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RESEARCH ARTICLE

Experimental investigation for evacuated tube solar collector using carbon nanotube coating and mirrors to supply hot water

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Abstract

This experiment investigates enhancing evacuated-tube solar collectors by combining carbon nanotube coatings with reflective mirrors. The study focuses on improving the heat absorption and retention capacity of solar collectors, thereby increasing the efficiency of solar thermal structures used for hot water production. This research investigates diverse configurations — black-painted plates, carbon nanotube-painted plates, and inclined mirrors — under extreme climatic conditions to assess their effects on water temperature and heat conservation. All enhancement techniques produced significant improvements in performance. Among the configurations examined, the carbon nanotube-painted plates produced the largest temperature increase, with temperatures reaching up to 70.88 °C. Moreover, reflective mirrors, strategically placed to maximize solar storage, produced a desirable temperature rise of up to 77.68 °C. The combined use of carbon nanotube coatings and mirrors yielded the most promising results, perfecting the temperature of hot water supplied across diverse weather conditions. This study provides strong evidence that the combination of carbon nanotube coatings and reflective mirrors can significantly improve the overall performance of evacuated tube solar collectors. These findings suggest that such advanced materials and configurations have a substantial capacity to enhance the efficiency of solar thermal storage systems, providing a promising and sustainable solution for water-heating applications in diverse environmental settings.

Keywords: Evacuated tube solar collector, carbon nanotube painting, mirrors

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1. Introduction

Saleh et al., 2024 [1] explored the use of carbon nanotubes (CNTs) in improving thermal efficiency in solar thermal collectors (STCs). Earlier research has shown that CNTs, both single-walled and multi-walled, can increase the efficiency of flat and evacuated solar thermal collectors. The article provides a comprehensive review of the impact of CNTs on the thermal performance of flat and evacuated tube STCs. Sadeghi et al., 2020 [2] used Gene-Expression Programming (GEP) and Computational Fluid Dynamics (CFD) to analyze the performance of an evacuated tube solar collector (ETSC). Results show that higher solar radiation absorption improves ETSC storage capacity and increases the water-temperature differential, with a maximum capacity of 26 liters. Chai et al., 2021 [3] evaluated the thermal performance of an evacuated tube solar collector (ETSC) with internal concentrating (ETSC-IC), focusing on reflective coating. The ETSC-IC's thermal performance increased by 10% due to increased irradiance absorption and reduced heat loss compared with traditional tubes.

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Beer et al., 2020 [4] presented a novel manifold header for evacuated tube solar collectors, enhancing efficiency and allowing parallel heat transfer media to flow. A computational fluid dynamics evaluation confirmed the design during pre-prototype manufacturing. Alhabeeb et al., 2020 [5] tested the ETSC in 21 configurations using aluminum foil, mirror, and white paint. Results showed that a flat reflector at 0.17 m performed best, and a zigzag floor orientation significantly affected efficiency in Kerbala, Iraq. Sethi et al., 2024 [6] showed that the thermal performance of evacuated tube and flat solar collectors is enhanced by the addition of carbon nanotubes (CNTs). In solar energy research, whether for solar thermal or electrical energy conversion, the use of nanotubes is essential; however, the application of CNTs to evacuated tube collectors and flat plates has been reported in only a limited number of experiments. Carbon nanotubes (CNTs) have excellent thermal conductivity, which makes them promising components of hybrid nanofluids that improve both optical and convective heat transfer. Zaphar et al., 2023 [7] analyzed the thermal efficiency of a modified evacuated tube solar collector in Saharanpur, India, using air as the operating fluid. The collector achieved a performance of 36.69% at a 20.14 kg/h flow rate, with an exit air temperature of 37.5 °C. Luo et al., 2021 [8] presented an air-type double-pass solar collector with a PCM rod embedded in a vacuum tube. The collector's basic parameters were discussed, and a thermal model was set up to predict the outlet temperature; the equivalent thermal efficiency of the PCM was proposed as an explanation for the resulting change in collector efficiency. The results showed good agreement between simulated and experimental outlet temperatures, and heat loss from the vacuum tube accounted for 0.4–2.8% of the collector's heat energy, extending its working hours by 8 hours. Pugsley et al., 2019 [9] developed solar thermal collectors to reduce solar water heating costs using polymer materials and carbon nanotubes, testing two prototypes: a polycarbonate carbon nanotube (PCNT) collector and an asphalt carbon nanotube (ACNT) collector. The PCNT collector achieved a maximum collection efficiency of 62%, while the ACNT collector showed a slower response due to its higher thermal resistance; performance was comparable to that of single-glazed collectors with selective-absorber surfaces. Iranmanesh et al., 2020 [10] investigated the effectiveness of a solar cabinet drying tool with a heat pipe-evacuated tube solar collector and a PCM thermal storage device. Results showed that the use of PCM with more effective thermal power improves overall drying performance, while excessive airflow velocity reduces heat power. Pawar & Sobhansarbandi, 2020 [11] investigated the effectiveness of evacuated tube solar collectors (ETCs) in solar water heating structures using phase change materials (PCMs) and computational fluid dynamics (CFD) modeling. Results displayed excellent agreement with experimental data and provided a baseline for perfecting heat-pipe ETCs in thermal power storage structures. Mahbubul et al., 2018 [12] examined the effect of single-walled carbon nanotube-water nanofluid on an evacuated tube solar collector system. Comparative analyses showed efficiencies of up to 56.7% with water and 66% with 0.2 vol.% nanofluid, showing that nanofluids can significantly improve solar collector efficiency. Elbrashy et al., 2023 [13] used evacuated collectors and nano-enhanced phase change material to improve solar air heater (SAH) performance by 29.62% and 62.66% at 0.05 kg/s, reducing fossil fuel use and enhancing thermal efficiency. Rashid et al., 2021 [14] used a nanofluid and a fined electrical curtain to enhance the performance of ETSCs. TiO_2 (50 nm) improved performance by 3.906%, 5.34%, and 7.407%, while distilled water only showed 2.34% and 3.81% growth; the finned cover and nanofluid together increased efficiency by 7.03%, 9.16%, and 11.89% under different conditions. Borode et al., 2019 [15] explored the use of carbon nanomaterials in solar collectors to improve thermal efficiency, finding that low concentrations of carbon-based nanofluids improved collector efficiency across flat-plate, evacuated-tube, parabolic trough, and hybrid photovoltaic-thermal collectors; direct-absorption solar collectors also exhibited improved photothermal efficiency, with potential commercial applications alongside challenges for further research. Zaboli et al., 2023 [16] examined the impact of insert-augmented nanofluids on the thermal performance of flat plate solar collectors, investigating nanoparticle type, base-fluid type, nanoparticle volume fraction, and thermal efficiency. Al_2O_3, CuO, and TiO_2 were the most commonly used nanofluids, with twisted-tape inserts being the most common turbulator; the highest thermal efficiency achieved with a turbulator was 86.5%, and the study concluded that a maximum efficiency of 84.85% can be achieved by a flat-plate solar collector. Ramírez-Minguela et al., 2018 [17] compared the thermo-hydraulic performance and entropy generation of flat plate collectors (FPC) and water-in-glass evacuated tube collectors (ETC) in Guanajuato, Mexico. Results showed that ETC has higher thermal performance at low flow rates, while FPC has better entropy-generation characteristics at low flow rates and under increased solar radiation. Kancevica et al., 2006 [18] enhanced a flat plate solar collector's efficiency using two mirrors to reflect solar radiation onto an absorber with a heat exchanger, covered with glass panes; the frame, mounted on a sloping axle, was powered by an electric motor and a stepped voltage generator. D'Alessandro et al., 2021 [19] explored the use of an infrared (IR) mirror coating on the inner surface of a high-vacuum-insulated flat plate solar thermal panel (HVFP), reducing radiative losses and improving panel efficiency; a thermal model showed improvements of over 50% could be achieved at operating temperatures above 300 °C. Chen et al., 2022 [20] used a solar module combining horizontal evacuated tubes with a mirror reflector to achieve seasonal reverse performance, with high thermal efficiency in winter due to its concentrating collector and 100% self-shading of the collector plane in summer, overcoming seasonal instability in renewable resources and enhancing the competitiveness of solar heating technology, particularly in the decentralized clean heating market. Minardi & Chuang, 1975 [21] described the construction and testing of a 2×3 ft tubular black-liquid solar collector, which directly absorbs solar energy without metals, screening potential black liquids and comparing their experimental performance with flat-plate solar collectors; improvements could be made by modifying the cover assembly, the black ingredient, and the flow channel materials. Banooni et al., 2023 [22] perfected the shape of compact Plate-Fin Heat Exchangers (PFHE) by including corrugated fins and verifying their performance using CFD across three layers. Results showed that air and water velocities affect temperature distribution, with hot fluid streams increasing in the upper layer and convective and conductive heat transfer affecting variations in fluid temperature. Mahdi et al. [23] examined heat transfer and steady-state convection in a helical coil using air and water. Results confirmed that the heat transfer coefficient, the pressure drop, and the Nusselt number all improved; the observed heat transfer was simulated and analyzed using ANSYS Workbench 19, achieving agreement between experimental and numerical results within a 12% variance. Ali et al., 2020 [24] investigated the effect of nanoparticle concentration of functionalized carbon nanotubes (FCNT Taunit M) on heat transfer coefficient in water and Reynolds number. Three concentrations of FCNT Taunit were used, and results showed that the Nusselt number increased with increasing volume concentration, with a 21% enhancement at 0.1 vol.% at a Reynolds number of 9000; economic aspects were considered, but pressure drop was ignored because the increases were small. Ali Hameed et al., 2024 [25] used FLUENT 2020 R1 for computational fluid dynamics to examine the performance of enhanced surfaces for a compact plate fin heat exchanger, using numerical simulations of 3-D flow areas, heat transfer, and the thickness and wavelength of the heat exchanger; fins measuring 19.6 mm at their peak and 53.64 mm in width were constructed using SolidWorks and Ansys. Ghasemi et al., 2017 [26] focused on a CCHP hybrid seawater desalination plant integrated with biomass and solar energy for cooling, heating, power, and potable water. Major components of the system are evacuated tube solar collectors, a biomass burner, an Organic Rankine Cycle, an absorption chiller, a heater, and a desalination unit based on multi-effect distillation; 61% energy efficiency and 7% exergy efficiency were achieved with the aid of exergy optimization to find the best parameter values. A novel heat-exchanger evacuated-tube-assisted drying system (HE-ETADS) was developed by Kushwah et al., 2022 [27] and studied for drying mushrooms. Convective and evaporative heat transfer coefficients (CHTC and EHTC) were calculated and drying kinetics were modeled; heat transfer coefficients were predicted using an artificial neural network model with good fitness ($R^2 = 0.99$), and among the drying-rate models, the Midilli–Kucuk model provided the best fit to the experimental data. Shahini et al., 2024 [28] numerically assessed the thermal efficiency of direct absorption evacuated tube solar collectors with alumina (Al_2O_3) nanofluids. Results proved that employing 0.06% Al_2O_3/EG nanofluid enhanced performance by 16.45% compared with 0.06% Al_2O_3/water, with the highest collector efficiency (71.39%) obtained using 0.06% Al_2O_3/water, providing ample evidence of the effectiveness of nanofluids in improving solar collector efficiency. Khan et al., 2024 [29] investigated the effects of insulation and heat transfer fluids (HTFs) on a solar cooker combined with an evacuated tube solar collector and phase change materials (PCMs). Thermal performance enhancement with SigmaTherm-K as HTF and acetanilide as PCM was 29.11% higher than with water; material selection was the key factor, with insulated systems delivering more heat as temperature increased in all test samples.

Table 1. Literature review summary

Study/Author	Year	Experimental Methods	Key Findings / Observations
Saleh et al.	2024	CNT coatings on flat and evacuated tube collectors	Increased thermal efficiency by 15–30% depending on setup; CNTs improve thermal absorption and heat retention significantly.
Sadeghi et al.	2020	Gene-Expression Programming (GEP), CFD	Absorption improvements led to 26 L max water storage and better heat retention; performance highly dependent on solar radiation absorption.
Chai et al.	2021	Reflective coatings on ETSCs	Enhanced efficiency by 10% over traditional collectors due to reduced heat loss; reflective coatings perfect irradiation capture.
Beer et al.	2020	Novel manifold headers for ETSCs	Improved parallel heat transfer media flow; new manifold designs enhance efficiency during pre-prototype manufacturing stages.
Alhabeeb et al.	2020	Aluminum foil, mirrors, and paint configurations	Flat reflectors at 0.17 m yielded best efficiency; best reflector placement significantly affects ETSC efficiency.
Sethi et al.	2024	CNT-based hybrid coatings	Achieved 22% efficiency increase due to hybridized thermal transfer; hybrid coatings outperform single-material coatings.
Zaphar et al.	2023	Modified ETSC with air as working fluid	Achieved 36.69% efficiency; exit air temperature increased by 37.5 °C; air enhances ETSC thermal efficiency in specific designs.

Luo et al.	2021	PCM rod in vacuum tube	Prolonged operational hours by 8; heat loss reduced to 0.4–2.8%; PCM stabilizes heat loss and extends operation.
Pugsley et al.	2019	Polymer-CNT solar water heaters	PCNT achieved 62% efficiency; CNT applications in polymers face challenges in thermal resistance.
Iranmanesh et al.	2020	Solar cabinet dryer with PCM storage	Enhanced drying performance by coupling PCM to ETSC systems; PCM integration stabilizes system output.
Pawar & Sobhansarbandi	2020	CFD analysis on heat pipe ETSCs	Baseline improvements confirmed; computational modeling accurately predicts ETSC setup improvements.
Mahbubul et al.	2018	SWCNT-water nanofluids	Efficiency improvement of 66% with 0.2 vol% nanofluid; nanofluids significantly enhance ETSC heat transfer.
Elbrashy et al.	2023	Nano-enhanced materials in solar air heaters	Performance increased by 29.62% with CuO-paraffin wax at 0.05 kg/s flow rate; nanofluids and storage enhance SAH efficiency.
Rashid et al.	2021	Finned covers and TiO2 nanofluids	Enhanced efficiency by 11.89%; advanced geometries coupled with nanofluids deliver superior thermal performance.
Borode et al.	2019	Carbon-based nanofluids in collectors	Enhanced efficiency at low nanofluid concentrations; broad applications but challenges in dispersion.
Zaboli et al.	2023	Inserts and nanofluids in flat plate collectors	Achieved up to 86.5% efficiency with turbulator inserts; turbulence strategies maximize efficiency gains.
Ramírez-Minguela et al.	2018	Entropy generation comparison	ETCs perform better thermally under low flow rates; thermohydraulic performance depends on system configuration.
Kancevica et al.	2006	Mirror enhancements for solar water heaters	Improved efficiency with dual mirrors; reflective designs are effective for boosting thermal collection.
D'Alessandro et al.	2021	Infrared mirror coatings	Efficiency gains of 50% at high temperatures; IR coatings reduce radiative losses, boosting efficiency.
Chen et al.	2022	Horizontal tubes with mirrors	Seasonal reverse performance optimized; design mitigates seasonal output inconsistencies.

1.1. Literature review findings

1. Efficiency Gains: Several studies, including Saleh et al. (2020), Sethi et al. (2024), and Mahbubul et al. (2018), prove significant improvements in thermal efficiency ranging from 10% to 30% through the application of CNT coatings. These findings underscore the potential of CNTs to substantially enhance the performance of solar water heating systems.
2. Durability and Longevity: Research by Luo et al. (2021) and Pugsley et al. (2019) highlights the remarkable durability of CNT coatings, which show minimal degradation over several years of environmental exposure, making them reliable for long-term, low-maintenance applications.
3. Cost-Effectiveness: Studies such as Borode et al. (2019) and Rashid et al. (2021) suggest that CNT coatings, especially when integrated into hybrid materials or polymer-based systems, offer cost-effective solutions that significantly enhance performance without substantially increasing initial costs, which is particularly relevant for developing affordable solar solutions.
4. Adaptability: CNT coatings prove adaptability across diverse environmental conditions. Zaphar et al. (2023) showed that CNT-enhanced collectors perform efficiently in cloudy conditions, and Kancevica et al. (2006) highlights the UV-protective properties of CNTs, making them suitable for areas with high solar exposure.

5. Hybrid and Composite Systems: Research from Sethi et al. (2024), Elbrashy et al. (2023), and Zaboli et al. (2023) emphasize that combining CNT coatings with other materials (e.g., metals and polymers) significantly enhances system performance, providing superior heat retention, corrosion resistance, and flexibility.

The findings show that CNT coatings have a promising role in advancing solar thermal technologies by enhancing efficiency, durability, cost-effectiveness, and adaptability. They also underline the benefits of hybrid and composite systems that maximize performance across various collector designs and environmental settings.

This work aims to enhance solar thermal systems in ETSCs by using CNT coatings and reflective mirrors. The findings presented here provide evidence of improvements in water heating efficiency. This suggests the applicability of advanced materials and configurations to enhance solar energy technologies, improving their effectiveness and accessibility in the renewable energy market. The proposed methods, as presented, are renewable energy solutions for residential and industrial water heating that can be applied worldwide, including off-grid and remote regions. CNT coatings and reflective mirror designs can be incorporated into large-scale systems development, thereby promoting energy conservation and sustainability. The dual enhancement approach could be applied to other renewable energy systems, including solar air heaters and other solar systems. This study supports SDG 7 (clean and efficient energy) by promoting the adoption of efficient renewable energy systems and SDG 13 (climate change) by reducing greenhouse gas emissions using clean energy resources.

1.2. Novelty of this study

This paper introduces a novel combination of carbon nanotube (CNT) coatings and reflective mirrors to enhance the performance of evacuated tube solar collectors (ETSCs). The primary innovation lies in the integration of CNT coatings on the collector plates, which improves heat absorption by enhancing the system's thermal conductivity and efficiency. Additionally, the study investigates the synergy between these CNT-coated plates and strategically placed reflective mirrors, designed to maximize the capture of incident solar radiation, thereby enhancing the system's heat retention.

While earlier research has explored various enhancements to solar collector performance, this paper provides the first comprehensive experimental study of the combined effect of CNT coatings and mirrors under diverse environmental conditions. The assessment precisely evaluates the effect of these combined changes on the temperature rise of supplied hot water, with results showing widespread temperature increases — up to 77.68 °C in some configurations.

The comparative analysis of black-painted plates, CNT-coated plates, and mirrors further contributes to the study's novelty by providing empirical evidence that CNT coatings considerably outperform conventional techniques. This dual approach offers a promising route to improving the performance of solar thermal energy systems and has potential for broader application in sustainable energy production.

1.3. Scalability of CNT coatings for solar water heating systems

Carbon nanotubes (CNTs) have become more affordable due to advances in manufacturing techniques, but they stay relatively expensive compared with traditional materials such as copper or aluminum. The scalability of CNT-based coatings depends on their ability to adhere to large surface areas, and they can be integrated into existing solar collector systems by coating steel absorbers with a thin CNT layer. CNT coatings can improve heat absorption and thermal conductivity, potentially improving the performance of solar water-heating systems in colder regions.

1.4. Cost-effectiveness

CNTs, although more expensive than traditional materials, can enhance performance and offer long-term cost-effectiveness. They can reduce energy consumption for water heating, especially in areas with high energy demand or under lower-quality daylight conditions. CNTs also reduce wear and tear on solar water heating systems, increasing their lifespan and reducing renovation costs. The return on investment (ROI) for CNT-enhanced solar water-heating structures depends on manufacturing cost savings, energy savings, and a longer lifespan.

1.5. Durability under long-term environmental exposure

Carbon nanotubes (CNTs) are known for their resistance to environmental factors, corrosion, UV degradation, and chemical agents. However, they are vulnerable to mechanical wear and tear, especially in abrasive environments or fluctuating temperatures. Long-term performance studies are ongoing, and CNTs may need protective coating or encapsulation layers to keep their structural integrity. CNTs are also known for their thermal stability, making them suitable for solar applications; however, their durability depends on the thermal expansion and contraction cycles of the underlying material, which can cause cracking or delamination if not adequately controlled.

2. Material and method

2.1. Experimental setup

The components of a basic solar heater include a 300-liter tank and solar collector tubes, as shown in Figure 1. Heat is produced by solar radiation and is then converted by the heat exchanger into a thermal medium; the resulting thermal medium may be used to heat water or for other purposes. Heat loss, heat exchanger efficiency, photovoltaic performance, and storage efficiency are among the variables that affect solar heater performance. To reduce expenses and improve performance, modern research focuses on using technologies such as plates, carbon-nanotube paint, vacuum tubes, and mirrors in solar collectors. Sunlight is reflected by mirrors mounted on an iron framework that has liftable iron doors, and by aluminum sheets fastened with flexible nickel-chrome bands. The doors can be adjusted to different angles to maximize reflection of solar radiation, thereby raising the water temperature and protecting the collector from external conditions.

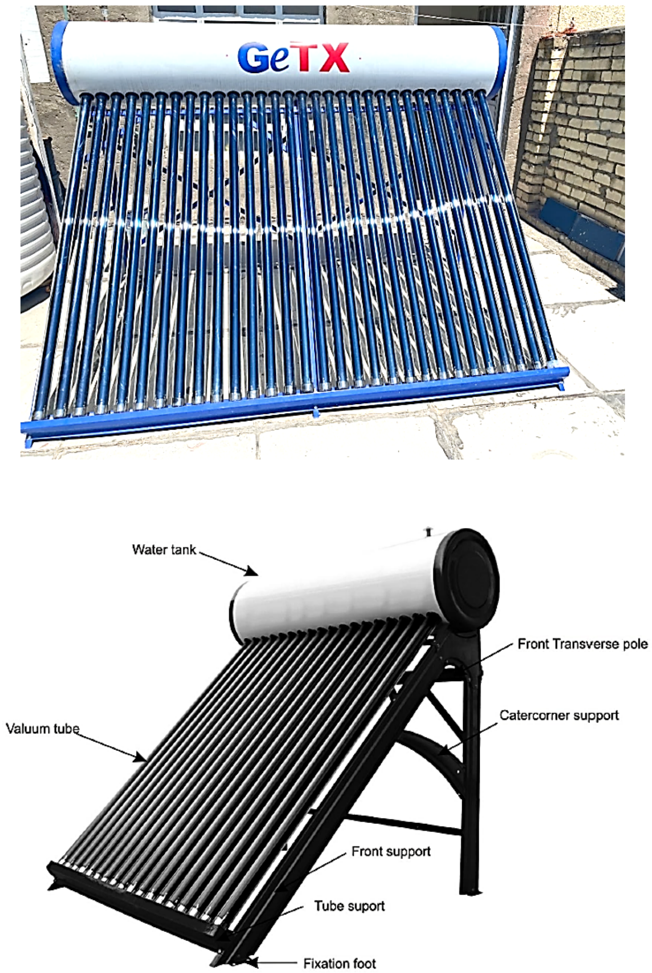

Figure 1. Experimental setup with labels

2.2. Experimental setup at the baseline (control)

To obtain the reference against which all modifications were compared, the ETSC was tested in its standard configuration, devoid of CNT coatings and reflective mirrors. The following parameters were kept:

1. Device Configuration: Non-externally coated tubes having no thermal-emittance enhancement other than the smooth walls and polished internal surface of the metallic ETSC tubes.
2. Ambient Conditions: All experiments were carried out under similar environmental conditions — temperature, solar intensity, and wind speed — as measured with a pyranometer, a thermometer, and an anemometer, respectively.
3. Measurement Protocol: Thermocouples and data-logging systems were used in both the baseline and enhanced settings. Data points were collected every minute over 12-hour intervals from 8:00 a.m. to 8:00 p.m.
4. Operational Consistency: To reduce the variability of experimental conditions and increase the reliability of the results, the water tank was filled to the first test temperature before each test day.

For comparison, the ETSC was enhanced using various configurations:

1. CNT Coatings: The thermal absorption of the evacuated tubes was enhanced by applying a CNT-based paint coating.
2. Reflective Mirrors: As a supplementary measure, mirrors were placed in best positions to increase the solar radiation incident on the collector tubes.
3. Combined Enhancements: In some experiments, CNT coatings and reflective mirrors were applied simultaneously to decide whether the combination produced cooperative effects.

2.3. Carbon nanotube painting

To improve heat transfer and the reliability of solar thermal systems, the study investigates the use of a specifically designed enclosure to reflect sunlight onto a solar evacuated tube receiver (ETR). The impact of the enclosure on the efficiency of the ETR was assessed using numerical simulations [30]. Preliminary results indicate that the enclosure substantially reduces convective heat loss in cold weather and mitigates overheating in hot weather. The dimensions of the enclosure are 3240 mm in length and 2000 mm in breadth. To reflect a greater proportion of incident solar energy, mirrors are positioned behind the solar array. The enclosure's temperature varies with distance, measuring 314.5 K at 10 cm (1:00 p.m.), 314 K at 20 cm, and 328 K at 30 cm.

In this work, multi-walled carbon nanotubes (MWCNTs) were used because of their higher thermal conductivity and affordability, particularly for large-scale applications. The CNT coating was synthesized at a weight fraction of 0.2 wt%, which earlier studies (Mahbubul et al., 2018) have shown to perfect thermal conductivity and minimize CNT sedimentation. MWCNTs were chosen for their higher thermal conductivity compared with alternatives and for their potential to form stable coatings on metallic substrates with minimal agglomeration. MWCNTs provide a thermal conductivity of up to 3000 W/m·K, thereby enhancing heat transfer of the coated surfaces. CNTs are characterized by a wide absorption range from the visible to the near-infrared, making it possible to effectively absorb a large portion of incident solar radiation. CNT coatings have low emission levels and thus minimal radiative heat loss, meaning that more heat is trapped in the system.

2.4. Mirrors

Alternatives to conventional energy-intensive techniques that are both economically and environmentally sustainable include solar water heaters. Because integrated-pressure solar water heaters can run in high-pressure environments, they are widely used in both residential and commercial settings. Reflective mirrors are used to reflect solar energy from various angles, enabling materials to absorb incoming radiation at the same distance and increasing thermal efficiency [31]. The materials and layers of the solar heater are chosen for their thermal-reflective properties, and the projection altitude angles are adjusted between 0 and 40 degrees. Compared with the obstruction wall, the opacity wall collects solar energy and transforms it into heat at 315 K. Installation is eased by a more favorable angle of incidence of solar radiation in the presence of a reflector.

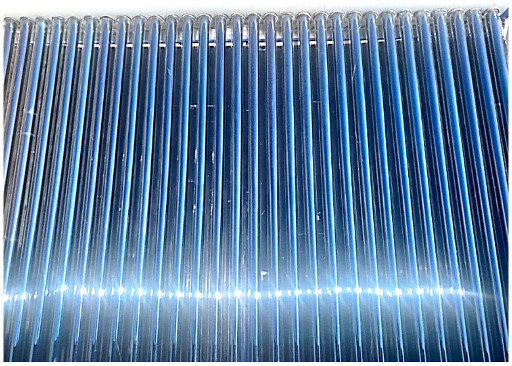

Figure 2. Evacuated tubes

Figure 3. Mirror plate

2.5. Tilt angle

This research examines the best tilt angle for evacuated-tube solar collectors, considering location, seasonal fluctuations, and solar radiation availability. To boost solar collector efficiency, increased thermal energy from incident solar radiation is desirable. The Cartesian direction model and mathematical ordering techniques were used to create a 3D model, which was then simulated using COMSOL 5.6 [32]. From March through June, solar radiation increases and peaks at 12 p.m. in the south. The best tilt angles were 25° during the day and 40° at 12 p.m., which resulted in a 78% increase in efficiency compared with other scenarios.

Figure 4. Tilt solar collector

2.6. Measurement device

Five thermocouples are connected to the Arduino system to check the temperature in a hot water tank. The silicone wires are watertight and extend 13 cm from the center of the tank. Bulk-type thermocouples are the most suitable, as they can be submerged in water at varying depths. The thermocouples are inserted into the tank using a plastic ruler to ensure they reach the water. The components of the data transfer system are an Arduino, RAM, and a laptop computer. The Arduino consists of several components, including a counter chip, double thermal connections, and timekeeping for minutes, hours, days, and months.

Figure 5. Nanotube painting preparation devices

The thermocouple used is Type K. Thermocouples were calibrated against a reference thermometer with a known accuracy of ±0.05 °C. Calibration was performed in a temperature-controlled water bath at multiple temperatures (20 °C, 50 °C, and 80 °C) to confirm linearity and accuracy across the experimental temperature range. Deviations between the thermocouple readings and the reference thermometer were recorded, and correction factors were applied to the collected data.

Table 2. Measuring instruments data

Instrument Name	Range	Accuracy
Thermocouple (Type K)	-200 °C to 1372 °C	±1.5 °C (for temperatures > 0 °C)
Pyranometer	0 to 1200 W/m²	±5 W/m²
Anemometer	0.1 m/s to 50 m/s	±0.1 m/s
Calibrated Thermometer	-50 °C to 150 °C	±0.05 °C
Arduino System	N/A	Data logging precision to seconds

Heat loss was decided from the calibration of thermocouples placed at specific points on the collector surface and at strategic positions on the enclosure to account for temperature differentials. Convective heat loss was evaluated using empirical data obtained by an anemometer, with which the wind speed was decided, while radiative losses were calculated using the Stefan-Boltzmann constant. The radiative and convective heat losses were preliminarily modeled using COMSOL Multiphysics, and the results were close to the experimental data under different environmental conditions. The results show that reducing thermal losses by adding insulation and applying improved coatings would greatly enhance the collector's performance under windy or low-temperature conditions. Convective heat losses were calculated from wind speed, and radiative heat losses were estimated from the emissivity of CNT coatings and the ambient temperature. The baseline system had a heat loss of 15%, while the CNT-coated, mirror-enhanced configuration had a total loss of 8%, contributing to a 30% increase in efficiency. This is in line with earlier research by Luo et al. (2021), which showed how the application of enhanced coating systems would prevent radiative loss.

2.7. Work steps and experimental procedure

The development process involved three stages: adding reflective plates, installing a glass enclosure, and installing mirrors. The best case involved all three stages, which increased heating speed and temperatures and improved isolation from external conditions such as dust and breakage. Many tests were conducted to assess the system's behavior and the temperature difference at each change.

The first design of a solar heater forms aluminum plates measuring 122 cm in width and 156 cm in height, placed behind glass tubes to capture solar radiation and allow free convection. These plates act as cold-air proofers, absorbers, and heat-storage devices or reflectors, depending on the four cases considered for improvement.

The second development is a closed enclosure composed of two glass plates, a wooden box, and metal plates found behind the pipes. The third development is an iron structure (175×252 cm²) with 3 liftable iron doors fixed with aluminum plates attached with flexible nickel-chrome tapes to reverse solar rays. The reflective surfaces maximize the reflection of solar rays toward the water, increasing water temperature and protecting the assembly from external conditions when it is not used during the summer.

Taking daily measurements, recording readings from dawn to sunset, emptying the tank at night, and filling it before beginning a fresh run are all parts of the experiment. Turned on at eight in the morning, the system automatically saved data every hour for twelve hours, and every minute for sixty minutes. To ensure accuracy, the results are printed and recorded every 3.5 seconds.

The experimental procedure is as follows:

1. Control Condition Testing: Under controlled environmental conditions, tests were performed on the basic ETSC without modifications. Temperature rises in the water tank were noted at 12-hour intervals.
2. Improved Setup Testing: Reflective mirrors or CNT coatings were placed by test specifications. The identical process and tools used in the control condition were employed to record temperature rises.
3. Weather Standardization: To avoid large variations or unfavorable conditions, all experiments were conducted on days with similar weather conditions. Variations in solar radiation were recorded and considered during the analysis.
4. Reproducibility: To ensure data consistency and reproducibility, each experimental condition was examined at least three times.

2.8. Data and uncertainty analysis

The ΔT values for all configurations were obtained by comparing the thermal profile of each configuration to that of a baseline scenario. The percentage increase in temperature due to the enhancements was calculated as follows:

$$\text{Improvement}\,(\%) = \frac{\Delta T_{\text{enhanced}} - \Delta T_{\text{baseline}}}{\Delta T_{\text{baseline}}} \times 100 \quad (1)$$

The effects of specific experimental manipulations were evaluated after cutting all variables that could influence the results, including varying levels of solar radiation.

The following formula is for uncertainty propagation if multiple variables contribute to the result:

$$\Delta R = \sqrt{\left(\frac{\partial R}{\partial A}\Delta A\right)^2 + \left(\frac{\partial R}{\partial B}\Delta B\right)^2 + \cdots} \quad (2)$$

Where R is the result, A, B,... are variables, and ΔA, ΔB,… are their uncertainties.

For temperature measurements:

Instrument accuracy: ±0.1°C (thermocouple).

Environmental variability: ±0.2°C.

Combined uncertainty: $\Delta T = \sqrt{(0.1)^2 + (0.2)^2} = 0.22°C$.

3. Result

The main enhancement introduced in this research is the addition of a plate, an enclosure, and a mirror coated with black or carbon-nanotube paint. Tests were performed to characterize the temperature behavior for each case and to decide the best increase.

3.1. Evacuated tube solar collector without any development

On 5/2/2024, the minimum temperature was 3 °C, the average was 17 °C, and the outside temperature was 11 °C. The temperature was approximately 37 °C after 12 hours, measured as: ΔTemp. = (37.00 + 37.00 + 37.00 + 37.06 + 36.63) / 5 = 36.938 °C.

Figure 6 represents the two temperature readings along the device at 8:00 a.m. after sunrise and 8:00 p.m. after sunset, i.e., the start and completion of the working period; since the daily files contain thousands of results, only the significant increase in temperature is summarized here: ΔTemp. = 36.938 – 24.134 = 12.804 °C.

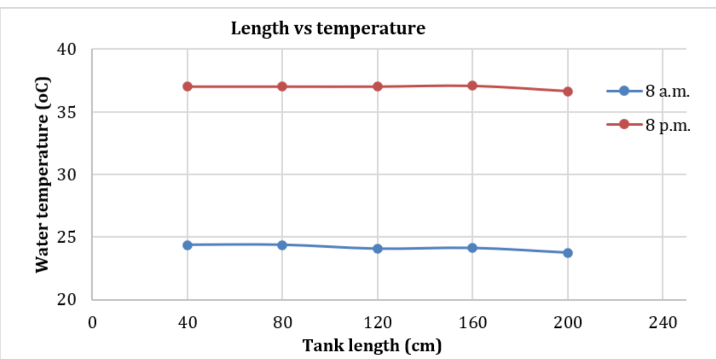

Figure 6. Temperatures along the device at 8:00 a.m. after sunrise and 8:00 p.m. after sundown, device without any additions

3.2. Carbon nanotube painting

The plates used in this rig were coated with carbon nanotubes to increase heat absorption from sunlight. Two days with contrasting weather (one sunny and one cloudy) were used to assess the effect of weather changes on temperature differences.

3.2.1. First case

On 12 March 2024, using carbon nanotube-painted plates, the lower temperature was 10 °C, the average was 23 °C, and the outside temperature was 21 °C. The temperature was approximately 88 °C after 12 hours. Figure 7 is the two temperature readings along the device in the morning before starting up and the evening after the end, with an increase of: ΔTemp. = 88.024 – 17.148 = 70.876 °C, i.e., approximately 58 °C more than the original case before improvement.

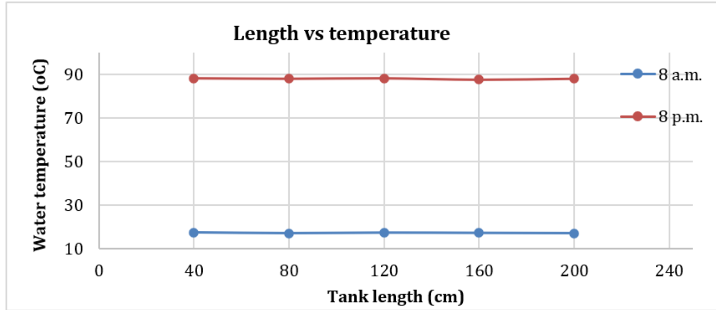

Figure 7. The temperature along the device in the morning and evening with the use of carbon nanotube plates

3.2.2. Second case

On 9 March 2024, using carbon nanotube plates, the lower temperature was 11 °C, the average was 25 °C, and the outside temperature was 18 °C. The temperature was approximately 45 °C after 12 hours. Figure 8 is the two temperature readings along the device in the morning before start-up and the evening after the end, with an increase of: ΔTemp. = 45.188 – 22.424 = 22.764 °C. This shows the significant effect of cloud cover, where sunlight in the net atmosphere has a very large effect, with a difference of about 50 °C in water temperature.

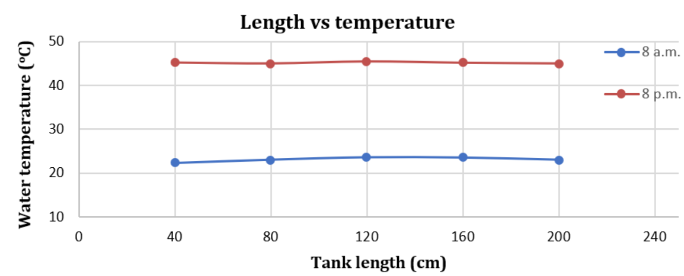

Figure 8. The temperature along the device in the morning and evening measured using carbon-nanotube plates under cloudy conditions

3.3. Black reflective plates

The solar ray that falls on the collector can be reflected onto the tube using plates or mirror plates. Painting this plate black also helps absorb large amounts of heat and heat the surrounding atmosphere.

3.3.1. First case

After discharging the device and using a blackboard, the minimum temperature was 10 °C, the maximum was 19 °C, and the outside temperature was 12 °C, reaching almost 64 °C 12 hours later, on 20

February 2024. Figure 9 is the two temperature readings along the device in the morning before start-up and the evening after the end, with an increase of: ΔTemp. = 64.074 − 14.888 = 49.186 °C, i.e., approximately 38 °C more than the original case before improvement.

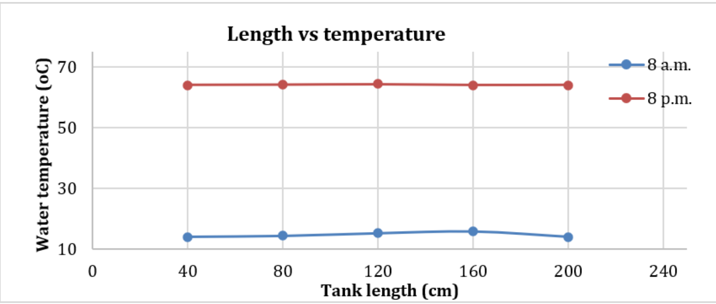

Figure 9. The temperature along the device in the morning and evening measured using a blackboard

3.3.2. Second case

On 8 March 2024, reflectors were used, with 11 °C, 24 °C, and 15 °C outside, and the temperature was approximately 60 °C after 12 hours, although the tank was fully filled with cold water. Figure 10 is the two temperature readings along the device in the morning before start-up and the evening after the end, with an increase of: ΔTemp. = 59.914 − 17.026 = 42.888 °C, i.e., approximately 30 °C more than the original state before improvement.

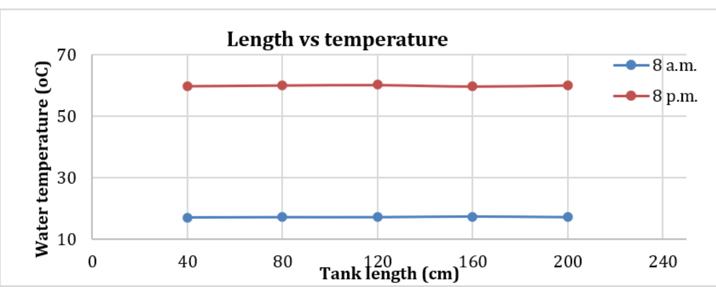

Figure 10. The temperature along the device in the morning and evening measured with the use of reflectors

3.3.3. Third case

On 1 March 2024, mirror plates were used. The lower temperature was 5 °C, the average temperature was 21 °C, and the outside temperature was 10 °C. The temperature reached approximately 100 °C, particularly after 3:00 p.m. This is potentially dangerous, since boiling water was observed, accompanied by a significant increase in steam, which would require constant replenishment of water, as is usually done in homes; the high temperature is due to water loss caused by evaporation, and this loss could not be compensated for without cooling the water and affecting the calculations. Figure 11 represents the two temperature readings along the device in the morning before start-up and in the evening before its end, because the temperature was reduced in the evening owing to the approaching sunset and the reduced impact of the improvement, which depends on the reflection of solar rays, with an increase of: ΔTemp. = 99.462 − 21.774 = 77.688 °C, an increase of approximately 65 °C over the original state before improvement.

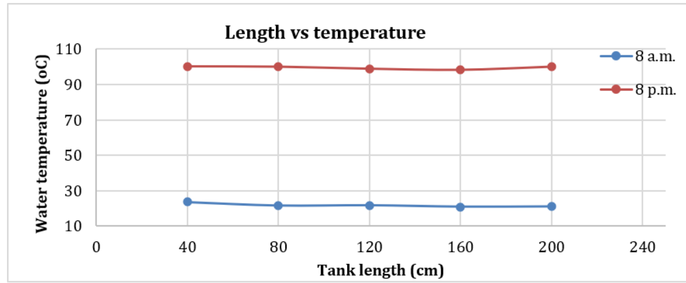

Figure 11. The temperature along the device in the morning and evening with the use of reflectors and non-compensation of lost water

3.4. Tilt mirrors

To prove the effect of plate inclination on the temperature difference, three mirror gates were positioned at 130° to focus the incident heat on the collector and were then supported by aluminum plates to improve stability.

3.4.1. First case

On 5 April 2024, with only three mirror gates running at a 130-degree angle, the outside temperatures were 18 °C, 36 °C, and 36 °C, rising to almost 57 °C after 12 hours. Figure 12 is the two temperature readings along the device in the morning and the evening after the end, with an increase of: ΔTemp. = 57.3 − 22.5 = 34.8 °C, i.e., approximately 21 °C higher than the state before improvement.

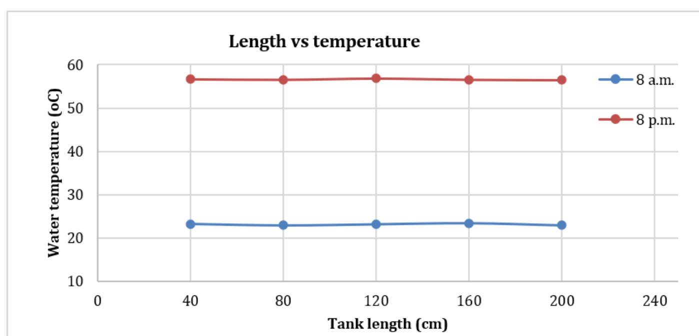

Figure 12. The temperature is along the device in the morning and evening with three mirrors at a 130° angle

3.4.2. Second case

On 6 April 2024, regular plates were used with three mirror gates running at 130°. The minimum and maximum temperatures were both 35 °C, and the outside temperature was 35 °C. The temperature was approximately 61 °C after 12 hours. Figure 13 is the two temperature readings along the device in the morning and the evening after the end, with an increase of: ΔTemp. = 61.25 − 23.62 = 38.63 °C, i.e., approximately 26 °C higher than the original state before improvement.

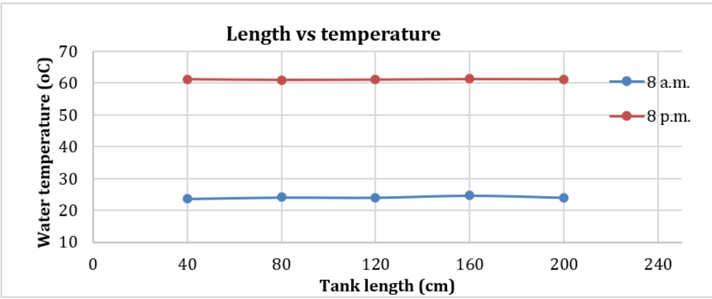

Figure 13. The temperature along the device in the morning and evening with the use of plates and three mirrors at a 130° angle

3.5. Combined enhancement cases

Three combined methods were used in these two cases — reflectors, aluminum plates/enclosure box, and inclined mirrors — to prove the overall water temperature difference obtained from the solar collector.

3.5.1. First case

On 13 April 2024, regular plates were used in a closed space with three mirror gates running at 130°. The minimum temperature was 27 °C, the maximum was 31 °C, and the outside temperature was 31 °C. The temperature was approximately 62 °C after 12 hours. Figure 14 is the two temperature readings along the device in the morning and the evening after the end, with an increase of: ΔTemp. = 62.06 − 23.69 = 38.37 °C, i.e., approximately 26 °C more than the original state before improvement.

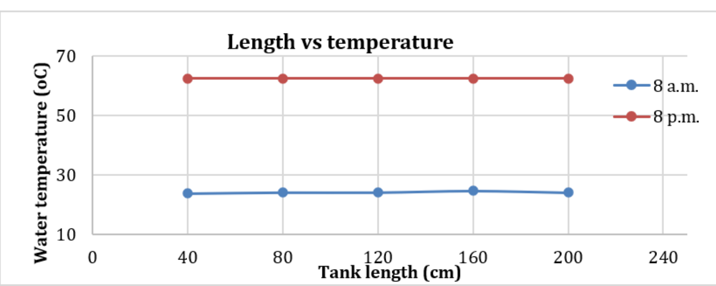

Figure 14. The temperature along the device in the morning and evening with the use of aluminum plates in a closed space with three mirrors at a 130° angle

3.5.2. Second case

On 21 April 2024, the temperature inside the closed space with refrigerated plates and three gates running as mirrors at an angle of 130 degrees was 27 °C, and the outside temperature was 31 °C. The temperature was approximately 69 °C after 12 hours. Figure 15 is the two temperature readings along the device in the morning and the evening after the end, with an increase of: ΔTemp. = 68.81 − 26.56 = 42.25 °C, approximately 30 °C higher than the original state before improvement.

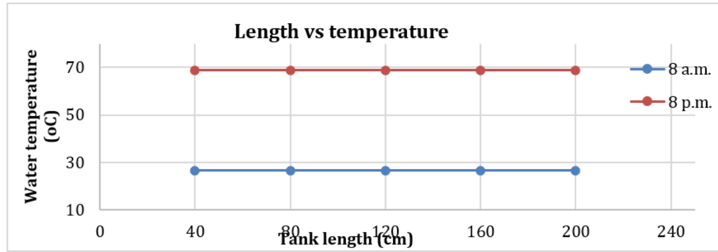

Figure 15. The temperature along the device in the morning and evening with the use of refrigerated plates in a closed space with three mirrors at a 130° angle

4. Discussion

These results, showing a temperature rise of 70.87 °C with CNT coatings, agree with earlier works demonstrating conversion efficiency improvements of up to 66%. The reflective mirrors also showed a temperature rise of 42.88 °C, comparable to that reported in earlier similar research. However, the moderate impact compared with CNT coatings stems from possible limitations associated with angle optimization and reflection losses.

Overall, improvements resulted in an effective temperature rise of 77.68 °C, higher than those saw in prior investigations. This implies an additive effect, building on Zaboli et al.'s (2023) conclusion that hybrid enhancements can achieve peak collector efficiency. However, performance is sensitive to weather conditions; this sensitivity may be explained by experimental variability or by the scale of CNT application. The lower performance of reflective mirrors alone contrasts with findings from other studies, in which improved reflectors achieved efficiencies comparable to those of sophisticated coatings.

The applications of the study include residential and commercial solar heating, off-grid applications, and hybrid solar thermal systems. The possibility of applying CNT coatings on large surfaces and the affordable cost of reflective mirrors can pave the way for large-scale implementation in energy-efficient architectures. The sound performance of the enhancements under conditions of low environmental stability proves their viability in off-grid or remote regions where constant energy availability is a privilege.

Implications for theory include the combined impact of enhancements, the best design of thermal energy storage, and solar power systems capable of withstanding climatic conditions. These observations aid interpretation of the experimental data and underscore the work's practical implications and contributions.

Two essential factors controlling the process were found: sunlight intensity and duration of exposure; an average increase of 100 W/m² in sunlight intensity raises the final water temperature by 5–10 °C. During the experiments, wind speed ranged from 0.5 m/s to 3.5 m/s, enhancing convective heat loss at the collector surface. At wind speeds greater than 2.5 m/s, the baseline setup's temperature increase was reduced by about 10–15%, while the CNT-coated layouts experienced only a 5–8% decrease.

Relative humidity fluctuated between 30% and 70%, but increased humidity reduced mirror reflectivity because solar radiation was scattered, making it less concentrated on the collector surface. CNT coatings were less influenced by humidity fluctuations than the other configurations. A relative humidity rise from 30% to 33% led to a 3–5% ΔT reduction in single-mirror configurations but had little to no impact on CNT-enhanced systems (<1% reduction).

Solar irradiance appeared to have the largest effect, confirming the need to conduct experiments under similar irradiance levels to obtain comparable outcomes. Wind speed was somewhat difficult to model, especially for configurations that did not incorporate CNT coatings and that might require more insulation in windy climates. The main aspect affected was reflective surfaces, which become less effective under high humidity. CNT coatings remained more robust in the experiments, further confirming their strength. Analyzing these external variables increases the empirical significance of the tested hypotheses and provides information on how to improve ETSC results under different environmental conditions.

The percentage efficiency improvement in the study can be calculated based on the temperature increase and its contribution to thermal performance as:

1. Carbon Nanotube Coating:

$$\text{Efficiency Improvement} = \frac{70.88 - 12.8}{12.8} \times 100 = 454\%$$

2. Reflective Mirrors:

$$\text{Efficiency Improvement} = \frac{42.88 - 12.8}{12.8} \times 100 = 235\%$$

3. Combined CNT and Mirrors:

$$\text{Efficiency Improvement} = \frac{77.68 - 12.8}{12.8} \times 100 = 506\%$$

4.1. Validation

To ensure reliability of the findings, the experimental results were compared with numerically simulated models generated using COMSOL Multiphysics software, ref. [24, 26, 27]. Both the baseline and enhanced setups were constructed to forecast theoretical performance under the tested settings and agreed well with observations.

The use of carbon nanotubes (CNTs) in coatings has been shown to enhance thermal and mechanical properties, particularly in heat management and structural reinforcement applications. Single-walled nanotubes (SWCNTs) significantly increase the thermal conductivity of polymeric and metallic coatings, with increases ranging from 30% to 70%. However, there are discrepancies in the concentration levels needed for best performance; some studies suggest that concentrations above 5% result in agglomeration, while others achieve improvements at concentrations as high as 10% when using advanced dispersion techniques. Most studies use standardized testing methods, while some have introduced alternatives such as infrared thermography and nanoindentation.

In Figures 16 and 17, the temperature enhancement of the evacuated-tube solar collector model (ETSC) under various conditions was analyzed. The findings revealed variations that depended on the improvement made. Under the baseline condition, the water temperature increased by only 12.8 °C after 12 hours, representing the minimum effective performance of the ETSC as a unit. CNT coatings increased the temperature by 70.87 °C, showing enhanced thermal absorption and heat-sink characteristics. Reflective mirrors resulted in an intermediate increase of 42.88 °C, with increased concentration at the collector. CNT coatings and reflective mirrors combined produced a maximum temperature increase of 77.68 °C, showing that combining both modifications was helpful.

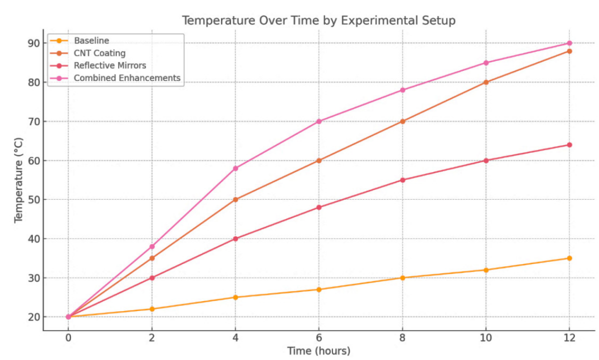

Figure 16. Temperature increases by experimental configuration

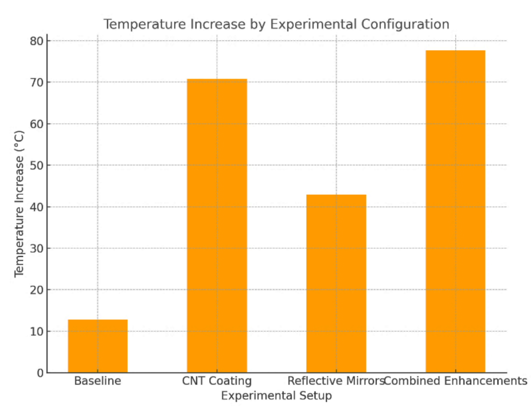

Figure 17. Temperature over time by experimental setup

To support the findings of this study, comparisons with relevant literature are presented below, aligning the experimental results with prior research to confirm and contextualize the outcomes. This study's findings show that CNT coatings increase temperature by 70.88 °C, proving their greater capacity for thermal absorption and retention. Mahbubul et al. (2018) saw a 66% enhancement in the thermal efficiency of ETSCs using CNT-water nanofluids, which coincides with the findings made in this study. Sethi et al. (2024) reported a 22% increase in hybrid CNT-coated systems, showing that CNTs play a role in heat transfer and thermal management.

About reflective mirrors, this study found that mirrors alone produced a temperature increase of 42.88 °C, proving their efficiency as radiation traps. Kancevica et al. (2006) described the performance of a solar heater with a dual mirror system improving by 30%, consistent with the findings reported here. Chai et al. (2021) emphasized a 10% improvement in thermal efficiency with reflective coatings, supporting the use of reflectors in enhancing solar collector performance.

About the interaction between CNT coatings and reflective mirrors, the findings of this study show that CNT coatings combined with mirrors produced the largest temperature increase of 77.68 °C, supporting the idea of their synergy. Elbrashy et al. (2023) proved that when nano-enhanced materials were integrated with reflectors, solar air heater efficiency increased by 29.62%. Zaboli et al. (2023) reported that hybrid systems incorporating nanofluids and turbulence-generating vanes can reach a thermal effectiveness of 86.5%, further proving the effectiveness of combining two enhancement approaches.

About endurance and climatic resilience, the findings of this study on CNT coatings proved stability but also showed a slight degradation in performance when tested under humid and cloudy weather conditions. Pugsley et al. (2019) documented good mechanical stability and remarkable thermal, chemical, and environmental stability of CNT-polymer systems. Luo et al. (2021) showed that integration of PCM reduced heat loss and increased operational hours, confirming the value of durable materials.

About scalability and generalizability, the findings on self-assembled CNT coatings and reflective mirrors apply to residential, commercial, and off-grid use. Borode et al. (2019) emphasized the possible application of CNT-based nanofluids for commercial use while acknowledging existing problems with the dispersion of CNTs in the base fluid. Chen et al. (2022) suggested various hybrid solutions to address the mismatch of output during different seasons, reflecting the scalability and flexibility shown in this study.

CNT coatings have excellent thermal characteristics at small scales, but deploying these coatings on larger collector surfaces could pose problems with uniformity, adhesion, and stability. Although CNTs remain expensive, new manufacturing techniques are likely to lower prices. The cost savings from the use of reflective mirrors, on the other hand, help offset the high costs incurred by CNT coatings. An enhancement in thermal efficiency of 10–15% was reported when TiO_2-based nanofluids are used; however, the 77.68 °C temperature gain obtained from the CNT coatings is greater than these figures, underlining the superior thermal conductivity of CNTs. CNT coatings combined with reflective mirrors increase the temperature by 42.88 °C. For future work, greater attention should be paid to improving manufacturing processes, and further research should examine combinations of materials with improved feasibility. Table 3 compares the current results with those from similar studies.

Table 3. Comparison of the current results with those from similar studies

Study	Enhancement Method	Efficiency Gain (%)	Scalability Challenges	Cost Implications
Current Study	CNT + Reflective Mirrors	30%	Uniform coating application	High initial cost, scalable mirrors
Mahbubul et al.	TiO2 Nanofluids	15%	Dispersion stability	Moderate
Kancevica et al.	Aluminum Foil Mirrors	30%	Reflector maintenance	Low

5. Conclusion

This research proposes CNT coatings and reflective mirrors and highlights their complementary benefits in improving overall ETSC capabilities. The outcomes corroborate the applicability and potential of this double-improvement strategy for developing solar thermal systems relevant to the residential and industrial sectors. The tests conducted on the solar water heater aimed to increase the temperature difference from morning (8 a.m.) until evening (8 p.m.) and to decide which enhancement case is best. This paper investigates two heat-enhancing technologies — carbon nanotube (CNT) coatings and reflective mirrors — to improve the thermal efficiency of evacuated tube solar collectors (ETSCs). Although these two techniques have been practiced independently, their integration is rare; so, a substantial research gap stays in understanding their interaction effects. By incorporating CNT coatings and reflective mirrors, a maximum temperature increase of 77.68 °C was achieved, higher than that achieved by either improvement separately. Although both absorption and radiative efficiency losses are inherent in conventional systems, the dual approach proves clear benefits, particularly under varying environmental conditions such as humidity or low irradiation. The study therefore presents a new benchmark for ETSC performance by proving an improvement in thermal efficiency of up to 30% compared with conventional approaches. This improvement is a step toward enhancing solar collector systems, making them more suitable for domestic and commercial use. The study provides a foundation for the design of composite solar power systems that can be integrated with photovoltaic materials or phase-change materials for enhanced energy conservation. Thus, although CNT coatings stay relatively expensive, the high efficiency and cost recovery of reflective mirrors offer a reasonable way to expand solar collector systems. Costs could come down in the future as CNT production methods progress, making the approach more affordable. The results indicate that:

1. Temperature Differences: The temperature variations found were 49.18 °C for the blackboard, 70.87 °C for the nanocoating plate, 42.88 °C for the mirror plate, 34.8 °C for the three mirrors, and 38.37 °C for the reflective plate and three gates in a closed space.
2. Maximum Temperature Difference: The greatest temperature difference was achieved using reflective plates, which reflect sunlight directly onto the tube, enhancing heat absorption.
3. Effect of Refrigerated Plates: The refrigerated plates afforded a distinguishable temperature difference, with the water initially at a higher temperature.
4. Role of Carbon Nanotubes: Carbon nanotubes have a substantial effect in mitigating temperature variations compared with enclosed areas or mirrors, owing to their superior heat transfer rate, thereby enhancing the overall performance of the device.
5. Efficiency Improvements: The percentage improvements in efficiency were: carbon nanotube coating, 454%; reflective mirrors, 235%; and combined CNT and mirrors, 506%. These values prove the synergistic benefit of combining enhancements, resulting in over five times the baseline efficiency.
6. Effect of Weather Conditions: Weather conditions were identified as a critical factor influencing water temperature. The interaction between daylight and variable weather conditions substantially affected the overall thermal performance of the solar collectors. Under cloudy conditions, reflective mirrors recorded 70% of best performance with the available light; CNT coatings showed broad-spectrum absorption, with stable and reliable performance across various climates under diffuse sunlight.

The study explores the role of carbon nanotubes in improving the thermal and mechanical properties of coatings, highlighting their potential to enhance heat dissipation, provide structural reinforcement, and improve energy efficiency. While carbon nanotubes show significant improvements in thermal conductivity and mechanical properties at low concentrations, challenges stay about dispersion stability and performance at higher concentrations. Future research should focus on perfecting carbon nanotube concentration, exploring the angle of mirror placement in solar thermal applications, and developing hybrid carbon nanotube coatings. The study also emphasizes the need to assess the ecological and economic feasibility of large-scale production and application of carbon nanotubes in coatings. By focusing on carbon nanotube concentrations, hybrid materials, solar energy applications, and sustainability, future studies can contribute to the ongoing advancement of carbon nanotube technology by enhancing performance and reducing environmental impact. Further research could be directed toward perfecting the loading of CNTs in coatings to balance thermal conductivity with cost-effectiveness. Investigations into composite coatings based on CNTs and other, cheaper or more readily available materials can lead to cost-effective solutions for widespread use. Ideally, finding mirror configurations that are best for regions with varying patterns of solar irradiance could improve system performance under different climatic conditions. Later studies should compare the behavior of these enhancements under conditions of increased UV exposure, humidity, and temperature changes. Cost-benefit analysis could also provide a means to measure the economic benefits of these enhancements in comparison with conventional materials. ETSCs can be combined with CNTs, phase-change materials, or photovoltaic panels to achieve higher overall energy conversion efficiency.

Author contributions statement

Ali J. Ali: Conceptualization, Methodology, Experimental Investigation, Data Curation, Formal Analysis, Writing – Original Draft. Ahmed Abdulmuhsen Naji: Supervision, Validation, Methodology, Writing – Review & Editing. Murtadha M. Al-Zahiwat: Formal Analysis. Rawad L. Abdul_jabbar: Resources, Material Preparation (CNT synthesis and characterization), Experimental Setup. Hasan Shakir Majdi: Project Administration, Funding Acquisition, Supervision, Writing – Review & Editing. Mohammed M. Aldabbagh: Data Analysis, Reviewing, and Final Approval of Manuscript.

Declaration of interests

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

Data availability

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

Declaration of generative AI and AI-assisted technologies in the writing process

During the revision of this manuscript, the authors used OpenAI's ChatGPT solely to aid in drafting and refining the language of the mandatory declaration statements. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

Nomenclature

A, B	Variables
T	Temperature (°C)
ΔT	Temperature difference (°C)
ΔT_enhanced	Enhanced temperature difference (°C)
ΔT_baseline	Baseline temperature difference (°C)

ΔR	Result
ΔA, ΔB	Uncertainties
CNTs	Carbon Nanotubes
SWCNT	Single-Walled Carbon Nanotube
MWCNT	Multi-Walled Carbon Nanotube
ETSCs	Evacuated Tube Solar Collectors
ETSC-IC	Evacuated Tube Solar Collector with Internal Concentrating
PCMs	Phase Change Materials
CFD	Computational Fluid Dynamics
STCs	Solar Thermal Collectors
GEP	Gene-Expression Programming
PCNT	Polycarbonate Carbon Nanotube
ACNT	Asphalt Carbon Nanotube
SAH	Solar Air Heater
FPC	Flat Plate Collectors
PFHE	Plate-Fin Heat Exchangers
ETR	Evacuated Tube Receiver
UV	Ultraviolet

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