



Experimental Enhancement of Solar Water Heater Performance Using Carbon Nanotube Coatings and Enclosure Modifications

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ABSTRACT

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The current study is an experimental research that aims at exploring the ways in which an evacuated tube solar collector (ETSC) can be thermally enhanced by varying absorber material and structural insulations. These were tested with nine variations in the outdoor conditions, and these conditions were aluminum plates, black-painted plates, absorbers, carbon nanotube (CNT)-coated plates, enclosure boxes, and adjustable reflectors at 45° and 90°. Multi-point temperature revealing of a 300 L storage tank was conducted to determine the performance of things in terms of thermal performance of the storage tank in daily cycles of operation. Placing a CNT-coated plate of aluminum into an insulated enclosure box was the most thermally improved, as it was able to increase the temperature the most, 64.24 °C over the baseline version. Enclosed plates, which were black painted, showed a 47.81 °C increase in temperature, whereas the aluminum plates showed a moderate improvement (20.71 °C). Mirror forms demonstrated uneven performance because of the shading effect, with maximum gains of 30.44 °C at 90° and just 4.80 °C at 45°. Findings show that the reduction of convective heat loss and absorber surface properties are the most important elements that affect the efficiency of the system, as compared to reflector position values. The CNT enclosure framework comprises CNT enclosure design, which represents a viable and economical design strategy towards facilitating domestic solar water heating in fluctuating climatic conditions.

1. INTRODUCTION

The technique of photo-thermal technology extracts solar radiation power through components that absorb solar light before transforming it into heat energy, which gets transferred to water or air as a working fluid. The generated heat has applications for residential, industrial, and agricultural purposes through direct usage or storage for later retrieval. The system utilizes surfaces that capture broad solar radiation while achieving effective reduction of thermal losses by conduction, convection, and radiation. Photo-thermal technologies have become a worldwide standard to produce thermal energy because their applications extend to water heating, space heating, and industrial process requirements [1]. The solar thermal collector constitutes a fundamental part of photo-thermal systems because of its specific characteristics described in the study of Xia and Chen [2]. Evacuated tube solar collectors (ETSCs) demonstrate superior performance across different environmental settings. These systems are

becoming more and more popular due to their minimal impact on global warming, long duration, and low cost [3].

Solar water heating systems are a good alternative to the use of fossil fuels and greenhouse gas emissions in homes. Etihad ETSCs are the most suitable and efficient technology among other technologies in terms of thermal efficiency, especially in cool and low-radiation weather, because the vacuum provides them with insulating properties. Nevertheless, convective loss, non-optimal absorber materials, and an inefficient reflector integration still hold back the system performance. Recent studies have been carried out on how to improve ETSC, which can be done by nanofluids, alteration of the absorber geometry, integration of a reflector, and optimization by computer. Research has demonstrated that nanofluids have the potential to enhance the properties of heat transfer, and a reflector system can enhance solar concentration under a controlled environment. Another wide use of computational fluid dynamics (CFD) has been in predicting thermal performance as well as in optimizing collector designs. In spite of such

developments, the majority of available studies consider single techniques of enhancement separately or use numerical modeling without further outdoor confirmation. Further, there has been very little literature that has experimentally tested the concomitant impact of surface modification on absorbers, enclosure inspired insulation, and manipulable reflectors in the actual climatic setup. Specifically, deploying carbon nanotube (CNT) coatings as solid layers (instead of nanofluid additives) in the layer of solid absorbers is an area that has not been fully explored in practice with regard to enhancing solar water heating. Additionally, reflector angle positioning has been found to affect shading losses in outdoor operating conditions, which has to be empirically confirmed. To deal with these gaps, the current research experimentally examines the nine modular designs incorporating:

- (1) CNT-coated aluminum plates of absorbent,
- (2) insulated structures of enclosure boxes to minimize the convective losses, and
- (3) 45 degree and 90 degree reflective mirrors that can be adjusted.

The system was operated in the actual outdoor conditions with multi-point temperature monitoring to check the daily thermal performance and heat retention properties of the system. The aim is to establish the best combination of material and geometry changes to enhance domestic solar water heating, to employ applied and least expensive solutions.

Recently, the enhancement of solar thermal collector performance has been the focus of several studies. In order to prevent solar collectors from overheating [4] has been developed two vacuum tube models by raising their infrared emissivity and heat convection coefficient, respectively. Found that the first model can negatively influence the collector's efficiency by at least 26%, whereas there was no effect on the second model. Fertahi et al. [5] proposed an improved model of a horizontal hot water storage tank of a solar water heater (SWH), and showed that there is a direct relationship between the horizontal tank's temperature on average and the number of heat pipes. Alfaro-Ayala et al. [6] modified the arrangement of ETSC, water in glass, and low temperature to forecast their ideal efficiency. Found that the thermal performance of the best form had increased in all running and environmental variables, with 14 fewer tubes and 38.9% lower cost compared to the industrial model. Salvi et al. [7] showed that the adjustments of the absorber's, and utilization of the thermal mirror films and appropriate nanoparticles can improve the performance of solar collectors. Teles et al. [8] proposed a numerical model of ETSC with low concentration. Showed that decreasing heat generated stress and maintaining a consistent temperature for the absorber were the two benefits of the reflective film, with a significant increase in thermal efficiency. Yurddaş [9] showed that the utilization of Cu-Water nano-fluid provides an improvement in heat transfer for ETSC. In addition, Cucumo et al. [10] studied the effectiveness of a solar thermal generator. Found that the largest losses were caused by the poor reflectance and distance of the mirrors, with around 38% wastage. Otherwise, about 11% of losses were due to the poor absorption of sunlight. In the study of Abo-Elfadl et al. [11], the integration of reflectors with ETSC-HP (evacuated tube solar collector-heat pipe) system on its thermal energy storage showed its capacity to increase the collector system's storage of energy in comparison with previous research. Furthermore, Madadi Avargani et al. [12] had analyzed an array of parabolic trough collectors (PTCs) for SWH as a new kind of technology. This

system showed better thermal efficiency compared with the traditional systems. According to the results of studies published over the past 10 years that used nano-fluids in ETSCs, Olfian et al. [13] showed that ETSCs were the most suitable choice among other solar collectors. The use of Single-Walled Carbon Nanotubes (SWCNTs) nanofluids provided beneficial effects for improving the heat pipe model. Nokhosteen and Sobhansarbandi [14] aimed to analyze the heat transfer mechanisms occurring in ETCs using a hybrid numerical tool. Accurate, quick forecasting came from the proposed Reduced-Order Proper Orthogonal Decomposition–Lattice Boltzmann Method (RNPOD-LBM) models according to Du et al. [15]. Solar thermal research extensively utilizes CFD as a fundamental tool because it enables thorough simulation of fluid movement coupled with thermal distribution and pressure differences across the collector framework. The thermal response of solar collectors running under different conditions becomes predictable through Navier-Stokes equation solutions alongside energy conservation models in CFD simulations. CFD processes represent an essential simulation method for system optimization that enhances design quality and reaches maximum thermal efficiency by reducing operational losses before prototype development. Kumar et al. [16] showed that the rise in solar radiation intensity, changes in tilt angles, rating of heat transfer forced and natural circulation, number of evacuated tubes, heat storage materials, depth of water in still, material of glass cover, and its mass flow rate and temperature had an impact on the evacuated tube's performance. Dinesh et al. [17] used a wavy and flat diffuse reflector in order to enhance the efficiency of the ETC- SWH. According to the results, using wavy and flat diffuse reflectors enhances the temperature of tank waters by 4 °C and 6 °C, respectively, throughout the day. Altaher et al. [18] showed that the utilization of aluminum foil as a collector surface cover of both main and secondary vertical reflectors resulted in a better thermal performance of the ETC. Rahimi-Ahar et al. [19] analyzed the thermal performance of several SWH types. Found that concentrated SWHs performance outperforms other types of heaters, as well. Combining these systems with heat pumps, phase change materials (PCMs), or energy storage components provides outperformed performance than traditional SWHs. The work discussed by Mokhlif et al. [20] showed that the thermal efficacy of integrated collector storage (ICS) with SWH used together with insulated reflectors as a cover was higher than that of the ICS-SWH without insulated reflectors by 23%. Al-Mamun et al. [21] showed that the application of base liquids and nanofluids, selection of the collectors' types, within the operating temperature range. Moreover, PCM integration with solar collectors or storage tanks could enhance the thermal properties of SWH systems in comparison to the conventional types. Furthermore, Abu-Zeid et al. [22] used a flat plate solar collector (FPSC), still, FPSC nanofluids, a reflecting mirror, and a v-corrugated basin in a conventional solar still (CSS), which significantly increased thermal performance and productivity (Pd) by increasing water temperature and the gradient between the hot and cold inner glass cover surfaces. Aljabair et al. [23] aimed to investigate the effect of different diameters and depths of the parabolic dish collectors on the focal point's location. Showed that the dish's diameter and the degree of angle of inclination can determine the focus's placement from the dish. The performance of thermal energy storage was examined experimentally by Abed et al. [24]

found that, the maximum thermal storage of 110 minutes is achieved in hot flow rate $q_h = 4$ LPM, cold flow rate $q_c = 5$ LPM, and $h = 20$ cm, in present of porous medium [25] investigated that, there was a direct relationship between the porous media's height level and hot water supply. As well, when the rate of solar radiation intensity increases and the average variation in temperature reduces, the collector's efficiency improves.

The technique mentioned is the ETSCs, which are becoming prominent as the technology of harnessing solar energy, especially in cold regions where there may not receive much sunlight. Studies are done to improve ETSC efficacy by means of nanofluids and algorithms optimization of systems, and to discover CNT nanotechnology coating to promote heat entry. Nevertheless, there are still some challenges, such as the absence of real-life testing of the optimizing elements and the lack of innovative ideas for providing affordable solar power to the community with limited resources. Available information about the performances of reflectors is not many especially on the angle and position of reflectors. The paper suggests the experiment with different design improvements of solar collectors, the use of CNT-buttered absorbers in insulated envelopes, and the importance of a comprehensive study of reflector angles to reduce the losses of shading. The almost optimal design was proven to be the one that had an experimental increase of maximum temperatures of 64.24 °C.

2. EXPERIMENTAL METHODOLOGY

2.1 Baseline solar water heating system

To carry out the experimental study, it was done using a typical ETSC system that has:

- Thirty evacuated glass tubes connected to a manifold.
- An insulated horizontal storage tank (255 cm 46 cm) with a capacity of 300 L.
- Steel frame reinforcement.
- Measurement and data acquisition system in terms of temperature.



Figure 1. Experimental test rig

The evacuated tubes are also used with under vacuum

insulation to reduce convective and conductive losses of heat. The radiation of the sun is absorbed by the inner absorber surface and passed to the circulating water inside the system. The base investing finishing (Case 1) will consist of the unmodified system in the absence of extra absorber plates, envelop box, and reflectors. This arrangement is used as the basis of performance comparison, see Figure 1.

2.2 Design modification parameters

The experimental study was structured around three independent design variables:

1. Absorber surface modification
2. Thermal insulation enhancement
3. Reflector geometry modification

Nine configurations were constructed by systematically combining these variables.

2.2.1 Absorber surface modification

Three types of absorber surfaces were studied in order to increase the solar radiation absorption and heat retention:

- Bare aluminum plate
- The aluminum plate is black-painted
- Plate composed of a coated aluminum plate with CNT

The size of the aluminum plates was [26]:

- Width: 156 cm
- Height: 122 cm

The plate was attached to the evacuated tubes [27] to reflect or absorb the incident solar radiation, depending on the treatment of the surface. The use of CNT coating was in order to improve the characteristics of solar absorptivity and thermal retention, as its absorptance and thermal conductivity qualities were high.

2.2.2 Thermal insulation enhancement (enclosure box)

A box was made around the evacuated tubes in order to decrease the convective heat loss and enhance heat storage.

The enclosure consisted of:

- Two polycarbonate (plastic glass) top panels.
- Wooden structural frame
- Rear metal plate backing
- Side insulation strips
- Internal air gap spacers

The enclosure is something of a semi-greenhouse, which:

- Minimizes convection due to the wind
- Maximizes heat savings when a building is dark
- Enhances thermal containment

For both with and without the enclosure box, the configurations have been tested. The enclosure box of the ETSC is important because it gathers heat, provides insulation for the system to avoid excessive heat loss, and gives protection from the weather, while still ensuring the components of the system are stable, see Figure 2. Normally constructed with heavy metal and its interior made with insulation that is efficient in terms of resilience, it helps blend the solar collector with the buildings. The design has two plates of glass and other materials to stabilize the structure, which they could not allow to bend, thus keeping the performance of the structure optimum. On the whole, the enclosure is crucial to add to the performance of the system, owing to minimizing its thermal loss and securing good functioning even in different temperature parameters [28, 29].



Figure 2. Enclosure box

2.2.3 Reflector geometry modification

Adjustable mirror gates at two angular positions were installed in order to study the redirection of solar radiation:

- 45° inclination
- 90° inclination

The collector was surrounded by three movable reflective panels that were made of iron frames. The aim was to determine whether reflectors cause an increment in the amount of incident solar radiation or create the shading effects that decrease the overall performance. The development is a structure with three lifetable iron doors, attached with aluminum plates and flexible nickel-chrome tapes. The doors can be moved at different angles to cover the compound. The reflective surfaces maximize solar radiation reversal, increasing water temperature and maintaining the compound from external conditions (Figure 3).



Figure 3. Test rig with three enhancements

2.3 Experimental matrix

The experimental configurations were defined by systematic combinations of the three design variables. Table 1 summarizes the complete test matrix.

This structured matrix ensures clear identification of independent variables and facilitates direct comparison between cases.

2.4 Measurement and data acquisition system

Thermal performance was monitored using:

- DS18B20 digital temperature sensors
- PT100 (PT10) resistance temperature sensors
- Measurement accuracy: ± 0.5 °C
- Resolution: 0.1 °C

Table 1. Experimental matrix of configurations

Case	Absorber Type	Enclosure Box	Reflector Angle	Purpose of Test
1	None (Baseline)	No	No	Reference condition
2	Black-painted plate	Yes	No	Effect of absorber + insulation (1 day) [30]
3	Black-painted plate	Yes	No	Extended exposure (2 days)
4	Aluminum plate	Yes	No	Effect of reflective metal absorber
5	Refrigerated plate	Yes	No	Alternative surface comparison
6	CNT-coated plate	Yes	No	High-absorption configuration
7	CNT-coated plate	Yes	45°	Reflector effect at 45°
8	CNT-coated plate	Yes	90°	Reflector effect at 90° (Case 1)
9	CNT-coated plate	Yes	90°	Reflector effect at 90° (Case 2)

Five temperature sensors were installed along the storage tank [31], at 40 cm intervals, to capture thermal stratification. Data acquisition system components included:

- Arduino microcontroller
- RAM data storage module
- Time-stamp counter
- Laptop interface for data processing

Temperature data were recorded at fixed intervals throughout daily operational cycles under real outdoor conditions, as shown in Figure 4.

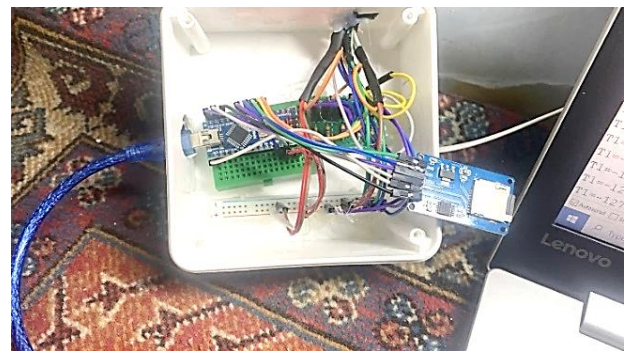


Figure 4. The Arduino board has the thermocouples installed, along with the RAM (memory chip) with the thermocouple connectors to the Arduino, and a counter and timer chip

2.5 Experimental procedure

Each configuration was tested under natural outdoor solar radiation. For each case:

- (1) Initial tank temperature was recorded at approximately 8:00 AM.
- (2) Final temperature was recorded at approximately 8:00 PM.

(3) Temperature rise (ΔT) was calculated as:

$$\Delta T = T_{final} - T_{initial} \quad (1)$$

Environmental conditions such as ambient temperature and cloud cover were documented.

3. RESULTS AND DISCUSSION

Thermal performance of the solar water heating system was tested in nine different configurations that took into consideration the influence of agents that changed the surface of the absorber, or the lack thereof, the enclosure, and reflector geometry. In order to enhance clarity and depth of analytical value, results are reported in a comparative manner as opposed to case by case.

3.1 Baseline thermal performance

The initial setting (Case 1) included the ETSC without any alteration in the case of the absorber plate, enclosure box, and reflector. The system was able to reach a temperature increase (12.87 °C), which was an objectively determined temperature increase (ΔT) (Table 1), which is the inherent heating ability of the collector. The base is used as the mark of measurement of the effect brought about by material and geometric changes.

The moderate level of temperature rise shows that the vacuum insulation decreases internal convectional losses in the tubes, external heat loss, and not favorable sunlight absorption limit the overall performance.

3.2 Performance comparison of different absorber plate materials

In order to determine the effect of absorber surface properties, three cases (Cases 2–6) were examined and compared under:

- Bare aluminum plates
- Aluminum plates that were painted black
- Plates covered with CNT

Table 2 provides a synopsis of the main thermal performance metrics of each of the configurations, which are the initial temperature, final temperature, temperature gain (Ah), and the efficiency change. Figure 5 summarizes the temperature increase of Cases 1–6 and makes it easy to compare the effects of the surface of the absorbers. Case 1, or the analysis of baseline thermal performance, is concerned with an ETSC with typical conditions; no enhancements were put to it in the form of an absorber plate, enclosure box insulation, or reflector integration. Such an arrangement can be regarded as a baseline for the evaluation of successions in the design and functionality of the system.

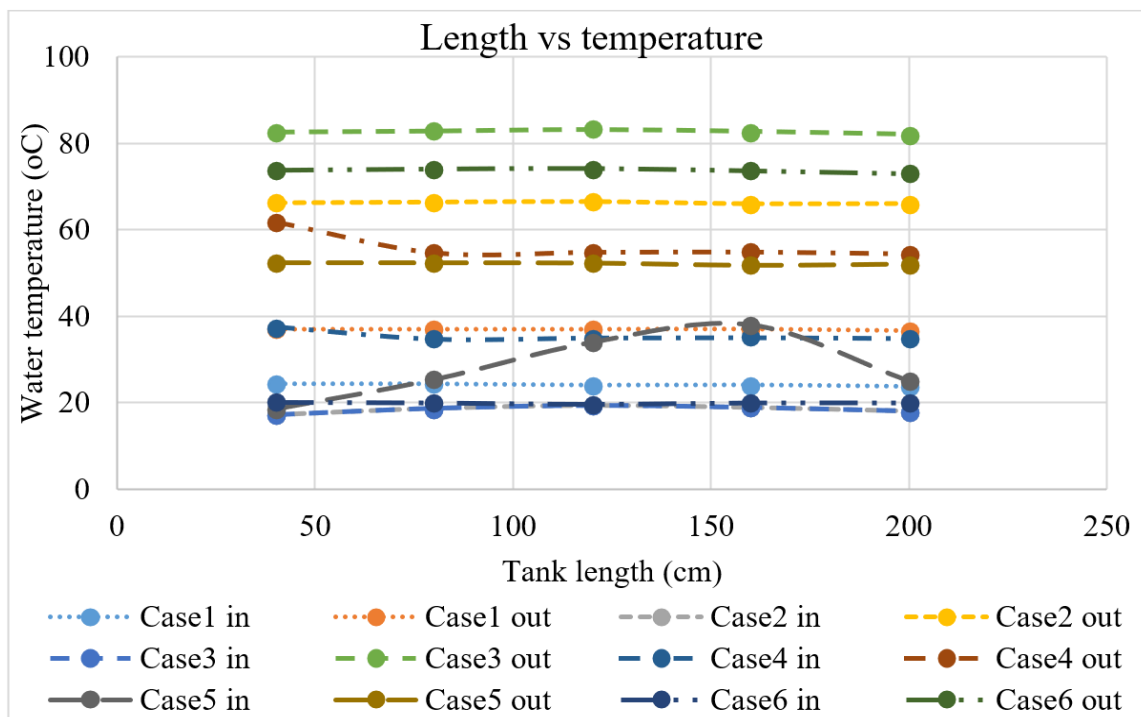


Figure 5. Temperature increase in Cases 1–6

Table 2. The numerical values

Case	Initial Temperature (°C)	Final Temperature (°C)	Temperature Rise (ΔT) (°C)	Relative Efficiency Improvement (%)
1	24.134	36.938	12.804	-
2	18.374	66.18	47.806	72.2
3	18.374	82.612	64.238	77.7
4	35.426	56.14	20.714	36.9
5	28.186	52.076	23.89	42.0
6	19.962	73.336	53.374	72.8

The data demonstrated by Figure 5 and Table 2 show that the baseline system has a moderate growth in temperatures during its daily working cycle. The longitudinal temperature profile over the storage tank represents a fairly homogeneous heating profile with little stratification effects across the top to bottom. Although there is this consistency, the general increase in temperature is low, which is a pointer to inefficiency in terms of performance. It is the moderate effectiveness of the baseline configuration due to a number of factors. Firstly, the enclosure of the heat is a major concern, also, the evacuated tubes are to operate under a vacuum situation that the internal convective and conductive heat losses are to be minimized through the vacuum enclosure the external factors like ambient wind are able to cool down the system, this is due to the fact that there is no surrounding structure to reduce the external heat losses through convection. The second factor contributing to the suboptimal performance is that there is no further plate of solar absorber, which increases the amount of solar radiation that is entrapped, and a fraction of the solar energy is reflected back or does not trap any solar energy effectively. In addition, the uncovered areas of the collector also carry energy dissipation effects by radiative and convective losses, particularly on elements such as the collector manifold and the structural elements.

3.3 Effect of reflector angle and shading mechanism

This paragraph talks about the physical phenomenon of the shading effect of reflector panels that are used to enhance incident sun radiation. It shows that in some designs of reflectors, the performance can even be worse than expected in theory, mostly because of self-shading. Reflector panels at a 45° angle will be able to prevent direct solar radiation at peak solar altitudes, thereby casting a shadow on the absorber

surface, resulting in lower net radiation gain than expected. On the other hand, at 90° angle, there is some redirection of low-angle radiations, but at the same time, vertical panels are able to block the lateral incidence of the sun, thereby providing performance inferior to that of a system employing a single enclosure. The results demonstrate one design reality according to which a geometry that optimizes reflective geometry should be adopted to consider the changes in the altitude of the sun. The paper underlines the fact that improper angular position may result in the net solar gain reduction, regardless of the theoretical benefits of the reflectors. This empirical evidence has culminated in the need to take into consideration the seasonal trajectory of the sun in the integration of a reflector design instead of working with the definite angle arrangement. Figure 6 and Table 3 investigated reflector integration at 45° and 90° angles for Cases 7–9.

3.4 Nighttime thermal retention performance

Study data demonstrated that the system maintained thermal energy efficiently during evening hours using enclosure boxes and high-absorptivity coatings that included CNTs. Vacuum insulation in the tube design prevents thermal losses due to both convection and conduction. An enclosure box created a thermal barrier to protect from wind-driven cooling and ambient air. The nighttime temperature decrease was minimal, because of which the system managed to sustain warm water temperatures throughout the early morning. The system improves thermal energy storage during nighttime, which benefits domestic water heating because users need hot water after dark. These design modifications improved daytime performance while extending the accessible stored thermal energy beyond the direct solar period, which gave the system better practical usability.

Table 3. The numerical values

Case	Initial Temperature (°C)	Final Temperature (°C)	Temperature Rise (ΔT) (°C)	Relative Efficiency Improvement (%)
6	19.962	73.336	53.374	72.8
7	19.912	46.224	26.312	56.9
8	39.94	45.38	5.44	12.0
9	20.94	51.38	30.44	59.2

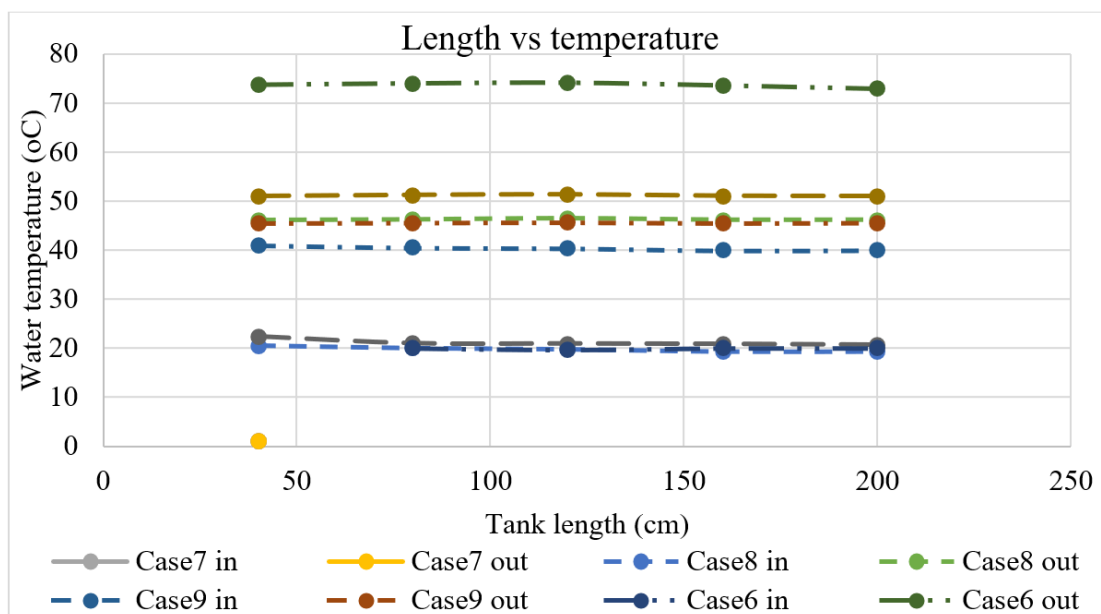


Figure 6. ΔT for no reflector (Case 6), 45° reflector (Case 7), 90° reflector (Cases 8–9)

Table 4. Comparative discussion of results with previous literature

Study Focus Area	Current Study Findings	Previous Literature	Advancements/Contributions
Carbon Nanotube Coating as Absorber Enhancement	Carbon nanotube-coated plates within enclosure boxes resulted in the highest temperature increase (up to 64.24 °C above baseline).	Olfian et al. [13] emphasized SWCNTs for nanofluid applications but not solid plate coatings.	Demonstrates that CNT-coated absorber plates offer scalable and practical performance gains without fluid handling complexities.
Enclosure Box Integration	Significantly reduced convective losses and improved nighttime thermal retention.	Abo-Elfadl et al. [11] and Mokhlif et al. [20] discussed insulation/reflectors but not full enclosure effects in real conditions.	Validates that enclosures enhance both daytime and nighttime efficiency with simple materials.
Reflector Placement and Angles	45° and 90° reflectors caused shadowing, reducing thermal gain compared to enclosure-only designs.	Teles et al. [8] and Altaher et al. [18] showed positive reflector results, but mainly through simulations.	Provides cautionary empirical evidence about reflector design trade-offs in real-world applications.
Real Outdoor Modular Testing	Nine configurations were tested under real solar exposure with 30-min interval logging.	Most studies rely on CFD or single-variable controlled tests (Du et al. [15]).	Bridges simulation-lab gap by offering robust experimental data for field-implementable designs.

3.5 Comparative discussion of results with previous literature

The mentioned information in Table 4 analyzes different aspects of enhanced solar collector findings by comparing them to earlier research works. This analysis examines the essential outcomes from this research work concerning CNT coatings and enclosure boxes, yet reveals that previous studies lacked complete real-world testing of combined solar water heating system enhancements. The table displays the advancements of the current study, which includes its real-world applications and its ability to scale while providing empirical evidence for choosing optimal reflectors. The analysis demonstrates why solar water heating systems should incorporate multiple low-cost modular techniques for better performance improvement.

4. CONCLUSIONS

The application of the experimental adjustments to a solar water heating system had a considerable positive effect on its thermal performance, and a maximum temperature difference of 64.238 °C was achieved relative to the baseline. When a combination of carbon nano tube-coated plates was used in an enclosure box, this proved to be the best possible set up. Although there was a measure of temperature control through the use of mirror gates at 45° and 90° angles, the inconsistent results were affected by shadow. Particularly, a maximum temperature difference of 30.44 °C was obtained with a 90 degrees mirror system, and only 4.802 °C was attained with 45 degrees mirrors. The paper has given importance to the insulation, as well as the optimal location of the mirrors to increase the effectiveness of the solar collector, and the paper has given recommendations that additional studies are needed to advance the use of solar collectors in larger platforms in both climatic conditions to achieve great findings in the savings of energy in the household hot water system.

This research employs outside testing to conduct quantitative analysis of nine combined enhancement methodologies, while previous studies focused on separate enhancement methods. The combination of CNT coatings applied to insulated enclosure structures produced the maximum thermal performance that became a standard for future economical and efficient solar water heating systems. The experimental findings provide essential evidence to

researchers and present useful guidelines for designing domestic solar thermal systems at different scales.

5. RESEARCH SCIENTIFIC INFLUENCE AND POLICYMAKERS GUIDE

The paper discusses ways of solar water heating systems by the use of CNTs, reflective materials, and outside boxes. Combining the experimental data with theoretical constructions, researchers today strive to enhance efficiency and create applications with the help of advanced materials. Results indicate that the developed performance criteria may be employed to make policy inferences on the use of renewable energy and provide incentives to adopt solar thermal in schools to present possible cost savings and higher feasibility in cold climates.

6. SUGGESTION ON FUTURE MODIFICATION

Future modifications of the solar collector system should incorporate the following specific recommendations that would optimize its performance. The research demonstrates that CNT-coated plates perform better, but fails to report how stable the coating remains over time. Laboratory tests should examine how CNT coatings endure because of prolonged exposure to solar conditions. Long-lasting nanotube coatings should be developed through testing various protective shield materials while maintaining high functionality. The tank storage heating abilities could decrease the performance of the solar system. Suggested Modification: Investigate different insulation materials for the storage tank. A test should be conducted to examine how vacuum-insulated panels or aerogel materials decrease heat leakage from the system while improving nighttime thermal efficiency. The aluminum plates managed to reflect sunlight, yet they performed inferior to the CNT-coated plates. An experiment should test different reflective materials and micro-structured coatings applied to aluminum plates for boosting sunlight reflections and heat absorption performance. The implementation of such optimization measures will lead to enhanced system performance when lights change conditionally.

It is recognized that the lack of validation of the current study is due to the absence of CFD. Although the practical performance validation would be possible through real-world

experimental data, the quantification of the heat transfer mechanisms would be available in detail with the use of numerical modeling. The CFD simulations will be incorporated in future research so that the study of velocity vectors, temperature distribution, and heat flux distribution near enclosure boundaries can be conducted to further prove the effectiveness of insulation.

This study did not test the long-term stability of the CNT coating during extended exposure to solar radiation, UV, and thermal cycling, even though the results of short-term thermal applications revealed superior performance of the coating. The next step in future research will be exploring how coating adhesion stability, delamination resistance, and the degradation of absorptivity can be studied using accelerated aging methods like UV exposure chamber and cyclic thermal stress analyzer.

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NOMENCLATURE

ETSC	evacuated tube solar collector
ETC	evacuated tube collector
CNT	carbon nanotube
PCM	phase change material
CFD	computational fluid dynamics
SWH	solar water heater
FPSC	flat plate solar collector
SWCNT	Single-Walled Carbon Nanotubes
LPM	liters per minute
LEED	leadership in energy and environmental design
BREEAM	building research establishment environmental assessment method
ECBC	energy conservation building code
W/m ² ·K	Watts per square meter per Kelvin (unit of heat transfer coefficient)
RAM	random access memory (data storage)
PT10	platinum resistance thermometer (sensor)
DS18B20	digital temperature sensor model