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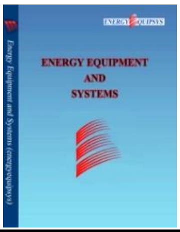

Recent innovations in evacuated tube solar water heating technology: A comprehensive review

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ABSTRACT

This paper reviews recent advancements in Evacuated Tube Solar Collectors (ETSCs), highlighting their high efficiency in harnessing solar energy for heating applications. ETSCs outperform traditional flat plate collectors, especially in colder climates, due to their superior heat retention and ability to utilize diffuse solar radiation. Integrating nanofluids, Phase Change Materials (PCMs), and optimizing designs can further enhance their performance and efficiency. Despite their higher initial costs, ETSCs offer significant long-term benefits in both residential and industrial applications. Future research should focus on improving tube durability, exploring advanced materials, and evaluating economic impacts. This paper focuses specifically on evacuated solar collectors, providing relevant background information and highlighting potential opportunities for further improvement of these systems..

Keywords: Evacuated Tube; Solar Water Heater; Phase Change Material; Nanofluid.

1. Introduction

Solar energy is widely recognized as one of the most promising and sustainable sources of clean, renewable energy available today, offering significant environmental and economic benefits to meet global energy needs. By harnessing sunlight through various technologies, solar energy can be converted into electrical energy, used for heating and cooling water, and even employed in industrial processes. The widespread adoption of solar energy conversion technologies has made it one of the primary sources of energy worldwide. Technological advancements have substantially reduced the costs associated with the installation and operation of these systems. Moreover, the utilization of solar energy supports sustainable development, diminishes reliance on fossil fuels, and lowers greenhouse gas emissions. Solar storage systems also have numerous applications in both domestic and industrial sectors, including water softening and industrial furnaces. Consequently, developing solutions to enhance the efficiency of these systems has been a focal point for researchers [1].

There are two primary types of collectors as shown in Fig. 1: stationery and tracking. Different configurations of these collectors can achieve a wide range of operating temperatures. For instance, flat plate collectors or FPCs operate within a temperature range of 20–80°C, while evacuated tube solar collectors which are also known as ETSCs can function at temperatures between 50–200°C. Despite their lower efficiency and output temperatures, FPCs are the most widely used and productive solar collectors because of their minimum amount of maintenance costs and simple design.

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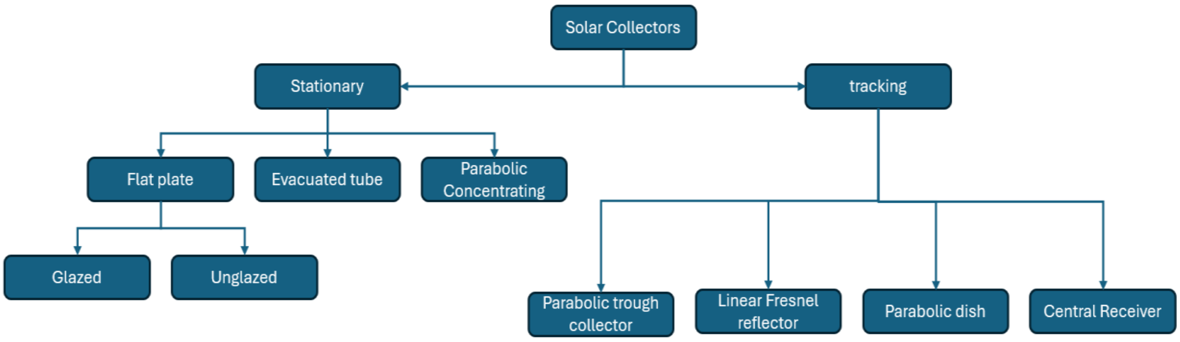

Fig. 1. Different categories of solar collectors [1].

One area in solar energy that has captured the attention of researchers is solar vacuum collector systems. Vacuum solar collectors, also known as evacuated tube collectors, are highly efficient systems designed to harness solar energy for heating purposes. These collectors are composed of multiple glass tubes, each housing an absorber tube inside a vacuum-sealed outer layer. The vacuum acts as an excellent insulator, significantly reducing heat loss and allowing the collectors to maintain high efficiency even in cold and cloudy conditions. The high efficiency of vacuum solar collectors is a key benefit, as the vacuum insulation minimizes heat loss, enabling the system to retain a higher proportion of the absorbed solar energy. This makes vacuum solar collectors more efficient than traditional flat-plate collectors, especially in colder climates or during winter months. Unlike some solar technologies that only perform well in direct sunlight, vacuum solar collectors can effectively utilize diffuse solar radiation. This capability allows them to generate heat even on overcast days, making them suitable for a wide range of geographic locations [2]. Farzan [3] assessed the energy performance of two solar systems: a flat plate collector and an evacuated tube collector, both operating under the same weather conditions. The energy performance of each system was compared over time. The results showed that, under identical conditions, the flat plate system collected less energy than the evacuated tube system. The flat plate system had an energy efficiency of 43% and a solar fraction of 50%, while the evacuated tube system achieved an energy efficiency of 51% and a solar fraction of 58%. Although neither system proved economically viable for the region, the evacuated tube system demonstrated higher efficiency in terms of performance. This finding could be a great incentive for researchers to focus more on the optimization of vacuum collectors in order to achieve even higher efficiency.

The construction of vacuum solar collectors is robust, with the vacuum-sealed tubes protecting the absorber from external weather conditions and corrosion, enhancing the system's lifespan and ensuring long-term reliability and reduced maintenance costs. These collectors can achieve higher operating temperatures compared to flat-plate collectors, making them ideal for applications that require higher temperatures, such as industrial processes, space heating, and high-temperature water heating. Additionally, vacuum solar collectors can be used in various applications, from residential water heating and space heating to commercial and industrial processes. Their ability to provide consistent performance across different scenarios makes them a versatile solution for renewable energy needs. This paper focuses specifically on evacuated solar collectors, providing relevant background information and highlighting potential opportunities for further improvement of these systems.

2. Evacuated Tube Solar Collectors

2.1. Evacuated solar collectors and their applications

This type of collector was first proposed over forty years ago. However, despite its purported benefits, only a limited number of manufacturers have brought commercial models to market. This reflects both the technical challenges involved in producing sealed panels at an affordable cost and the general lack of understanding regarding the advantages these panels can offer.

In a study published in 2018, a simulation of a vacuum bed system has been investigated. In this study, which closely modeled experimental efficiency measurements, after validating numerical modeling, released data for an industrialized EFP system were compared with an effort for an optimal design [4]. Gao et al [5] explored a solar heating system taking advantage of a new evacuated flat plate solar collector. To assess its feasibility and effectiveness, an experimental study and demonstration of the regional energy system were conducted. The results indicate that this system can greatly enhance solar energy efficiency and reduce the required space by the amount of 66.9%. Additionally, since solar energy supply and heating demand typically follow opposite patterns throughout the day, this creates a need for substantial energy storage capacity and increased land use. To address this daily solar energy difference, a solar heating strategy incorporating EFP and virtual energy storage was proposed. Consequently, this approach can considerably minimize the land footprint of solar power installations and holds significant potential for advancing solar energy adoption and lowering carbon transmitted emissions. In another study done by Gholipour et al [6], they investigated the thermal performance of a tubular solar vacuum collector by taking advantage of three different types of absorber tubes: spiral, helical spiral, and U-shaped tubes. The experimental setup measured inlet and outlet temperatures and other parameters to compare the thermal performance of the different tube configurations. The results demonstrated that both spiral and helical tubes significantly improved efficiency, with helical tubes showing superior performance. Additionally, economic analysis that was done in this project showed that using spiral and helical tubes increased costs by 60% and 72%, respectively. The introduction of nanofluid in helical spiral tubes raised the cost by 3.4 times. Fertahi and the team of researchers [7] used CFD simulations and experimental studies to design optimal hot water storage tanks integrated with solar vacuum collectors. This research paid special attention to the number of heating pipes placed in the tank and its effect on the energy performance of the tank, including the heat transfer coefficient. The results show that by increasing the number of heating pipes, the average temperature of the tank increases, and the flow structure is affected in terms of flow regime. To optimize vacuum collectors, Alfaro-Ayala et al. [8] explored optimizing the solar vacuum collector by employing an artificial distillation approach combined with computational fluid dynamics (CFD) modeling. During the optimization, the absorber surface was evaluated in three distinct configurations, focusing on key geometric factors such as tube length, diameter, and quantity. In total, more than 200 unique collector shapes were designed carefully, manufactured, and simulated. The design of all conducted studies revealed that the most influential factors on the thermal efficiency of the solar collector are tube diameter, absorber surface area, and fluid mass flow rate. The optimization results indicated that the least amount of the absorber plate surface area for an optimal design is 2.5 m^2, which is around 20% smaller compared to the commercial design with the same outlet temperature. Additionally, the tube diameter was increased by approximately 30%, the tube length was reduced by 40%, and both the price of the optimal design and the number of evacuated tubes decreased by 39%. Finally, the thermal efficiency increased by 26% compared to the geometries available in the market. In another research related to solar vacuum collectors, Kocer et al. [9] presented the “F-chart” method. This method made it possible to easily determine and evaluate the thermal performance of solar heating setups. This article introduced a novel approach utilizing the F-chart method to analyze the hot water demand in hotels. The heating load was estimated based on the number of residents and the collector surface area. Finally, the performance of two different types of solar collectors, flat plate and vacuum type, was compared. As depicted in Fig. 2, a smaller number of solar vacuum collectors are needed for energy supply which once again showed the superiority of vacuum solar collectors over flat plate collectors.

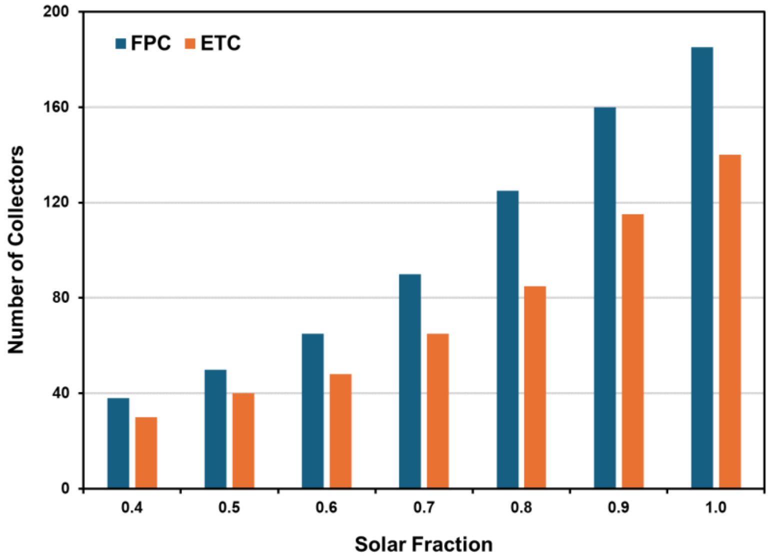

Fig. 2. The effect of the number of collectors on the solar fraction for 100 people at the hot water temperature of 50°C [9].

2.2. Impact of shapes and configuration

The configuration and shapes of solar collectors have always intrigued researchers. Kim et al. [10] investigated the thermal behavior of the evacuated tube solar collector (ETSC) utilizing four different shapes for the absorbers. The absorber shapes were a finned tube (Model 1), a tube with a circular fin welded inside (Model 2), a U-tube welded on a copper plate (Model 3), and a U-tube welded inside a rectangular duct (Model 4), as illustrated in Fig. 3.

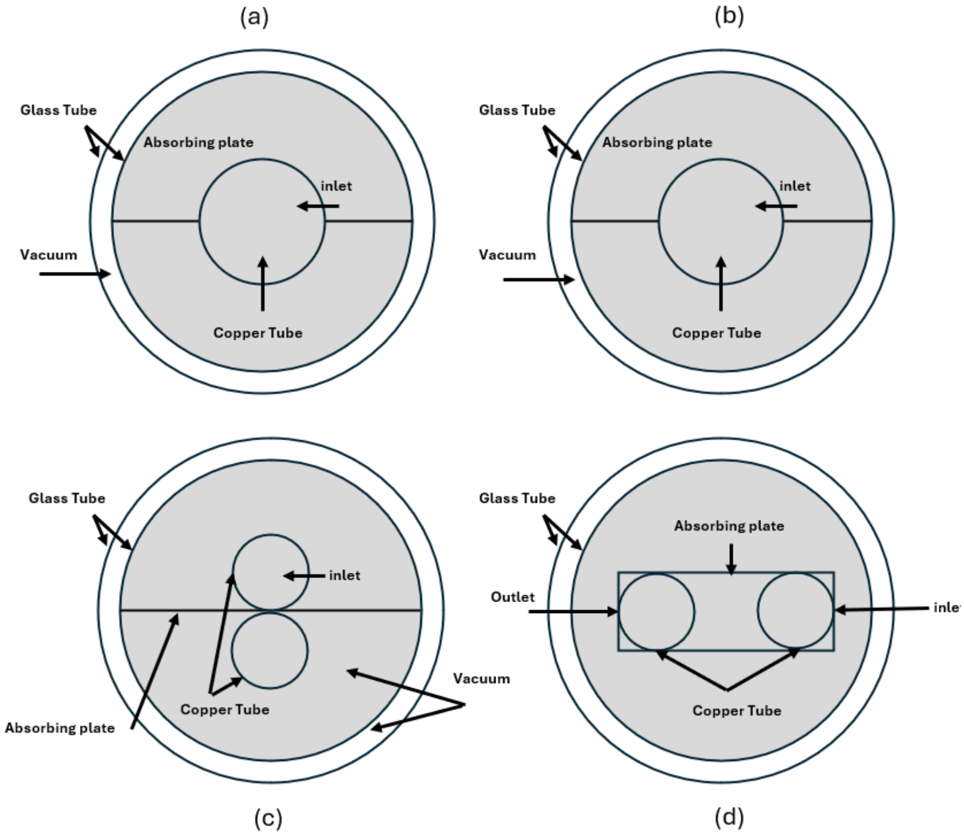

Fig. 3. Cross-section of (a) Model 1, (b) Model 2, (c) Model 3, and (d) Model IV [10].

Initially, the study focused on the performance of a single collector tube considering only beam radiation, revealing that the incidence angle significantly affects collector efficiency. Model 3 demonstrated the greatest efficiency when operating at low incidence angles, but as the incidence angle increased, Model 2's efficiency surpassed that of Model 3. When considering diffuse radiation and shadow effects, the incidence angle's impact on collector performance was minimal, with Model 3 demonstrating the best performance across all incidence angle ranges. Gholipour et al. [11] worked on vacuum tube collectors with three absorbent tube configurations such as spiral coil, spiral tube, and U-tube have been investigated. These settings have been experimentally evaluated at four different volumetric flow rates (10 to 40 L/h). Absorber tubes are arranged inside the vacuum tube solar collector to ensure a uniform working fluid volume. Tests for all three configurations are conducted simultaneously on separate days. The purpose of this evaluation was to investigate how the arrangement of absorber tubes affects thermal energy storage. The findings indicate that the thermal efficiency of evacuated collectors improves across all setups when volumetric flow rates are increased. In addition, the spiral pipe shows better performance compared to other piping. In 2017, Andemeskel et al [12] investigated the appropriate thickness for this aluminum fin and the solar absorber coating that is placed on it. This research aimed to investigate the effect of the thickness of the aluminum fin covered with solar absorbing material on the thermal efficiency of ETSC. In this study, commercially available aluminum fins with different thicknesses were used, which were coated with Thurmolax 250 solar absorber black coating in three distinct thicknesses. Spectral reflectance and thickness of coated layers were measured by UV-Vis-NIR spectrophotometer (in wavelengths of 2500-300 nm) and Mini Test 730 device, respectively. Solar absorption of the layer was calculated based on the relationship between the observed reflectance (R) and AM 1.5 solar spectral radiation in the entire wavelength. The thermal performance of the defined system with different thicknesses of the aluminum fin was evaluated according to the standard. As a result, it was found that α which is the solar absorption rate is the same for all thicknesses of the solar paints considered, which clearly shows that the thickness of the solar paint has a negligible effect on solar absorption. Performance, heat removal coefficient (FR), and UL were calculated for variable thicknesses of Al fin, and it was found that these values increase with decreasing thickness of Al fin solar absorber. The results showed that FR played a significant role in increasing η by decreasing the thickness of the Al fin solar absorber. Based on this study, it was determined that thinner aluminum fins (11 μm) with a single layer of coating are more suitable for use in ETSC due to their relatively larger value of efficiency and FR, including lightweight and low cost. Chopra et al. [13] experimentally evaluated the use of SR-EVTC (spiral vacuum tube collector) combined with a copper annular fin and a fluid to store energy (SR-EVTC/SS-AF). In this research, the developed system and an EVTC without the mentioned items (SR-EVTC/CS) in the same working environment in different locations and during different weather conditions for three different water flow rates, i.e. 0.08, 0.012, and 0.016 m^3/h were investigated. In the experimental study conducted on clear days, the SR-EVTC/SS-AF and SR-EVTC/CS systems achieved the highest average daily energy efficiencies, measuring 82.5% and 63.98%, respectively, at a flow rate of 0.016 m^3/h, and on cloudy days, the highest value of performance value for EVTC/SS and EVTC/WSS was 88% and 75%, respectively, at a flow rate of 0.008 m^3/h. In this study, the researchers concluded that the efficiency of the system goes up by 19-29% in clear weather and 18-30% in cloudy weather when using the copper annular fin.

Similar to other types of solar systems, vacuum solar collectors are also impacted by environmental factors, particularly dust in the air. In 2009, El-Nashar et al. [14] conducted research to examine the impact of seasonal dust accumulation on a large array of vacuum tube collectors at a desalination plant near Abu Dhabi. The study included seasonal measurement of the dust on the system and developed a mathematical model within the SOLDES program to predict system efficiency by accounting for the effects of dust buildup and the frequency of cleaning the surface of the collectors. The research found that dust deposition, particularly during the summer months of June to August when sandstorms are common in the area, significantly affected the plant's performance, causing a reduction of 10-18% in light transmission through the glass tubes. This decline in light passage due to dust can greatly diminish the facility's overall efficiency. For example, by reducing the transmittance from an initial value of 0.98 (clean glass conditions) to a low level of 0.6 (high level of dust accumulated on the glass) the collector output drops from 100% to 40%. According to the results of this study, it was determined that weekly cleaning resulted in maximum annual water production for that facility. It was also found that dust deposition reduces specific water production (m^3/kJ of incident solar radiation) and increases specific electricity consumption (kWh/m^3). In 2024, Abrofarrokh et al. [15] employed CFD to explore the influence of metal foam on the thermal efficiency of solar air heaters with vacuum tube solar collectors and integrated baffles (IBMF/ETSC/SAH). A 3D model was used to analyze the system under steady-state conditions. A major outcome was that the inclusion of metal foam significantly improved thermal efficiency, with an average increase of around 300%. The study evaluated how varying the void fraction in the metal foam influenced the effectiveness of the IBMF/ETSC/SAH at Reynolds numbers ranging from 6,000 to 18,000. The findings indicated that lowering the void fraction from 0.95 by only 0.05 led to a 7% improvement in energy efficiency. Furthermore, the IBMF/ETC/SAH exhibited a significant drop in overall entropy production compared to the version without metal foam. In 2015, Alfaro et al [16] studied the glass vacuum tube solar collector using CFD simulation. The exit temperature of the solar collector was predicted by two different methods of simulating the effects of buoyancy. In the first model, Boussinesq estimation (BA) was used, and for the second simulation, they used a variation of the proprieties with temperature (VPT), in which water properties were allowed to change with temperature. Four tests were carried out in real conditions based on the official Mexican standard to experimentally measure the outlet temperature of the collector. The results showed that the outlet temperature predicted by the BA model was closer to the actual temperature compared to the outlet temperature predicted by the VPT model. In an experimental study, Abo-Elfadl et al. [17] evaluated the energy and exergy effect of combining reflectors with the vacuum tube heat pipe solar collector system (ESTC/HP) on thermal energy storage. In this study, the effect of using reflectors at the top, bottom, and top and bottom on thermal energy storage, energy input, and energy losses, the effectiveness of reflectors, and energy efficiency and exergy have been evaluated. The findings of this study showed that the use of reflectors with ETSC/HP increases input and storage energy, efficiency of energy usage, and exergy but reduces convective losses. The inclusion of upper, lower, and dual reflectors increased the energy supplied to the collector by 15%, 22%, and 37%, respectively, while the stored energy output per day rose by 14%, 22%, and 35%, in comparison to a system lacking reflectors. As shown in Fig. 4, the daily energy conversion efficiency of the ETSC-HP system with these reflectors was measured at 63%, 71%, and 76%, respectively, whereas the system without reflectors achieved an efficiency of 60.5%. Incorporating reflectors into these systems enhanced the system's energy transfer curve efficiency by approximately 16% relative to the version without reflectors. Additionally, employing dual reflectors resulted in a 25.3% average improvement in daily exergy efficiency. This study demonstrated that adding reflectors significantly boosts the energy storage capacity of the ETSC-HP system.

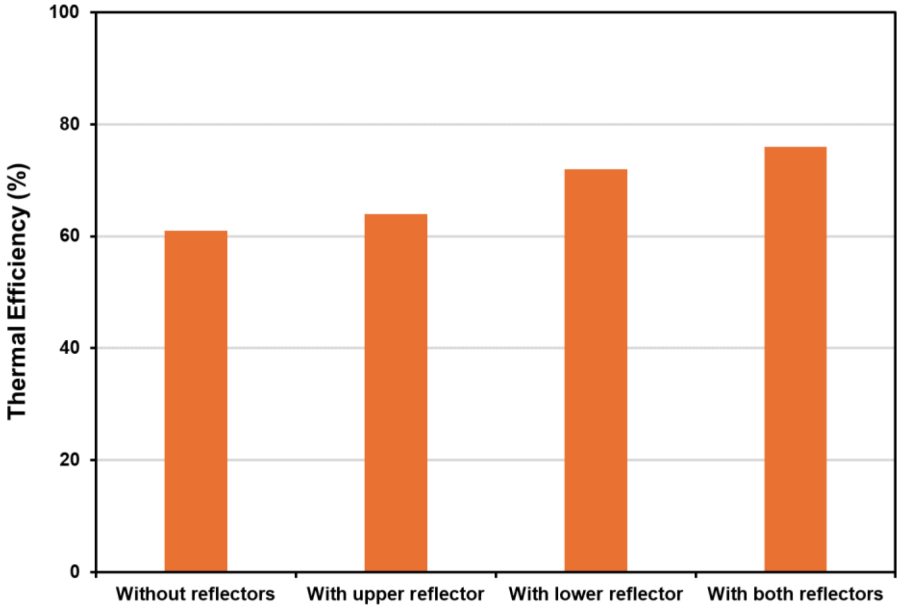

Fig.4. The average daily thermal efficiency of ETSC-HP systems with various configurations [17].

2.3. Implementation of nanofluid material in evacuated solar collectors

A method to enhance the utilization of solar vacuum collectors is the use of nanofluids, where researchers have investigated the mixing of nanoparticles in the working fluid to increase the heat transfer properties.

Sharafeldin et al. [18] investigated the application of CeO_2/H_2O and WO_3/H_2O nanofluids and showed significant improvements in the thermal performance of vacuum tube solar collectors. Similarly, Sabiha et al. [19] conducted comprehensive studies to determine the effect of different nanoparticle volume fractions on collector efficiency and elucidated promising ways to increase performance. In another recently published research, López-Núñez et al. in 2024 [20], used the computational fluid dynamics method and made a numerical comparison between the thermal performance of three different working fluids (pure water and nanofluids based on SiO_2 and TiO_2) in a vacuum tube solar collector was implemented. In this study, considering the change in solar radiation and input mass rate, thermohydraulic performance was investigated in local and overall entropy production rates. The results indicated that nanofluids exhibit superior effectiveness under reduced sunlight conditions and achieve higher discharge temperature, flow rate, energy efficiency, and exergy efficiency compared to plain water. However, at higher solar radiation levels, the yield of SiO_2 water-based nanofluid decreases due to its effect on specific heat. It was also found that the rate of entropy production in water-based nanofluid TiO_2 decreases up to 79%. The performance of water-based SiO_2 nanofluid at high irradiance was almost equal to that of pure water. Tuncer et al. [21] conducted a study on the use of magnetic nanofluids instead of water as the working fluid of heat pipe solar vacuum collectors (ESTC/HP). In this research, magnetic nanofluid $NiFe_2O_4$/water was used instead of water as the working fluid in an HP/ETSC. For this purpose, $NiFe_2O_4$ nanoparticles with a weight ratio of 2% were mixed with distilled water. Performance tests were performed at different flow rates using distilled water and magnetic nanofluid $NiFe_2O_4$/water. The general results of this research showed the positive effect of using magnetic working fluid on ETSC/HP efficiency. The use of this fluid in HP-ETSC as a working fluid increased the thermal efficiency on average by 38, 40, and 45% at flow rates of 0.016, 0.033, and 0.05 kg/s, respectively. In addition, the use of the mentioned magnetic nanofluid improved the exergy efficiency by 61, 56, and 60% at flow rates of 0.016, 0.033, and 0.05 kg/s. In another research study by

Tabarhosseini and Sheikholeslami [22], the authors evaluated the thermal and thermodynamic performance of a buoyancy-driven evacuated tube solar collector and the impact of CuO nanoparticle dispersion in the working fluid. Natural convection was analyzed across different vertical sections of the absorber tube, comparing water and a CuO-based nanofluid over time. Results show that the nanofluid enhances the mean wall temperature and heat transfer coefficient, improving thermal performance. An irreversibility assessment indicates that while fluid friction-related irreversibility increases with the nanofluid, entropy generation due to heat transfer is higher for pure water. Specifically, heat transfer entropy generation decreases by 6.3% with a 5% CuO volume fraction after one hour, while viscosity-related entropy generation rises by 23%. This difference is attributed to the low-velocity nature of natural convection.

2.4. Utilization of PCM in various ETSC configurations

The use of phase change materials (PCMs) in solar systems has gained significant attention for enhancing energy storage and efficiency. PCMs absorb and release thermal energy during their transition between solid and liquid states, making them ideal for stabilizing temperatures and extending the usability of solar energy beyond daylight hours. By integrating PCMs into solar collectors, the systems can store excess heat generated during peak sunlight and release it during periods of low solar radiation, such as at night or on cloudy days. This capability not only improves the overall efficiency and reliability of solar thermal systems but also helps in maintaining a consistent energy supply, thereby optimizing the performance of solar heating and cooling applications.

Jobair and Nima [23] investigated a solar air heater with a copper foam absorber plate and PCM for drying applications in Baghdad. They evaluated the effects of mass flow rate, PCM, and solar radiation on performance parameters. In the end, they concluded that using PCM in a system outperforms a flat plate solar dryer, showing improved thermal efficiency by 15 to 22% depending on the flow rate. Sharahi et al. [24] reviewed the performance enhancement of finned solar cells using PCM materials. Their study explored the impact of fin geometry on the performance of phase change PCM integrated photovoltaic systems. Increasing fin length improves efficiency and reduces panel temperature. Triple-branched fins enhance system performance by 1.5% compared to rectangular fins. Non-rectangular PCM encapsulations offer better cooling and higher PCM melting rates than traditional designs. In the area of vacuum collectors, Feliński et al. [25] investigated the effect of incorporating PCM inside a solar vacuum collector and its impact on the performance of a solar water heating system. The study determined the temperature of hot water within the tank and the ratio of solar energy absorption in a domestic hot water system for Czestochowa, Poland. The efficiency of solar vacuum collectors with PCM materials ranged between 33% and 66%, depending on radiation intensity and PCM temperature. They also showed that utilizing PCM for energy storage during peak consumption times, such as afternoons, was beneficial. The phase change of these materials allowed for continuous heat release during periods of insufficient solar radiation, thereby enhancing system performance. Bouhal and colleagues [26] proposed an optimal and efficient solar hot water production system through the design and embedding of PCM modules in solar storage tanks. They investigated two numerical methods to simulate the performance of solar thermal energy storage systems with PCM under real conditions and typical consumption needs. The results indicated that selecting an appropriate numerical method could significantly enhance system performance and optimize PCM phase change materials. Increasing the amount of PCM was shown to reduce melting speed and heat transfer to the environment. Renfei and colleagues [27] further improved system performance by using solar air collectors with phase change materials (SAC/PCM) and adding a fan. This approach increased the system's output air temperature and reduced energy consumption, demonstrating that integrating SAC/PCM with a fan can significantly enhance heating system efficiency.

Alshukri et al. [28] conducted an experimental experiment in which the effect of using phase change materials in the vacuum tube (ET) and two separate tanks in the vicinity of the collector water tank of the vacuum solar water heater with heat pipe (HP/ETSC) was checked on efficiency. In the first step, the vacuum tube was filled with some sort of paraffin material, and two separate tanks next to it were filled with paraffin wax as a heat storage source. Thus, it was expected that due to the thermal insulation of the vacuum tube and the PCM storage tanks, the heat would be stored more effectively and for a longer period. The positive aspect of this new approach is that it improves the overall performance of the solar water heater by delaying the release of heat and providing hot water for a longer time during peak times or when the intensity of the sun is low. In this comparative study, four HP/ETSC devices with gravity-assisted heat pipes were used. The first ETSC/HP used PCM in the ETSC and two storage tanks. In the second ETSC/HP, PCM was used in only ETSC, and the third one, PCM was used in only two storage tanks. Meanwhile, the fourth ETSC/HP remained without having PCM in it. Each heat pipe was filled with pure acetone at a rate of 0.7, and the experiments were carried out at two different water flow rates. The findings indicated that the use of PCM in both the ETSC and the two tanks next to it (the first case) improves the efficiency by 56%, while the use of PCM only in the ETSC (the second case) and the use of phase change material only in the side tanks, it leads to an efficiency increase of 50% and 37%, respectively, compared to the collector without PCM. The performance summary of each system is compared in Fig. 5. In this figure, ETSC/HP (A) represents the system without PCM material, ETSC/HP (B) includes two additional PCM tanks, ETC/HP (C) features PCM material inside the ETSC along with two additional PCM tanks, and ETSC/HP (D) has PCM located inside the ETSC. This research clearly showed the positive effect of using PCM materials in solar systems, especially in solar vacuum systems.

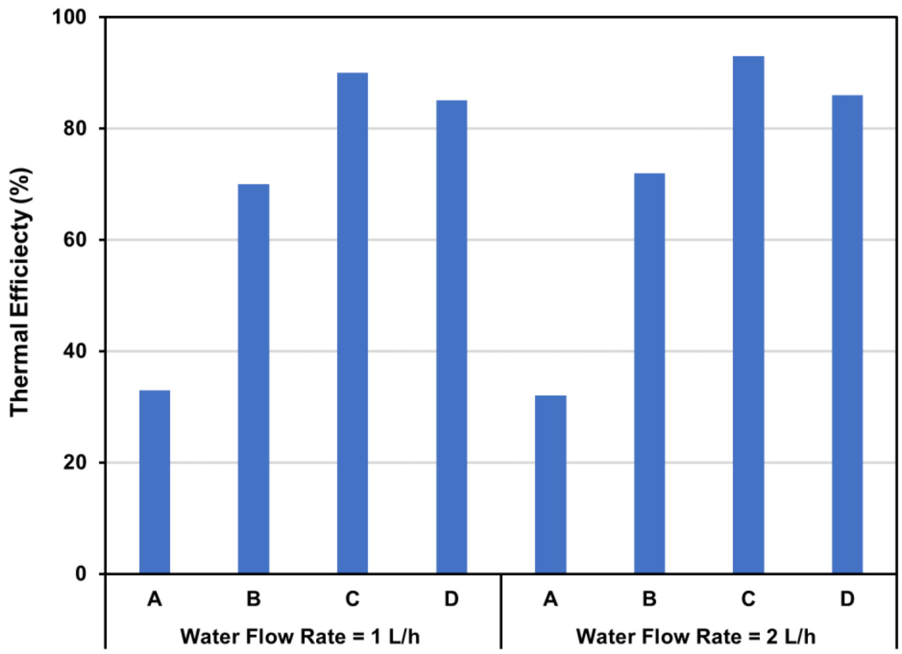

Fig 4. The effect of ETSC/HP systems configuration on their daily efficiency [28].

By embedding PCM within metal foam and incorporating plate fins, the efficiency of heat transfer and energy storage is significantly increased. Numerical simulations showed that this configuration can reduce the time required for the heat storage and release process by up to 9% compared to using PCM alone. The combination of metal foam and fins optimizes the thermal management within the system, highlighting the potential for PCM to enhance ETSC performance [29]. Additionally, annual performance evaluations of ETSCs using PCM (such as acetamide) for thermal storage have shown that these systems can effectively provide hot air even during non-sunny periods. This consistency in energy supply demonstrates the practical benefits of PCM in ensuring a reliable and efficient energy output throughout the year [30]. Numerical studies on ETSCs incorporating Nano-PCM with fins have highlighted significant enhancements in thermal performance. Adding copper nanoparticles to paraffin wax PCM improves heat absorption and storage, resulting in higher efficiency and better thermal management. This integration of nanotechnology with PCM shows promising potential for further optimizing solar collector systems [31]. Furthermore, integrating PCM into ETSCs has been shown to improve overall system efficiency by enhancing energy storage, reducing temperature fluctuations, and increasing reliability. Computational fluid dynamics (CFD) modeling of ETSCs with PCM and nanofluids reveals that combining these materials can significantly optimize heat transfer and storage, making solar collectors more efficient and effective [32].

2.5. Cost impact and efficiency improvement

The economic analysis of evacuated collectors is crucial for assessing the feasibility of integrating this technology into industrial systems.

In 2005, Morrison et al. [33] focused on measuring and simulating the flow rate in a water-in-glass evacuated tube solar water heater. The researchers found that the circulation flow rate through the tubes greatly impacted the temperature of the fluid in the tank and the intensity of the radiation on the absorber. The study included the use of 21 evacuated tubes and reported an optical efficiency of 0.58. Additionally, the research suggested that a pre-heater system with an evacuated collector could achieve an annual energy saving of 45% in Sydney. Mangel et al. [34] discussed the durability and maintenance advantages of evacuated tube solar collectors (ETSCs) over flat plate collectors (FPCs). It was mentioned that ETSCs are strong and long-lasting, and if any tube breaks, only the broken tube needs replacement, which is cheaper compared to replacing the entire flat plate collector. The reference emphasized the cost-effectiveness and lower maintenance requirements of ETSCs, particularly highlighting their advantage in below zero temperatures where anti-icing systems are necessary for FPCs. Arefin et al. [35] carried out research on the characteristics and economic assessment of an automated solar water heating system in Bangladesh. It was determined that a solar water system has a durability of 30 years, significantly longer than the 5-year lifespan of an electric water system. The cost analysis showed that after implementation, solar water heaters have zero upkeep costs, making them more advantageous and economical than electric water systems. The operating temperature of the system was found to be 50°C, sufficient for domestic use, and the system proved to be more economical over its lifespan. Tang and a team of researchers [36] examined the effect of various angular positions on the efficiency of solar water heaters with ETSCs. The study constructed two identical systems with angular positions of 22° and 46°. The findings revealed that while the heat removal to the water storage tank was not affected by the angular positions, the daily solar heat gain and radiation were significantly influenced. It was concluded that for maximum annual solar radiation and heat gain, collectors should be inclined at an optimal angle, maximizing the efficiency of solar water heaters. Budihardjo et al [37] evaluated the performance of water-in-glass evacuated tube solar water heaters. It was found that the optical and heat loss characteristics play a crucial role in the overall efficiency of the system. The study compared the performance of ETSCs with flat plate collectors (FPCs), reporting that 2-panel flat plate arrays exhibited higher efficiency compared to 30 evacuated tube arrays. The research emphasized the importance of design parameters in enhancing the performance of solar water heaters. Shukla et al. reviewed [38] recent advances in solar water heating systems, particularly focusing on the performance of ETSCs. It highlights that ETSCs can produce higher temperatures compared to FPCs, making them more efficient for various applications. However, the initial cost of ETSCs is higher, which has limited their widespread adoption. The paper suggested that despite the higher initial investment, the long-term benefits and efficiency of ETSCs make them a superior choice for solar water heating.

3. Conclusion

This paper provides a comprehensive review of research on evacuated tube solar collectors and underscores their considerable potential for applications in both the industrial and residential sectors. ETSCs have been utilized for various applications including water heaters, air conditioning, and heating, among others. These collectors are particularly advantageous for higher temperature applications due to their ability to easily achieve and maintain high temperatures, even in cold weather conditions. In countries with ample sunshine, ETSCs demonstrate exceptional efficiency. Furthermore, integrating ETSCs with nanofluids and phase change materials (PCMs) could revolutionize these systems, as such combinations can substantially enhance their performance. A summary of the reviewed papers is presented in Table 1.

Table 1. Overview of the reviewed papers and their potential gap topics.

Ref.	Analysis	Collector	Fluid	Summary	Potential Gap
[2]	Numerical	Evacuated	Water, nanofluid	Performance comparison of evacuated flat plate collectors with conventional panels.	Lifecycle cost analysis of different solar collectors.
[3]	Experimental	Both	Water	Performance comparison of FPSC and ETSC for domestic water heating systems in Kerman, Iran.	Generalizability of the results to other climatic regions. Long-term performance variation and maintenance considerations.
[4]	Experimental	Evacuated	Water	Evaluation of a novel space heating system using evacuated flat plate collectors.	Integration feasibility in existing building systems.
[5]	Experimental	Evacuated	Water	Providing scenarios for enhancing vacuum U-tube solar collectors efficiency.	Comparative long-term performance under real conditions.
[6]	Experimental	Evacuated	Water	Experimental and CFD study of heat transfer in ETSC.	Material innovations for improved thermal efficiency.
[7]	Numerical	Evacuated	Water	Optimization of solar collectors using simulated annealing and CFD modeling.	Practical field implementation and validation.
[8]	Experimental	Evacuated	Water	Using the F-chart method to evaluate FPSC and ETSC performance.	Study of the Impact of different installation configurations on efficiency.
[9]	Experimental	Evacuated	Water	Performance comparison of different absorber shapes in ETSC.	Evaluation of the performance in varying environmental conditions.
[10]	Experimental	Evacuated	Water	Experimental assessment of different vacuum tube configurations.	The durability of tests under extreme weather conditions.

[11]	Experimental	Evacuated	Water	Evaluation of the effect of aluminum fin thickness on ETSC performance.	Long-term stability and degradation study.
[12]	Experimental	Evacuated	Water	Experimental evaluation of SR-EVTC with copper annular fins.	Scaling up of the system for industrial applications.
[13]	Experimental	Evacuated	Water	Enhancement of a vacuum tube collector system by integrating sensible storage materials and copper fins to improve thermal performance, reduce overheating, and stabilize heat output.	Applicability of the findings to other system configurations. Long-term durability of the integrated materials and their performance under varying environmental conditions.
[14]	Numerical	Evacuated	Water	Evaluation of the effect of dust deposition on solar collector efficiency in arid environments.	Study of optimal cleaning techniques and cost analysis.
[15]	Numerical	Evacuated	Water	CFD analysis of metal foam integration in vacuum tube collectors.	Experimental validation of CFD predictions.
[16]	Numerical	Evacuated	Water	Numerical study of water-in-glass ETSC.	Field testing to validate theoretical results.
[17]	Experimental	Evacuated	Water	Energy and exergy assessment of reflectors in ETSC/HP.	Comparison with alternative enhancement techniques.
[18]	Experimental	Evacuated	Nanofluid	Use of WO_3/Water nanofluid in ETSC.	Evaluation of environmental impact and sustainability of the nanofluids.
[19]	Experimental	Evacuated	Nanofluid	Evaluation of the effect of nanoparticle volume fraction in improving collector efficiency.	Long-term stability and economic feasibility of the nanofluids.
[20]	Numerical	Evacuated	Nanofluid	CFD study to compare thermal performance of pure water and nanofluids in ETSC.	Optimal nanofluids composition for maximum efficiency.
[21]	Numerical	Evacuated	Nanofluid	Use of magnetic nanofluids to enhance ETSC efficiency.	Field testing and scalability in real-world applications.
[22]	Numerical	Evacuated	Nanofluid	Analysis of thermal and thermodynamic effects of using CuO-based nanofluids in solar collectors.	Long-term stability and practical implementation challenges in real-world solar collector systems.
[23]	Numerical	Evacuated	Water, PCM	Integration of PCM into ETSC for thermal storage.	Comparison of different PCM materials under varying conditions.
[24]	Experimental	Evacuated	PCM	Assessment of a solar dryer enhanced with a porous absorber plate and phase change material (PCM) heat storage.	Generalizability of the results. Long-term stability and maintenance requirements of the PCM and porous materials.
[25]	Numerical	Evacuated	PCM	Exploration of thermal management of finned solar cells will various fin shapes (circular, triangular, square, rectangular) using nanofluids and PCMs.	Lack of experimental validation to confirm the findings. Investigation of the practical implementation of the proposed designs in real-world applications.

[26]	Experimental	Evacuated	Water, PCM	Numerical analysis of PCM-enhanced solar water heaters.	Experimental validation under real operational conditions.
[27]	Experimental	Evacuated	Water, PCM	Use of fans to improve heating efficiency in solar air collectors with PCM.	Economic analysis of PCM-fan combination in different climates.
[28]	Experimental	Evacuated	Water, PCM	Experimental evaluation of PCM and separate storage tanks in solar collectors.	Providing optimization strategies for better energy retention.
[29]	Experimental	Evacuated	Water, PCM	Assessment of the effect of PCM and vibration on ETSC efficiency.	Comparison with other heat storage methods for solar systems.
[30]	Experimental	Evacuated	Water, PCM	Annual performance evaluation of ETSC with PCM storage.	Scalability of PCM-enhanced systems for industrial use.
[31]	Numerical	Evacuated	Water, PCM	Numerical study on nano-PCM integration for improved heat transfer.	Material selection for optimal performance in different regions. Experimental validation to verify the results
[32]	Experimental	Evacuated	Water, PCM	Experimental analysis of phase-change fluid impact on ETSC efficiency.	Providing potential alternative PCMs for different climates.
[33]	Both	Evacuated	Water	Study on flow rate impact in water-in-glass evacuated tube solar collectors.	Study of optimization strategies for better fluid circulation.
[34]	Review	Both	Water, nanofluid, PCM	Comparison of durability and maintenance aspects of ETSC and flat plate collectors.	Long-term operational costs and real-world case studies.
[35]	Experimental	Flat plate	Water	Economic and durability assessment of automated solar heating systems.	Payback period comparison for different solar technologies.
[36]	Experimental	Evacuated	Water	Study on the effect of tilt angle variations on solar water heater efficiency.	Study of optimal angles for different geographical locations.
[37]	Numerical	Both	Water	Performance evaluation of water-in-glass evacuated tube solar heaters. Comparison of its performance with flat plate ones.	Investigation of Heat loss mechanisms and mitigation strategies.
[38]	Review	Both	Water, nanofluid, PCM	Review of recent advances in solar water heating systems with ETSC focus.	Policy and incentive analysis for solar adoption worldwide.

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