 14.6% increment in the efficiency of the evacuated tube solar collector using aqueous Al_2O_3 nanofluid as compared to pure water. Shafieian et al. [91] carried out an investigation to increase the performance of heat pipe-based ETC water heaters. For this purpose, they proposed a new variable technique to regulate the flow rate. In the study, Al_2O_3 was taken as the nanoparticle in a base fluid of deionized water, and sodium dodecyl Benzene Silfona was taken as the surfactant. It was observed that by varying the mass flow rate of the solar working fluid and the warm water extraction, the exergy degradation of the system decreased. Ozsoy et al. [92] investigated the performance of heat pipe-based ETCs in which the heat pipe was charged with a pure water and silver water nanofluid. The results showed that ETC's efficiency increased between 20.9–40% with the use of the silver water nanofluid when compared to the efficiency of ETCs using pure water. Collective and summarized information on ETCs, PCMs, and nanofiller-based heaters is tabulated in Table 3.

Table 3. Summary of investigation on heat pipe ETC-PCM/nanofluid-based systems.

S.N.	Author	Year	E/N	Key Features	Outcome
1.	Felinski et al. [79]	2017	E	Paraffin used as a PCM	The total amount of useful heat obtained from the paraffin-integrated ETC/S system was increased by 45–79%, depending on the mass flow rate of the heating medium during the discharge cycle.
2.	Felinski et al. [93]	2017	E	Hydrotreated technical-grade paraffin with a melting point of 58 °C was used as a PCM	The charging efficiency of the evacuated tube collector/storage was obtained in the range of 33 to 66%, which depends on the solar radiation intensity and the temperature of the PCM.
3.	Wu et al. [80]	2018	E	Oscillating heat pipe and paraffin wax used as a PCM	On summer nights, the exit water temperature (EWT) with PCMs can stay over 50 °C. On winter nights, COP with PCMs is over 3.0, which can make the EWT reach 50 °C in a much shorter time than that of without PCMs.
4	Hasan et al. [94]	2019	E	Paraffin used as a PCM	The enhancement in the overall daily efficiency of the heat pipe system over the thermosyphon system was 22.5% for no load, 42.5% for intermittent loading, and 32.4% for continuous loading.
5	Shafieian et al. [91]	2019	N	-	Hot water consumption pattern had a remarkable impact on the optimum design of the ETCs. Lowering the flow rate of the fluid had a positive impact on the outlet temperature of the fluid.
6.	Essa et al. [95]	2020	E	Helically finned heat pipe	The helical fins were found to achieve daily efficiency enhancements over the conventional one by 15% and 13.6% for the flow rates of 0.5 and 0.665 L/min, respectively.
7.	Chopra et al. [83]	2020	E	Stearic acid as a PCM	The daily thermal efficiency of the evacuated tube solar collector with and without phase change materials was varied in the range of 42–55% and 79–87%, respectively, and the daily thermal efficiency for both the systems was maximum at the flow rate of 20 L per h.

Table 3. Summary of investigation on heat pipe ETC-PCM/nanofluid-based systems.

S.N.	Author	Year	E/N	Key Features	Outcome
8.	Chopra et al. [84]	2020	E	Stearic acid as a PCM	ETC/S obtained higher energy and exergy efficiencies in comparison to the ETC/WS design. The maximum attained values of average daily energy efficiency for ETC/S and ETC/WS were 78.36% and 54.10%, respectively, at a flow rate of 24 L per h.
9.	Tamuli et al. [76]	2022	E	Dual-heat pipe array-based ETC	Average efficiency varies between 70–80%, and there is an enhancement in heat extraction by 15–20% using an additional heat pipe.
10	Hong et al. [96]	2022	E and N	Stainless-steel-based hydroformed manifold	There is a 29% increase in the convective heat transfer coefficient of the chevron-hydroformed manifold compared with the smooth-hydroformed manifold.

5. Other Modifications on Solar Water Heaters

Several authors have proposed new designs of solar water heaters apart from the abovementioned ETC water heaters. Siqueira et al. [97] developed a low-cost solar water heater that is composed of polymeric materials. It was found that the average cost of 100 L of water produced from the proposed solar water heater was four times less than the cost of water produced from a conventional solar water heater of the same capacity. Chong et al. [98] proposed an economical V-trough solar water heater. The results revealed that by using an electric heater in place of a V-trough solar water heater, a yearly saving of electricity of USD 44.46 can be achieved. Marmoush et al. [99], in their study, merged a tubular daylight device with a solar water heater in order to utilize the space around the tubular light device. The outcomes of the novel merged system stated that the outlet temperature of the water reached up to 62 °C, leading to an increase in the instantaneous efficiency of 21.17%. Yassen et al. [100] presented a solar water heater with corrugated absorber surfaces. The capability of the developed system was found to deliver 140 L of water at 42 °C. Moreover, the daily thermal efficiencies were found to be 59%, 65%, and 67% at the flow rates of 0.005 kg/s, 0.0095 kg/s, and 0.0013 kg/s, respectively. Touaba et al. [101] used waste engine oil as the heat transfer fluid in a solar water heater. The results revealed that the average efficiency of the proposed model solar collector was 71%, and the heat efficiency rate was found to be 65%. Dhinakaran et al. [102] used a copper coil as a collector in order to heat up the water. Aluminum oxide was used as a nanofiller in order to enhance the performance of the developed system, and the results stated that the temperature of the water increased by 33% using nanofillers. Various nanofillers have been used and showed positive results in the enhancement of the efficiency and other parameters of ETCs. Moreover, the latest trend showed that the novel and latest nanofillers are under examination for further improvement in ETCs, which requires past knowledge of the ETCs with nanofillers.

Wang et al. [103] performed an experiment and compared the traditional and transparent kinds of solar collectors integrated with flat micro-heat pipe arrays. This study is based on several locations of absorption coatings introduced within the absorber tube. It has been observed that the thermal efficiency of conventional solar collectors is 8% less than that of the transparent-type collector. Zhang et al. [104] introduced a heat shield to a direct-flow coaxial evacuated collector to examine the thermal performance of the system. Heat shields are very productive and inexpensive materials used to reduce heat loss in ETCs. The results showed that there is a 31.49% increase in the collection efficiency of ETCs by using heat shields. Wang et al. [105] used a reactionary mesh of stainless steel among the concentric tubes and inner glass tubes of glass evacuated collectors, due to which, heat is transferred from the coating material to the heat transfer fluid. This results in the improvement of the thermal efficiency of the collector and a decrease in the manufacturing cost.

6. Numerical Studies on ETCs

The above discussion confirms that in the past, mostly experimental and analytical works have been carried out on ETCs. However, in the recent years, emphasis has also been given to the numerical methods. It is well known that large amounts of capital investment and huge amounts of time are required to conduct experimental works. On the other hand, the numerical approach is slightly faster, more adaptive, and more economical, although it provides an approximate solution. Henceforth, researchers in this domain have also started using this methodology to investigate problems pertaining to ETCs. Essa et al. [20] performed a numerical investigation of all-glass tube ETCs to examine their thermal performance. The results show that incident angle and solar intensity have significant impacts on the flow patterns formed inside the tube. Li et al. [23] studied the variation and distribution pattern of the temperature and the velocity fields in the horizontal double-row all-glass ETCs. It has been observed that instantaneous efficiency is improved when increasing the declination angle. The declination angle has a major impact on the velocity and temperature field inside the ETC tubes. The thermal performance of the ETCs is also predicted by the combination of computational fluid dynamics (CFD) and artificial neural networks (ANN) (Du et al. [23]). The outcomes revealed that alone CFD model has provided poorer accuracy as compared to an ANN model. The convolution neural network model provides a reasonably good ANN model to predict better accuracy. The mathematical modeling of U-tube ETCs is performed by Cui et al. [41] using different working mediums. The results revealed that the flow rate of the working fluid, collector length, and solar intensity influenced the thermal performance of the collector. However, the inlet temperature of the working fluid was not significantly affected. Olfian et al. [52] have proposed the spirally corrugated tube instead of a simple tube in U-tube-based ETCs. The findings of their work revealed that the corrugated tube enhances the thermal efficiency by 21.55% as compared to a simple tube. In the same proposed model, Olfian et al. [55] again numerically investigated the impact of the diameter of a U-tube on thermal performance. They found that the optimum diameter of the U-tube is 6 mm for both the charging and discharging processes, and the developed model increased the thermal energy process by 20%. Feng et al. [54] also performed transient numerical simulations and carried out a parametric study of the efficiency of solar ETCs integrated with phase change materials. It is concluded that the efficiency of the ETC-PCM system can be improved by decreasing the melting point of the PCM from 50 °C to 35 °C. A chevron-hydroformed manifold of heat pipe-based ETCs was proposed by Hong et al. [96]. The hydrodynamic and heat transfer characteristics are obtained by CFD modeling. The results state that there is a 29% increase in the convective heat transfer coefficient by introducing the chevron patterns onto the manifold.

7. Economic, Environmental, and Life Cycle Assessment of ETCs

It is well recognized that ETC solar water heaters have mainly evolved to overcome certain drawbacks associated with flat plate collectors. They are capable of supplying hot water at higher rates and minimizing the cost as compared to other configurations of solar water heaters. Yanhua et al. [106] analyzed the thermal performance and economic aspects of the ETC solar water heater with an auxiliary electric heater (ETSAEX). The findings depict that the annual and present cost of ETSAEX was 3.3% lesser than coal-fired boilers and 83.04% lesser than air-conditioning systems. Sohansefat et al. [107] investigated the environmental and thermos-economic aspects of ETC and flat plate solar water heaters. It has been observed that the annual useful energy for ETCs and FPCs was 30,260 MJ/year and 21,340 MJ/year, respectively. Moreover, the thermos-economic analysis of the ETC solar water heater was 41% better than FPC. Li et al. [23] studied economic, environmental, and energy analyses of ETCs with different declination angles. The results revealed that the declination angle is a crucial factor for energy convergence, stratification, and maintaining flow patterns inside the ETC. When decreasing the declination angle lesser than zero, an inversion phenomenon appears. It may be presumed that the thermal effect can be increased without much increase in economical liability. Garcia et al. [108] analyzed the exergo-economic and environmental aspects of the ETC solar water heater in the meat industry situated in Europe. Initially, the annual energy demand of the company was 8500 kWh, which was reduced by 24–42% using an ETC solar water heater. The payback period of the ETC system was around 9 years, and CO_2 emission was reduced by more than 15,000 kg of CO_2 per year. Tewari et al. [109] investigated environmental, exergy, and economic analyses of modified solar water heaters integrated with a glass PV module. The results state that the carbon cost mitigation was obtained at USD 403.23 and USD 48.61 for the energy and exergy analyses, respectively. Chopra et al. [84] performed thermos-economic, energy, and exergy analyses of ETCs with energy storage (ETC/S) and ETCs without energy storage in solar water heaters (ETC/WS). Three different mass flow rates have been considered in this study, i.e., 8 LPH, 16 LPH, and 24 LPH. The daily average energy and exergy efficiencies were 54.10% and 20.06%, respectively. The mean exergy efficiency was improved with an increase in the mass flow rate of the fluid. It is also understood from the thermos-economic analysis that the production cost of the hot water for ETC/S is lesser than ETC/WS and an electric geyser.

Life cycle assessment (LCA) is a technique to compute, identify, and help to minimize the impact of the process on the environment. LCA is one of the most acceptable methods for the environmental analysis of the ETCs and FPCs. While performing the LCA of ETCs, it is worth mentioning that its fabrication procedure is quite crucial and shares a major part of the consumed energy in manufacturing. Brondani et al. [110] presented an LCA analysis of ETCs and flat plate collectors. The outcome reveals that the carcinogens used in the fabrication of both of the collectors significantly affect the environment. Moreover, in FPCs, the major sources of pollution are minerals, while in ETCs, the respiratory organic category is the main pollutant impacting the environment. Moreover, the authors pointed out that both of the collectors are better options for solar water-heating applications owing to the absence of combustible gases in their manufacturing processes. Furthermore, it has been concluded that, in view of the economic and environmental aspects, ETCs are more desirable than FPCs

8. Conclusions

Over time, various modifications and advancements have been performed to increase the thermal performance of the evacuated tube solar water heater. The literature confirms that the evolution of different techniques and the integration of energy storage materials with ETCs have enabled, to some extent, facilitating an energy supply even during late nights and cloudy climates. Moreover, it has also been noted that ETC-based systems can also accommodate new design amendments needed for their diverse applications. Based on the present literature review, the following conclusion points have been drawn.

i. ETC-based solar water heaters are a viable system for domestic and industrial hot water requirements. They also eliminate certain drawbacks of flat plate-based solar water heaters. Besides, ETCs are more adaptable to design modifications, and the inclusion of consistent efforts is required to improve the ETC-based collector's design so that more solar insolation can be absorbed. Various extended surfaces or fins can also be incorporated that will help ETCs to perform within a specified temperature range.
ii. The utilization of nanofluids as working fluids increases the heat transfer rate due to the higher heat-carrying capacity of the nanoparticles.
iii. The intermittent nature of the hot water supply can be eliminated to some extent by the inclusion of thermal energy storage materials. The literature indicates that suitable PCMs can be a viable solution owing to their inherent properties. However, the successful utilization of the PCM highly depends on its proper filling and packing within the developed system.

iv. A loss of thermal energy significantly affects the performance of solar water heaters. Hence, appropriate insulating materials should be used across the piping network and the storage tanks.

9. Future Scope

Evacuated tube solar water heaters have rapidly captured the market due to their advantages over other types of solar water heaters. To further improve the performance and make this technology more reliable and versatile, some points are suggested below. Some important areas are highlighted that should be focused on for research work.

i. Consistent efforts are required to increase the absorbing capacity of solar radiation by the evacuated tube; hence, research work may be accelerated to explore more effective absorber coatings on the surface of the ETC.
ii. The literature indicates that on the evacuated type solar water heaters, fewer numerical studies have been performed; therefore, in addition to other approaches, it is suggested to expedite this methodology. Numerical techniques provide faster solutions, and it is also a convenient, economic, and less time-consuming method.
iii. Highly conductive fluid may be utilized as a working fluid in ETC-based water heaters; it can help to extract more heat from the ETC and transfer it to the water.
iv. Although several works have been reported in which PCMs are used with solar ETC water heaters, it is not well established so far. It is suggested to explore suitable PCMs and their proper integration techniques with solar water heaters so that the system can be compact and may provide hot water for longer durations in the absence of solar radiation.
v. It has been observed that evacuated tubes are highly brittle in nature; hence, research work in this direction is required by utilizing nanofibers in the glass material to increase the strength and durability of the glass tube.
vi. Usually, the inner surface of an ETC is smooth. If it would be provided with artificial roughness and certain perturbation, it could be helpful to introduce turbulence into the flow, which may improve the heat transfer.

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