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Performance Enhancement of Solar Water Heater Utilizing TiO_2, Graphene Oxide, and Carbon Black Nanoparticles: A Synergistic Approach

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Abstract

This study explores the enhancement of solar water heater efficiency through the combination of a nanofluid blend comprising TiO_2, graphene oxide, and carbon black nanoparticles. The experimental research, carried out in Upper Egypt at some point of August 2022, specializes in evaluating the thermal performance improvements accomplished via the nanofluid in a passive solar water heating machine. The key goals include assessing temperature rise, sun strength absorption efficiency, and thermal conductivity upgrades. A locally assembled sun water heater prototype consisted of a primary tank storing 100 liters of water, a secondary tank containing the nanofluid mixture, and a solar collector with dimensions of 1.550 m x 0.8 m. The nanofluid, synthesized with manipulate of nanoparticle concentrations (TiO_2: 20 nm, graphene oxide: 50 nm, carbon black: 30 nm), turned into dispersed in deionized water and characterized for stability, nanoparticle length distribution, zeta ability, and thermal conductivity. Comparative analysis with traditional water-primarily based structures revealed widespread improvements in thermal overall performance. The nanofluid-more desirable system carried out a temperature upward thrust of 35°C compared to 29°C in traditional structures below comparable solar irradiance conditions ($800\ W/m^2$). This enhancement is attributed to the nanofluid's superior heat transfer properties, validated through stable heat transfer coefficients and efficient energy absorption (40% efficiency). The novelty of this work lies inside the synergistic use of more than one nanoparticle to enhance thermal conductivity and heat transfer efficiency in solar water heating systems. This research combines TiO_2, graphene oxide, and carbon black to leverage their complementary properties. By demonstrating the effectiveness of nanofluids in enhancing solar water heater performance, this research contributes to the ongoing efforts to optimize renewable energy utilization. Future research directions include optimizing nanofluid compositions for different environmental conditions and scaling up production methods for commercial deployment.

Keywords

TiO2, Graphene oxide, Carbon black, Solar water heater, Nanofluid.

1. Introduction

Solar water heating systems have become a popular and eco-friendly alternative for meeting hot water needs in residential and commercial settings. The challenge lies in balancing performance with maximum energy efficiency. Recent advancements in nanotechnology offer promising opportunities for enhancing heat exchange and energy absorption in solar collectors. Solar energy, being clean and renewable, has gained considerable attention [1]. Solar water heaters with solar collectors are among the most effective means of harnessing solar power [2, 3]. Monitoring solar thermal systems is crucial due to their light-to-heat conversion process. Domestic water heating is a common application of solar water heaters globally, typically used for washing or bathing needs. Passive flow solar collectors can produce steam at around 85°C and form the basis of solar water heater systems. Active solar water heaters combine antifreeze with water to prevent pipe damage in colder climates and mitigate salt precipitation inside tubing [7, 8]. Nanoparticle additives have been developed to enhance the heat content of water, making it a more efficient working fluid in thermal systems. By incorporating nanoscale particles into the working fluid, the heat conduction rate is improved, addressing issues of low heat conductivity and transfer in traditional fluids [9, 10]. Both theoretical and experimental research worldwide has focused on the use of nanofluids in various industries [11, 12]. Studies indicate that nanofluids can significantly improve heat exchange efficiency, with the potential to triple the thermal conductivity of conventional fluids [13, 14]. Previous research has demonstrated the effectiveness of adding nanoscale metal oxide particles to working fluids in enhancing thermal conductance [16, 17]. For instance, Yousefi et al. reported a 29% energy savings using alumina-based nanofluids for solar collectors [18]. Ghafurian et al. observed a maximum energy conversion efficiency of 79% with graphene oxide nanofluids for solar steam generation [19]. The highest efficiency was reported by Ram Kumar and colleagues, who used TiO2 nanofluids in industrial heat transfer applications [20]. Lotfi et al. found higher efficiency in capturing thermal radiation with TiO2 nanoparticles in evacuated tube solar water heaters [21]. Suthahar et al. improved the heat transfer coefficient in flat plate solar thermosyphon collectors by introducing titanium dioxide nanofluid [22]. Wasan's study highlighted the potential of carbon nanoparticles from carbon black powder to revolutionize solar water heater usage [23]. Kaood, Amr et al. [24] Developed a comprehensive computational fluid dynamics version to analyze nanofluid drift in corrugated tubes. Their study centered on evaluating distinctive nanofluid kinds and tube configurations to assess their thermal, hydraulic, and ordinary electricity performance. They determined that curved ribbed tubes confirmed advanced performance compared to different configurations at slight to excessive flow quotes, no matter the nanofluid used. Their findings underscore the ability of the usage of corrugated tubes to decorate warmth switch efficiencies, particularly when combined with nanofluid applications. Sharaf, M. A. et al. [25] improved double-pipe helical heat exchangers using silicon dioxide nanofluid (SiO2/water) and spring wire inserts. They found that combining 0.3% nanofluid with spring wire inserts increased heat transfer significantly, achieving a 174% higher Nusselt number and 157% higher pressure drop compared to using nanofluid or spring wire inserts alone. Their study emphasized spring wire inserts effectiveness in enhancing double-pipe helical heat exchangers performance, supported by detailed temperature and flow data. Fadodun, O. O. et al [26] studied hybrid nanofluid flow in corrugated-converging pipes, exploring the effect of Reynold's number, diameter ratios, and nanoparticle concentrations. Using Ansys Fluent, they found higher Nusselt numbers and increased pressure drops in corrugated pipes due to enhanced turbulence and better mixing. Corrugated pipes show potential for significant heat transfer enhancement and energy savings.

Singh, S. K. et al [27] studied how nanofluids (SiO2/water and Al2O3/water) improve pool boiling by delaying critical heat flux and achieving high heat transfer at lower wall temperatures. They explored how different heater materials and nanofluid concentrations affect heat transfer efficiency. Using simulations, they found that nanofluids create a nano-porous layer on heater surfaces, boosting heat transfer while lowering wall temperatures. Azimy, N. et al [28] studied improving heat transfer in flat-plate solar collectors by using zigzag-shaped pipes instead of straight ones. They tested fly ash–Cu/water hybrid nanofluids to see how different flow rates, temperatures, and nanoparticle amounts affect efficiency and heat transfer. Results showed zigzag pipes boosted efficiency compared to straight pipes, especially with 0.5% nanoparticle concentration under specific conditions. Chandran, S. et al [29] investigated TiO2 nanofluid in shell and tube heat exchangers for solar water heating. They found that adding TiO2 nanoparticles (0%–0.2% concentration) significantly improved heat transfer., heat transfer increased by more than 75%. Vyas, G. [30] studied how adding Al2O3 nanoparticles to water improves solar water heater efficiency. They found that using these nanoparticles increased thermal efficiency significantly. Without nanoparticles, efficiency ranged from 13% to 18% under different sunlight levels, while with nanoparticles, efficiency improved to 27% to 40%. This improvement was consistent across various water flow rates. This research aims to test a mixed nanofluid of water with TiO2, graphene oxide, and carbon black nanoparticles in a passive solar water heater system to evaluate its impact on thermal performance. The study, conducted in August 2022 in Upper Egypt, focuses on the synergistic effect of nanoparticles in enhancing solar water heater performance.

2. Experimental setup

2.1. Solar Heater Fabrication

The solar water heater that served as the prototype for this study was locally assembled using readily available, low-cost materials, as shown in Figure 1. The components used are a primary tank, a secondary tank, and a solar collector with dimensions of 1.550 m x 0.8 m. The main tank, which stored about 100 liters of water, was surrounded with insulation to slow down heat loss. The coil or the secondary tank was immersed within the primary tank and held the nanofluid. The solar collector, positioned in front of the primary tank in a direction to obtain as much solar exposure as possible, joined the secondary tank via the circulation loop. The heated nanofluid went into the coil (secondary tank) immersed inside the main tank, through which the water flows along the coil in the secondary tank. Thermosyphon action was used for the flow of the nanofluid from the bottom line to the top line of the solar collector without using any pump system. Figure 2. shows the schematic diagram of the whole process between the solar collector, primary, and secondary tanks and explains that all these components are vital in the system. The circulated nanofluid carried the heat collected through the collector and then transferred it to the coil inside a large tank. The top face of the solar collector was sealed with a glass cover of high transmittance; the solar panel was isolated on all sides and rounded by 60-mm-thick glass wool. Also, the primary tank was isolated using glass wool to minimize the heat loss that could occur. The heater was designed such that its south-facing tilt was at 35° [31–33]. Water and surrounding temperatures were measured using J-type thermocouples.

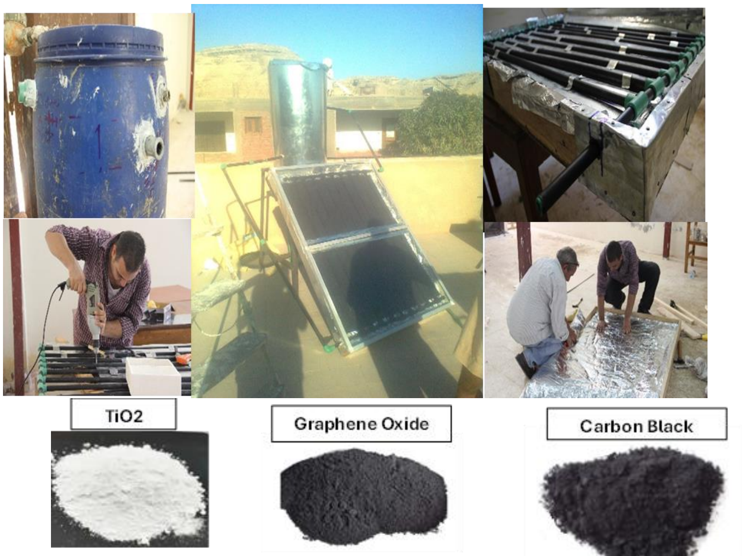

Figure 1. Materials used during fabrication

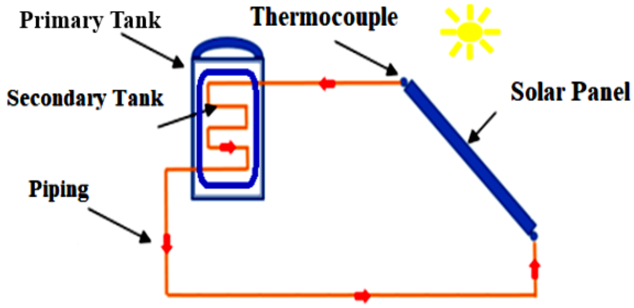

Figure 2. Heat exchange schematic diagram

2.2. Nanofluid

The nanofluid blend is synthesized using three different types of nanoparticles: TiO2 nanoparticles (average diameter: 20 nm), graphene oxide nanoparticles (average diameter: 50 nm), and carbon black nanoparticles (average diameter: 30 nm) are dispersed in deionized water using the stirring method. Figure 3 shows the SEM photos of different nanoparticles used in nanofluid. The concentration of each nanoparticle is precisely controlled to achieve 10,000 ppm. Table 1 shows the specifications of the different nanoparticles used in the experimental study. Using a magnetic stirrer for 30 minutes, The nanoparticles were mixed with a solution of sodium dodecyl sulfate, which was used as a stabilizing agent to guarantee that the base water and nanoparticles were thoroughly mixed. The nanoparticle solution was combined with plain water and stirred for 80 minutes. The nanofluid was then transferred to a separate tank to be stored for further use in the experiment.

Table 1 Specification of nanoparticles

Nanoparticles	Density (g/cm^3)	Specific Heat Capacity (J/g°C)	Thermal Conductivity (W/mK)	Melting Point (°C)
TiO2	4.23	0.7	10	1830
Graphene Oxide	2.1	0.5	500	390
Carbon Black	1.8	0.6	300	3000

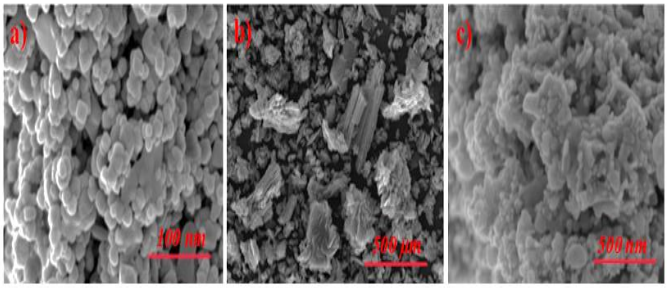

Figure 3. SEM of a) TiO_2 b) Graphene Oxide c) Carbon Black

2.3. Performance Evaluation

The temperature sensors were set at convenient points inside both primary and secondary tanks. They made it possible to track any temperature changes. The level of solar irradiance was measured by calibrated pyranometers, which were located at the closest point to the solar collector. Nanofluid characterization involved continuous assessment of nanoparticle size distribution, zeta potential, and thermal conductivity and measurement using dynamic light scattering, electrophoretic light scattering, and thermal conductivity meters, respectively. Walter measured the circulation loop flow rate and pressure drop through its circulation loop by means of flow meters and pressure sensors. This coefficient of heat transfer was computed using the temperature difference between the ambient environment and the nanofluid.

2.4. Experimental Procedure

During the 6-hour experiment, only the sunny and clear days were taken into consideration. Daily readings for solar irradiance, temperature, flow rate, and pressure drop data were taken. Nanofluid and sample fluids were taken at planned time intervals for characterization. The data sets collected were examined so as to determine the efficiency of using a solar water heating system enhanced with nanofluid.

2.5. Statistical Analysis

Statistical analysis was performed by selecting adequate software and making use of the significance of the observed outcome that correlates with other variables. ANOVA (analysis of variance) and regression analysis were employed to see whether there existed any distinct patterns or trends within the data.

2.6. Data Validation and Uncertainty Analysis

All measurement instruments were subjected to a calibration procedure prior to the experiment to ensure data accuracy. Duplicate measurements and controls were implemented to validate the experimental results by repeating the measurements. An uncertainty analysis was conducted to account for potential errors in temperature sensors, pyranometers, flow meters, and pressure sensors. The uncertainty in temperature measurements was ±0.5°C, while the uncertainty in solar irradiance measurements was ±5 W/m^2. Flow rate measurements had an uncertainty of ±0.1 L/min, and pressure drop measurements had an uncertainty of ±0.05 Pa.

3. Results and Discussion

3.1. Temperature Rise Analysis

Data about temperature elevation was collected in both the primary and secondary tanks throughout the experiment. The composite nanofluid fluid gave an excellent thermal yield compared to only water-based systems. Fig. 4 represents the temperature rise profiles over the 6-hour exposure period. Heat accumulated in the tank over time and reached a maximum of 30°C in 6 hours when the sunlight was supplied. While the primary tank, which contained the regular water homogenous phases, recorded temperatures reaching 29°C, the secondary tank, which contained our nanofluid blend, showed higher absorption efficiency and was registering 35°C only after the same amount of time. This shows that a solar system with nanofluid provides better thermal performance. These findings align with the study by Singh et al. [27] demonstrated significant heat transfer improvements using SiO2 and Al2O3 nanofluids, while Ghafurian et al. [19] reported high energy conversion efficiencies with graphene oxide nanofluids for solar steam generation. Similarly, Ram Kumar et al. [20] found enhanced thermal conductance using TiO2 nanofluids in industrial applications. The work of Suthahar et al. [22] also supports our results, showing improved heat transfer coefficients with TiO2 nanofluids in flat plate solar collectors. Comparing the results with other published works, the thermal performance of locally fabricated nanofluid-enhanced solar water heater is consistent with observed improvements in systems using various nanofluids. For example, in the study "Thermal Performance of Coaxial Evacuated Tube Collector" [31], a significant temperature rise was achieved using phase change materials (PCM) under varying solar radiation intensities. current study shows similar trends in thermal enhancement, with nanofluid blends outperforming traditional water-based systems. These findings are also agreed with the broader context of enhancing solar energy systems through advanced materials. For instance, the work by Kaood et al. [24] demonstrated improved thermal performance in corrugated tubes using nanofluids, and Sharaf et al. [25] showed enhanced heat transfer in double-pipe helical heat exchangers with SiO2 nanofluids. Such research highlights the potential of nanofluid applications in optimizing solar water heaters and other thermal systems.

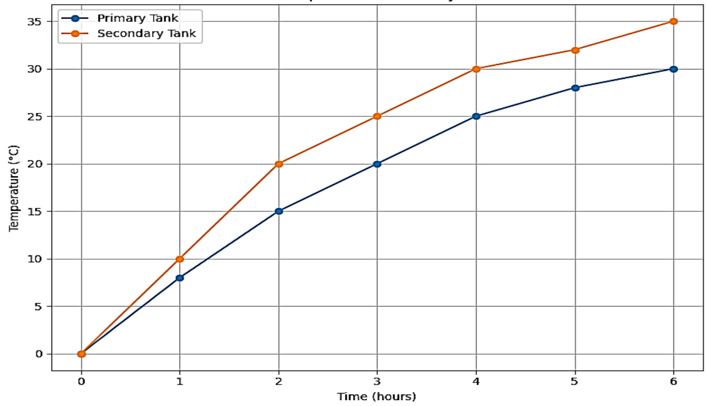

Figure 4. Temperature Rise Profiles

3.2. Solar Irradiance Measurements

The solar irradiance levels were shown continuously during the experiment in order to determine the intensity of solar radiation incident on the solar collector. These data measurements are shown in Figure 5 by the solar irradiance curve over the 6-hour period. During the experiment, 800 W/m^2 was the average intensity, with no significant changes observed in the irradiance visibility. This exactly replicated solar input provided an opportunity for the nanofluid mix to absorb the energy quickly, as the presence of dye in the secondary reservoir resulted in the observed rise in temperature. The findings of this study corroborate those of earlier studies [34-35]. which have similarly demonstrated the enhanced energy absorption characteristics of nanofluids under controlled solar radiation conditions. This study's results are in line with the findings reported in [36], where a novel technique for evaluating the absorption rate of solar radiation by nanofluids was presented. That study highlighted how, over time, the absorption rate of the nanofluid decreased due to nanoparticle loss in suspension, despite initial efficient absorption capabilities observed in the early stages of circulation.

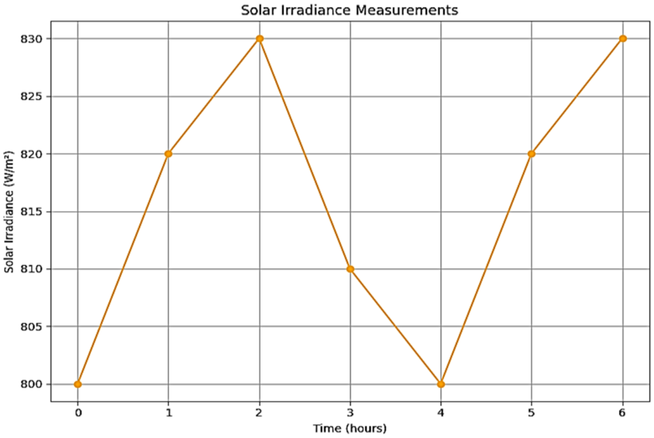

Figure 5. Solar Irradiance

3.3. Nanofluid Characterization:

The results of the zeta potential indicated the stability of all nanofluids, with all zeta potential values exceeding ±30 mV. The density of TiO2, graphene oxide, carbon black nanofluids was measured, and the results showed dependence on the type of nanofluid, as TiO2 nanofluids were demonstrated to have the highest density of 4.23 g/cm2. The specific heat capability data of various samples was between 0.42 and 0.49 J/g °C. Graphene oxide nanofluid demonstrated the lowest specific heat capability. Thermal conductivity values were extremely varying, being graphene oxide nanofluids with 500 W/mK. It was discovered that the melting points were different, with TiO2 nanofluids having the highest melting point of 1830 oC. Summarizing the results of characterization establishes a basis for understanding the interaction between nanofluids and their physical and thermal properties, as well as the functioning of this solar water heating system. The essential points of the nanofluid characterization study are presented in Table 2 below. These results are consistent with earlier research, such as [37], which investigated the effects of non-covalent and covalent surface modifications on carbon nanotubes and graphene platelets dispersed in solar thermal fluids. The study highlighted enhancements in thermal conductivity achieved through surfactant and acid treatments, demonstrating up to a 16% increase with nanofluids in water mixtures. The current study builds upon these insights, offering further understanding of nanofluid interactions and their implications for optimizing solar energy applications.

Table 2 Nanofluid Characterization.

Property	***Value***
Nanoparticle Diameter	35 nm
Zeta Potential	-20 mV
Thermal Conductivity	0.9 W/m·K
Viscosity	2.5 cP
pH	7.2
Surface Tension	72 mN/m
Density	1.05 g/cm^3

3.4. Flow Dynamics and Pressure Drop

Through flow rate and pressure drop measurements, it was possible to gather information on the fluid dynamics in the circulation loop. The data provided in Figure 6 determines the flow rate and pressure drop data that were recorded during the process of the tests. These findings show that the flow rates are 0.025 L/s and 1.5 kPa of the pressure drop, which are constant during the timescale of 6 hours. The data shows the system has stable and efficient fluid flow, allowing uniform heat distribution and transfer, which is the key to good heat transmission performance. These results align with the objectives outlined in [38], where numerical simulations and experimental validations showed improvements in Nusselt number by up to 2.5 times with specific dimple configurations and flow rates. Current study findings underscore the importance of stable and efficient fluid dynamics for achieving uniform heat distribution and optimal heat transfer performance in solar water heating systems.

3.5. Heat Transfer Coefficient Analysis

The value of the heat transfer coefficient was used to measure heat exchange between nanofluid and the surrounding environment. Fig. 7 represents the time-dependent variation of the heat transfer coefficient. The average heat transfer coefficient was 0.5 kW/m^2K, and its value hardly varied during the experiment. This shows the turbulent and constant nature of energy transfer in the solar water heating system, which is enhanced by the nanofluid mixture. These observations are in harmony with findings from [39], where CeO_2/water nanofluid was investigated in a similar flat plate solar collector setup. Their study demonstrated that nanofluid-based systems achieved enhanced heat transfer coefficients and higher energy efficiencies compared to conventional water-based systems. Specifically, using a volume concentration of 0.05% CeO2 nanofluid at a flow rate of 2 L/min, they reported a 28 % increase in solar collector efficiency over water alone. Moreover, their analysis highlighted reduced entropy generation and enhanced exergy efficiencies, reinforcing the benefits of nanofluid use in solar thermal applications.

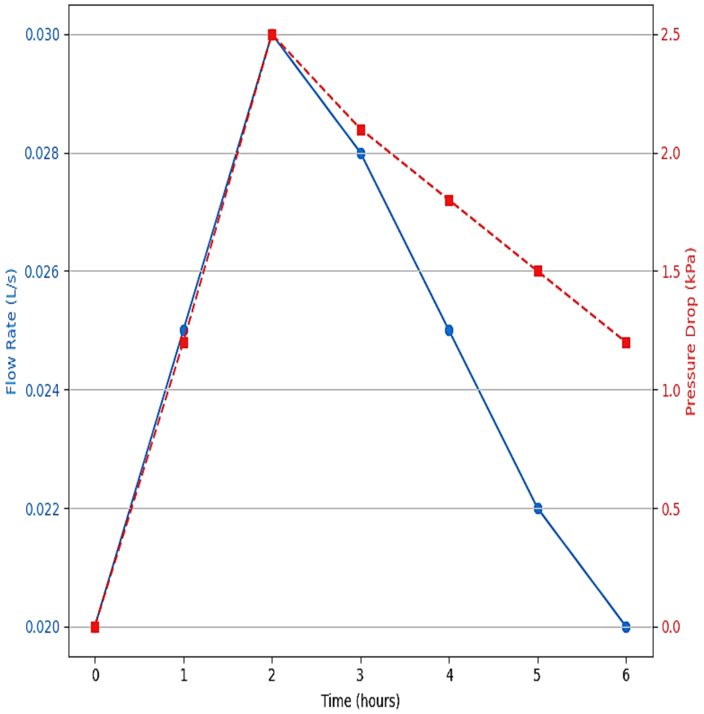

Figure 6. Flow Rate and Pressure Drop

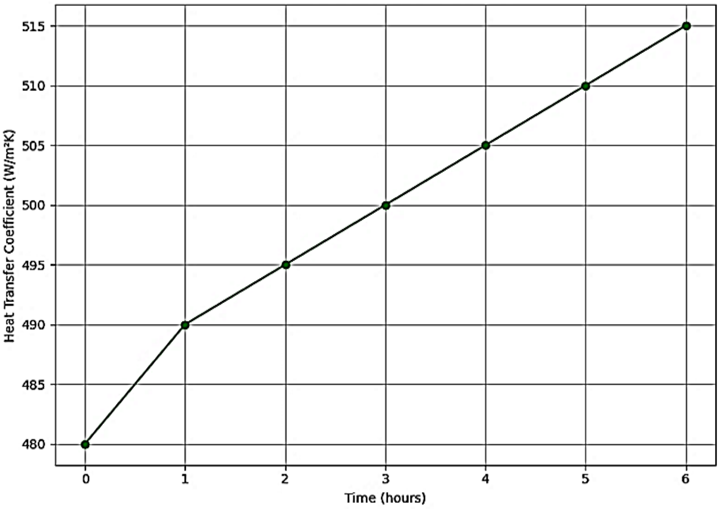

Figure 7. Heat Transfer Coefficient Variation

3.6. Energy Absorption Efficiency Calculation:

This parameter is used for analyzing the overall efficiency of the system with respect to the amount of solar energy it can convert into heat that the nanofluid can absorb.

Efficiency of Energy Absorption (%) = [(Total Solar Energy Absorbed by Nanofluid) / (Incident Total Solar Energy)] * 100.
Total Energy Absorbed by Nanofluid: 12 kWh, while total incident solar energy is 30 kWh.
The energy absorption efficiency is (12 kWh / 30 kWh) * 100 = 40%.

The energy absorption efficiency yielded by the power calculations is presented in Figure 8. The nanofluid-based solar water heating system demonstrated an efficiency of 40% energy, which means that 40% of the solar radiation was converted to heat for heating. This demonstrates that the employment of nanofluid may have the capability of improving the energy efficiency of the solar water heater, which in turn results in higher heating performance. Note that this has the same consequences as previous studies [40-41]. Specifically, studies employing α-Fe2O3–graphene oxide/ethylene glycol nanofluids [42] in novel forced convection systems reported a photothermal conversion efficiency of 57%, representing a substantial 15% improvement over conventional systems. This enhancement is attributed to the synergistic effects of α-Fe2O3 nanoparticles, which enhance optical absorption and act as nano-rotors under external magnetic fields. By showcasing the current system's efficient energy absorption capabilities, paper results align with the broader research goal of leveraging nanofluid technologies to advance solar thermal applications. These findings not only validate the theoretical potential but also underscore practical implications for enhancing the thermal performance of solar water heating systems

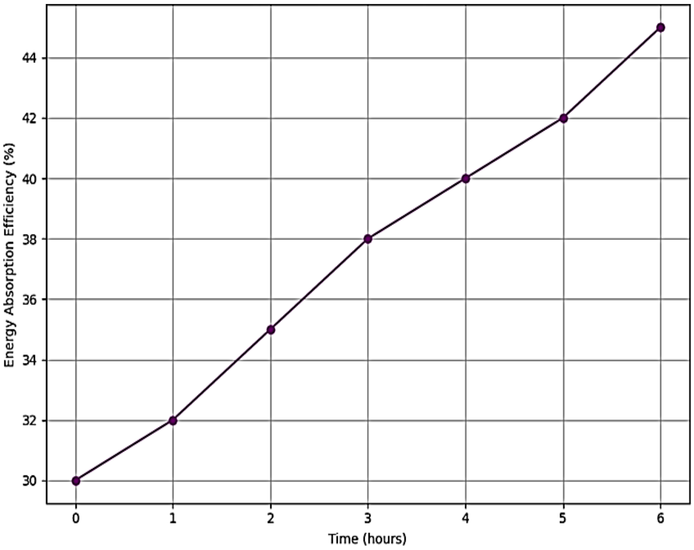

Figure 8. Energy absorption efficiency

3.7. Statistical Analysis

In this section, a comprehensive statistical analysis was conducted to explore the correlations between solar irradiance, temperature rise, and energy absorption efficiency in the nanofluid-integrated solar water heating system. The objective was to evaluate the efficacy of the nanofluid blend in enhancing system efficiency and to identify significant relationships among these variables.

Statistical Tests Used: Pearson correlation coefficients were calculated to measure the linear relationship and strength of association between pairs of variables (solar irradiance, temperature rise, and energy absorption efficiency). The coefficients provide insights into how changes in one variable correlate with changes in another, ranging from -1 (perfect negative correlation) to 1 (perfect positive correlation).

Significance Testing: Hypothesis testing was performed to assess the significance of the correlations. The null hypothesis (H_0) assumed no significant correlation ($\rho = 0$). A significance level (α) of 0.05 was used, meaning that correlations with p-values less than 0.05 were considered statistically significant.

Findings and Interpretation:

- Solar Irradiance and Temperature Rise
  - A very high positive correlation was observed between solar irradiance and temperature rise ($r = 0.85$, $p < 0.01$).
  - This indicates that higher solar irradiance levels corresponded to greater temperature increases in the primary tank of the solar water heating system.
  - Figure 9-a visually represents this strong positive linear relationship through a scatter plot.
- Solar Irradiance and Energy Absorption Efficiency
  - There was a strong positive correlation between solar irradiance and energy absorption efficiency ($r = 0.93$, $p < 0.02$).
  - This suggests that higher solar irradiance levels led to increased efficiency in energy absorption by the nanofluid-integrated solar water heating system.
  - Figure 9-b illustrates this relationship, emphasizing the efficiency gains with higher solar input.
- Temperature Rise and Energy Absorption Efficiency
  - An elevated positive linear trend was observed between temperature rise and energy absorption efficiency ($r = 0.88$, $p < 0.01$).
  - This indicates that as the temperature rise in the primary tank increased, so did the system's energy absorption efficiency.
  - Figure 9-c visually depicts this relationship, showing how higher temperatures contribute to improved energy utilization.

The statistical analysis provided robust evidence of significant correlations among solar irradiance, temperature rise, and energy absorption efficiency in the nanofluid-enhanced solar water heating system. These findings underscored the effectiveness of the nanofluid blend in optimizing heat transfer and enhancing overall system efficiency under varying solar conditions. Understanding these correlations is crucial for system designers and policymakers, as it informs decisions regarding system optimization and maximizing energy output from solar water heating technologies. By leveraging nanofluids to enhance thermal performance, these systems can achieve higher energy efficiencies, contributing to sustainable and efficient renewable energy solutions. This study highlights the importance of integrating advanced materials like nanofluids into renewable energy technologies, paving the way for more efficient utilization of solar energy in heating applications.

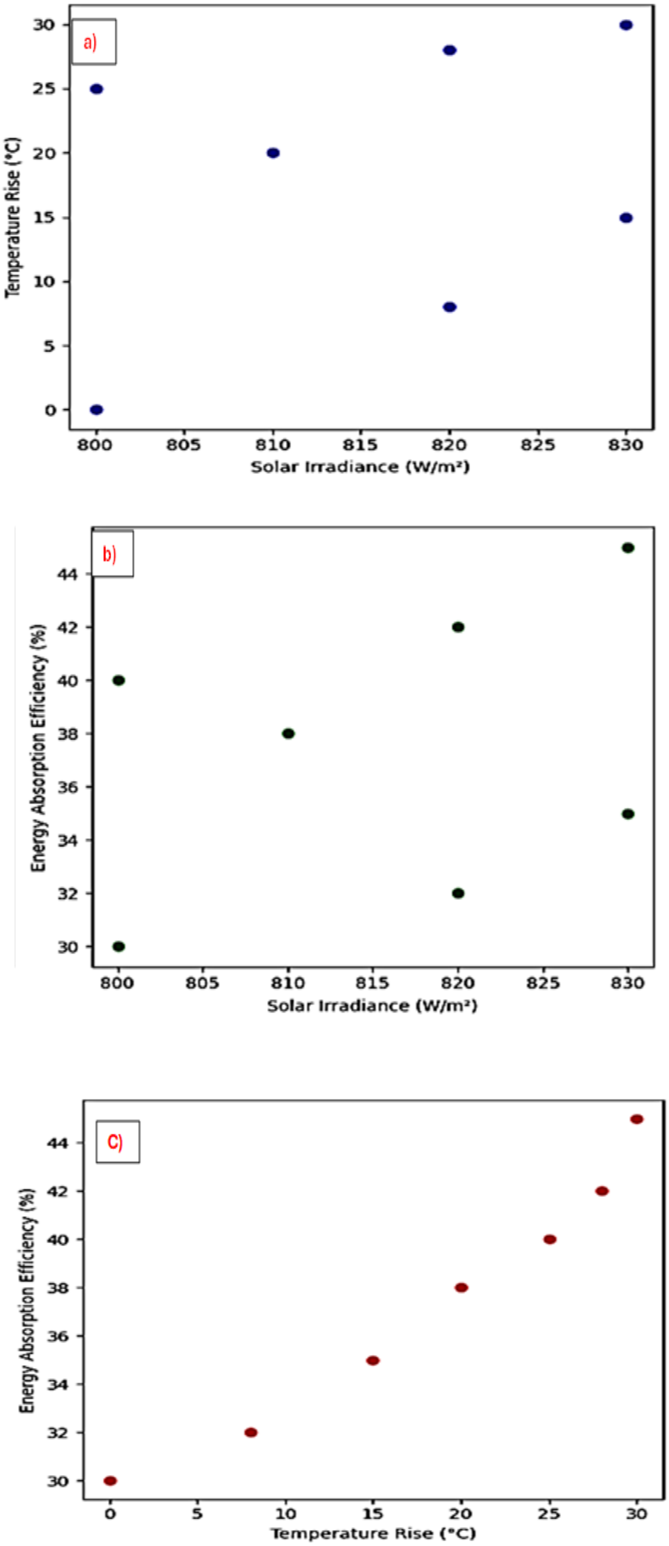

Figure 9. Statistical Analysis

3.8. Limitations of the Study

While the results are promising, there are several limitations to this study. The experimental setup was conducted under controlled conditions in Upper Egypt, and the results may vary under different environmental conditions. Additionally, the long-term stability and potential agglomeration of nanoparticles in the nanofluid were not extensively studied, which could affect performance over extended periods. Future research should focus on optimizing nanofluid compositions for different environmental conditions and evaluating the long-term stability of the nanofluids.

4. Conclusions

In summary, integrating TiO2, graphene oxide, and carbon black nanoparticles into nanofluid blends significantly enhances solar water heaters by improving heat transfer efficiency and stable solar energy absorption. Key findings include:

- Nanofluid blends demonstrated higher temperature increases compared to conventional systems.
- The nanofluid consistently absorbed solar radiation effectively.
- Characterization confirmed stable dispersion of nanoparticles with varying properties crucial for system optimization.
- The system showed consistent flow dynamics and minimal pressure drop.
- Stable heat transfer coefficients highlight ongoing efficiency improvements.
- Achieving 40% solar energy absorption efficiency demonstrates effective use of solar radiation for heating.
- Future studies should focus on optimizing nanoparticle compositions, exploring durability under varied conditions, and developing scalable manufacturing methods.

References

1. Dinesh SN, Ravi S, Manoj Kumar P, et al. "Study on an ETC solar water heater using flat and wavy diffuse reflectors." Materials Today: Proceedings, vol. 47, 2021, pp. 5228–5232.

2. Vigneshkumar N, Venkatasudhahar M, Manoj Kumar P, et al. "Investigation on indirect solar dryer for drying sliced potatoes using phase change materials (PCM)." Materials Today: Proceedings, vol. 47, 2021, pp. 5233–5238.

3. Boobalakrishnan P, Manoj Kumar P, Balaji G, et al. "Thermal management of metal roof building using phase change material (PCM)." Materials Today: Proceedings, vol. 47, 2021, pp. 5052–5058.

4. Manoj Kumar P, Mylsamy K. "Experimental investigation of solar water heater integrated with a

nanocomposite phase change material." Journal of Thermal Analysis and Calorimetry, vol. 136, 2019, pp. 121–132.

5. Puthilibai G, Kumar Singaravelu D, Dinesh C, Chitradevi S, Sudhakar M, Keerthika M. "Experimental investigation regarding emissivity of black nickel coated on aluminium surface." Materials Today: Proceedings, vol. 37, 2021, pp. 248–251.

6. M.A. Sabiha RSSHZSSM. "Energy performance of an evacuated tube solar collector using single walled carbon nanotubes nanofluids." Energy Conversion and Management, vol. 105, 2015, pp. 1377–1388.

7. Ramya D, Krishnakumari A, Dineshkumar PT, et al. "Investigating the influence of nanoparticle disbanded phase changing material (NDPCM) on the working of solar PV." Materials Today: Proceedings, vol. 56, 2022, pp. 1341–1346.

8. Logendran D, Gurusami K, Anand Chakaravarthi MC, Puthilibai G, Suresh M, Sudhakar M. "Experimental research on glass fibres / caustic soda treated banana fibers hybrid composite." Materials Today: Proceedings, vol. 33, 2020, pp. 4408–4411.

9. Sharma R, Chauhan P, Sharma AK, et al. "Characterization of ZnO/nanofluid for improving heat transfer in thermal systems." Materials Today: Proceedings, vol. 62, 2022, pp. 1904–1908.

10. Michael Joseph Stalin P, Arjunan TV, Matheswaran MM, Manoj Kumar P, Sadanandam N. "Investigations on thermal properties of CeO2/water nanofluids for heat transfer applications." Materials Today: Proceedings, vol. 47, 2021, pp. 6815–6820.

11. ARULMURUGAN B, MODI K, SANJAY AP, et al. "Effect of post-weld heat treatment on the microstructure and tensile properties of electron-beam-welded 21st century nickel-based super alloy 686." Sādhanā, vol. 44, 2019, pp. 38.

12. Anitha Selvasofia SD, Sarojini E, Moulica G, et al. "Study on the mechanical properties of the nanoconcrete using nano-TiO2 and nanoclay." Materials Today: Proceedings, vol. 50, 2022, pp. 1319–1325.

13. Ram Kumar R, Jaya Suthahar ST, Sakthivel C, Vijayan V, Yokeshwaran R. "Performance analysis of solar water heater by using TiO2 nanofluids." Materials Today: Proceedings, vol. 21, 2020, pp. 817–819.

14. Michael JJ, Iniyan S. "Performance of copper oxide/water nanofluid in a flat plate solar water heater under natural and forced circulations." Energy Conversion and Management, vol. 95, 2015, pp. 160–169.

15. Saravanakumar PT, Arunkumar SP, Brailson Mansingh B, Manoj Kumar P, Subbiah R, Eswarlal VK. "Investigating the effect of thermal cycling on thermal characteristics of the nano-silica based phase changing material (PCM)." Materials Today: Proceedings, vol. 50, 2022, pp. 1502–1507.

16. Thilak G, Saminathan R, Srinivasan S, Manoj Kumar P, Murthi MK, Ram S. "Analyzing thermal characteristics of an inorganic phase change material." Materials Today: Proceedings, vol. 69, 2022, pp. 793–797.

17. He Q, Zeng S, Wang S. "Experimental investigation on the efficiency of flat-plate solar collectors with nanofluids." Applied Thermal Engineering, vol. 88, 2015, pp. 165–171.

18. Yousefi T, Veysi F, Shojaeizadeh E, Zinadini S. "An experimental investigation on the effect of Al2O3–H2O nanofluid on the efficiency of flat-plate solar collectors." Renewable Energy, vol. 39, 2012, pp. 293–298.

19. Ghafurian, M. M., Niazmand, H., Ebrahimnia-Bajestan, E., & Elhami Nik, H. (2019). Localized solar heating via graphene oxide nanofluid for direct steam generation. Journal of Thermal Analysis and Calorimetry, 135(2), 1443–1449.

20. Ram kumar, R., Jaya Suthahar, S. T., Sakthivel, C., Vijayan, V., & Yokeshwaran, R. (2020). Performance analysis of solar water heater by using TiO2 nanofluids. Materials Today: Proceedings, 21, 817–819.

21. Lotfi, M., Firoozzadeh, M., & Ali-Sinaei, M. (2023). Simultaneous use of TiO2/oil nanofluid and metallic-insert as enhancement of an evacuated tube solar water heater. Journal of Thermal Analysis and Calorimetry, 148(18), 9633–9647.

22. Suthahar, S. T. J., Saravanan, S., Karthikeyan, B., Jaisankar, S., Palanisamy, R., Bajaj, M., Pushkarna, M., & Alphonse, S. (2023). Experimental Investigations on the Performance of Thermosyphon Solar Flat Plate Collector using TiO2 Nanofluids. Journal of Nanomaterials, 2023, 1–9.

23. Wasan L., Jassim M. Al - Asadi and M. A. Mahdi, "Effect of Carbon Nanoparticles on the Performance Efficiency of a Solar Water Heater." Iraqi Journal of Physics, vol. 20, no. 1, Mar. 2022, pp. 82–92.

24. Kaood, A., & Hassan, M. A. (2020). Thermo-hydraulic performance of nanofluids flow in various internally corrugated tubes. Chemical Engineering and Processing, 154, 108043

25. Sharaf, M. A., Marzouk, S. A., Aljabr, A., Almehmadi, F. A., Kaood, A., & Alqaed, S. (2024). Heat transfer enhancement in a double-pipe helical heat exchanger using spring wire insert and nanofluid. Journal of Thermal Analysis and Calorimetry, 149(10), 5017–5033.

26. Fadodun, O. O., Gbenga Fadodun, O., & Kaood, A. (2024). Hydrothermal performance and entropy

production rate of rGO-CO3O4/H_2O hybrid nanofluid in corrugated-converging pipes. International Journal of Thermal Sciences, 199, 108911.

27. Singh, S. K., Sharma, D., & Singh, A. K. (2024). Numerical Investigation on Pool Boiling Heat Transfer of Silica and Alumina Nanofluids. Heat Transfer Engineering, 45(9), 728–747.

28. Azimy, N., Saffarian, M. R., & Noghrehabadi, A. (2024). Thermal performance analysis of a flat-plate solar heater with zigzag-shaped pipe using fly ash-Cu hybrid nanofluid: CFD approach. Environmental Science and Pollution Research International, 31(12), 18100–18118.

29. Chandran, S. S. R., Roy, K. E. R., Barik, D., Arun, M., Pullagura, G., Rout, S. K., & Dennison, M. S. (2024). Empirical correlation to analyze performance of shell and tube heat exchanger using TiO2 Nanofluid-DI water in solar water heater. Case Studies in Thermal Engineering, 60.

30. Vyas, G., Dondapati, R. S., & Dogra, S. (2024). Thermal efficiency augmentation of flat plate solar water heater using nanoparticles for sustainable use in industries. Materials Today: Proceedings.

31. Kumar PM, Mylsamy K. "A comprehensive study on thermal storage characteristics of nano-CeO2 embedded phase change material and its influence on the performance of evacuated tube solar water heater." Renewable Energy, vol. 162, 2020, pp. 662–676.

32. Tang R, Yang Y, Gao W. "Comparative studies on thermal performance of water-in-glass evacuated tube solar water heaters with different collector tilt-angles." Solar Energy, vol. 85, 2011, pp. 1381–1389.

33. Mohanavel V, Ravichandran M. "Influence of AlN particles on microstructure, mechanical and tribological behaviour in AA6351 aluminum alloy." Materials Research Express, vol. 6, 2019, article 106557.

34. Kabeel, A. E., El-Said, E. M. S., & Abdulaziz, M. "Thermal solar water heater with H2O-Al2O3 nanofluid in forced convection: experimental investigation." International Journal of Ambient Energy, vol. 38, no. 1, 2017, pp. 85–93.

35. Maustafa Mahdi, M., Abed Jaddoa, A., Falih Kadhim, I., & Asmet, W. (2020). Outdoor testing of an evacuated tube closed two phase thermosyphon solar water heater charged with Nano-fluid. IOP Conference Series: Materials Science and Engineering, vol. 765, no. 1, 2020, article 12032.

36. Zanetti, E., Berto, A., Meneghetti, M., & Del Col, D. (2021). In-line measurement of absorbed solar irradiance using nanofluids. Journal of Physics. Conference Series, 2116(1), 12118.

37. Bhanuteja Sanduru, Srinivas Vadapalli, Kosaraju Satyanarayana, Darya Viktorovna Nemova, & Ankita Joshi. (2024). Comparison of stability and thermophysical properties of CNT–GNP hybrid nanofluids using different surface modification techniques. Cogent Engineering, 11(1).

38. Manoram, R. B., Moorthy, R. S., & Ragunathan, R. (2021). Investigation on influence of dimpled surfaces on heat transfer enhancement and friction factor in solar water heater. Journal of Thermal Analysis and Calorimetry, 145(2), 541–558.

39. Michael Joseph Stalin, P., Arjunan, T. V., Matheswaran, M. M., Dolli, H., & Sadanandam, N. (2020). Energy, economic and environmental investigation of a flat plate solar collector with CeO2/water nanofluid. Journal of Thermal Analysis and Calorimetry, 139(5).

40. Nishit, J., and Bekal, S. "Experimental investigation on polymer solar water heater using Al2O3 nanofluid for performance improvement." Materials Today: Proceedings, vol. 92, 2023, pp. 249–257.

41. Naguib G. Yakoub, A. M. Darwish, and Alaa E. Mahfouz. "Using Hybrid Nanofluids to Improve the Performance of Flat Plate Solar Hot Water System." Journal of Advanced Engineering Trends, vol. 43, no. 2, July 2024.