Exploiting the Potential of Carbon Nanotubes and Nanofluids to Boost Efficiency in Solar Applications

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Abstract This work comprehensively reviews recent advancements and applications of Carbon Nanotube (CNT) nanofluids, specifically concentrating on their integration into energy harvesting systems, particularly solar collectors. The effectiveness of collectors. Utilizing CNT nanofluids is assessed, accompanied by exploring preparation methods and factors influencing thermal conductivity and optical properties. Also mentioned are the drawbacks and potential directions for using CNT nanofluids in thermal collectors. CNTs, possessing the highest thermal conductivity among known nanoparticles, offer promising potential as heat transfer fluids when dispersed into various base fluids, creating CNT nanofluids. However, maintaining prepared CNT nanofluids' homogeneity and sustained durability poses a significant challenge. The paper provides a detailed study of the preparation techniques and reported stability periods of stationary CNT nanofluids. Various treatment methods, including chemical and physical treatments, are systematically analyzed, offering insights into overcoming stability challenges and future directions. The paper advocates for a balanced combination of techniques to achieve CNT dispersion without excessive treatment. Methods for analyzing nanofluid stability are also surveyed, emphasizing the need for cost-effective and rapid stability prediction methods.

Keywords Carbon nanotubes (CNT) · Nanomaterials · Carbon-based materials nanofluid · Solar collectors · Thermal conductivity · Nanofluid stability · Covalent functionalization surfactant · Energy efficiency

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1 Introduction

In the last several decades, research in nanoscience and nanotechnologies has risen quickly, positioning it at the vanguard of contemporary scientific advancements. Because of their excellent thermal, physical, optical, and electrical qualities, carbon nanotubes (CNTs) have significantly contributed to the nano revolution. These remarkable attributes have propelled CNTs into becoming among the most comprehensive scrutinized Materials at the nanoscale.

The astonishingly high thermal conductivity of CNTs is one of its most noticeable features, which sets them apart from other nanoparticles. The revelation of this remarkable thermal conductivity in nanoparticles has ignited significant interest in research endeavors focusing on heat transfer fluids. The pioneering work of Choi et al. [1] marked the inception of this concept, as they stumbled upon an unexpectedly increased thermal conductivity in nanofluids in contrast to their base fluids. This discovery triggered a flurry of research efforts, documented in the literature, exploring various nanofluids in the context of energy harvesting and cooling systems. Consistent results throughout this research show how incorporating nanoparticles inside the fluid substantially enhances heat transmission. A specific emphasis is placed on the various preparation techniques used to maintain the stability of these nanofluids. While it is worth acknowledging that a few earlier review articles have explored this subject, it is imperative to highlight the burgeoning research trends revealed by the Scopus database. These trends unequivocally indicate a consistent upward trajectory in research activities related to CNT-infused nanofluids, with the past couple of years witnessing an unprecedented surge in interest from researchers worldwide.

Notably, most of the previously mentioned review articles predominantly focused on the thermal aspects of CNT nanofluids. A sizable body of research has recently been devoted to improving heat transfer by altering the thermophysical characteristics of working fluids. Their exceptional strength, electrical conductivity, and thermal conductivity result from their distinctive atomic arrangement. CNTs find applications across materials science, electronics, and nanotechnology, reflecting their potential for diverse technological and scientific progress.

A few reviews delved into the chemical and non-chemical modification of CNTs. t is worth noting that stability analysis presents a significant challenge, often requiring costly equipment and substantial time. In numerous studies, stability was either not addressed or was reported insufficient. Consequently, there is a pressing need to develop an economical and rapid approach to forecasting the stability of CNT nanofluids. Furthermore, it is noted that chemical and material scientists conduct most studies and investigations associated with preparing CNT nanofluids. In contrast, scientists in mechanical, chemical, and thermophysical engineering. Primarily investigate the thermal applications of nanofluids. Bridging this interdisciplinary gap and fostering knowledge exchange among these fields is essential for advancing the development of stable CNT nanofluids for thermal applications.

Furthermore, surfactants are more accessible to remove than polymers or proteins, and surfactant-attached CNTs can be easily removed by rinsing with deionized water

(DIW). SDS has found extensive application in preparing CNT solutions for various purposes, including nanocomposites, nanofluids, substances with antibacterial properties, and materials for coating applications. Numerous research studies have investigated the influence of SDS surfactants in solutions containing CNTs, considering variables like temperature, SDS concentration, sonication power, and binding energy.

There has been constrained investigation into the optimal Concentration of SDS in solutions containing carbon nanotubes for electrokinetic manipulation systems, specifically in the context of dielectrophoretic deposition multi-walled carbon nanotubes (MWCNTs) involving the use of non-uniform electric fields to manipulate and position CNTs within a solution.

CNTs have emerged as promising reinforcements for high-strength metal matrix composites. Compared to pure metals, a metal matrix composite featuring CNTs boasts a higher strength-to-density ratio, specific modulus, improved fatigue resistance, and a lower coefficient of thermal expansion (CTE). Among MMCs, aluminum-based composites have gained significant attention and found applications across various industrial sectors due to their outstanding strength and a favorable combination of properties. The synergistic effects resulting from the unique properties of CNTs and aluminum alloys have prompted extensive research into manufacturing aluminum/CNT nanocomposites, especially for weight-sensitive applications. Typically, significant enhancements in the strength of aluminum alloys occur with the addition of small concentrations of CNTs. However, a substantial increase in reinforcement content can lead to embrittlement of the composite. Achieving an increase in strength with only a slight reduction in flexibility is possible by incorporating CNTs in small concentrations.

One significant approach that has garnered attention in recent years is using nanofluids. Nanofluids are a class of engineered fluids consisting of a base fluid and solid nanoparticles Suspended at nanoscale dimensions within the base fluid. Incorporating nanofluids into various thermal devices has shown promise in modifying their performance. For instance, scientists have evaluated the effectiveness of a pulsating heat pipe when filled with water and a nanofluid consisting of graphene oxide and water, demonstrating a significant lowering of heat resistance when utilizing nanofluid, ascribed to altered thermal conductivity and the presence of nucleation sites. In another study, Ni/water-glycerol nanofluid was used in a thermosyphon, revealing a decrease in overall thermal performance due to the addition of Ni nanoparticles. Nanofluids have also found applications in heat exchangers, where the use of TiO_2 /water nanofluid resulted in a substantial improvement in heat transfer compared to pure water. In addition to these applications, nanofluids have been integrated into clean energy technologies to enhance their efficiency. Geothermal systems, for example, benefit from nanofluids in heat exchangers, leading to size reduction and efficiency improvements. Nanofluids have also found application in fuel cells for thermal management, enhancing the reliability of these systems. However, one area where nanofluids have demonstrated significant potential is in solar technologies. They have been utilized in various solar systems, including solar collectors, ponds, and PVT systems, contributing to increased efficiency. The choice of nanofluid type and solid nanoparticles significantly impacts thermal performance, as the thermophysical properties depend on the specific materials used. Carbon nanotubes, known for their excellent heat transfer properties, have become a focus of Concern about solar energy devices' utilization of nanofluids.

2 Categories and Arrangement

While carbon is abundant in the natural world, CNTs are a product of human engineering. These methods yield distinct shapes of CNTs, categorized into Single-walled carbon nanotubes (SWCNTs), composed of a mono seamless graphene layer rolled into a cylinder, and MWCNTs, formed from multiple rolled-up graphene sheets. The nearest example we found was a study where researchers used this approach to create nanofluids containing carbon nanoparticles in flake form, which are distinct from carbon nanotubes. Traditional Essential fluids like water and ethylene glycol oil are frequently used as coolants, and primary fluids like water and ethylene glycol oil are commonly used as heat storage mediums. Still, they have limitations regarding their thermal and physical properties. Incorporating nanoparticles into these fluids has demonstrated a notable improvement in their thermophysical characteristics, leading to the emergence of novel terminologies and distinct functions for these nanoparticle-dispersed fluids. These include nano coolants or heat-storage nanofluids, nano lubricants, nano greases, nano refrigerants, and nanofluids. A different class of foundational fluid, an ionic liquid, essentially consists of molten salt and exhibits unique thermal and physical attributes, including a notable heat storage capacity, outstanding thermal resilience, and elevated viscosity. The dispersion of nanoparticles into ionic liquids gives rise to nanofluids. However, the concept of nanofluids was first proposed.

2.1 Carbon Nanotubes

CNTs are truly exceptional formations, representing a significant advancement in nanostructures. They are cylindrical monolayer sheets of carbon atoms and can be synthesized in various ways. Such frameworks are excellent for various applications because of their unique characteristics. SWCNTs, for instance, are constructed by seamlessly rolling a single graphene sheet into a tube, while MWCNTs are formed by rolling multiple graphene sheets. This classification is based on how many layers there are comprising the nanotube and affects their dimensions, density, and specific characteristics. This exceptional thermal conductivity makes CNTs an attractive candidate for improving the thermal properties of various fluids.

To harness the benefits of CNTs in heat transfer applications, researchers have explored the creation of CNT nanofluids. These nanofluids involve dispersing CNTs into different fluids or solvents, such as H_2O, ethylene glycol, or ionic liquids, to enhance their thermal and physical properties. Similarly, adding CNTs to engine oil at a 2% volume concentration results in a 30% conductivity of heat rising.

These improvements in thermal conductivity suggest that CNT-based nanofluids hold promise as heat transfer fluids. Various studies have investigated their impact on heat transfer in different applications. For instance, researchers have used CNT nanofluids in pulsating heat pipes, heat exchangers, and other thermal devices, consistently observing reductions in thermal resistance and enhancements in heat transfer performance. In solar thermal technologies, where the efficiency of systems heavily relies on the heat transfer properties of the operating fluid, the incorporation of CNTs can be transformative. CNTs not only possess superior thermal conductivity but also exhibit favorable optical properties. When dispersed in fluids, they can alter the spectral absorptivity of the fluid across the solar spectrum. By reducing transmittance, CNT-based nanofluids can enhance their performance in solar systems. Studies have demonstrated that nanofluids containing CNTs reduce the transmittance of light, particularly in the visible and long-wavelength ranges. The extent of transmittance reduction is correlated with a specified volume fraction of CNTs in the primary fluid. Additionally, the absorption properties of nanofluids with CNTs significantly improve, making them efficient radiation absorbers. This enhanced absorption is especially beneficial in solar applications, as it allows for the effective utilization of solar energy-based nanofluids and offers exciting prospects for enhancing heat transfer efficiency and solar energy utilization.

2.2 CNT-Based Nanofluids

The distinguishing factors between these two types include differences in length, diameter, density, and other intrinsic traits, rendering them suitable for specific applications. The historical development of CNTs reveals that the first CNT was an MWCNT.

Traditional base fluids like water have been conventionally employed for cooling and heat storage, albeit with limited thermal and physical capabilities. The addition of nanoparticles to these fluids enhances their heat transfer capabilities, leading to the emergence of nanofluids with various designations, including nano coolants, heat-storage nanofluids, nano lubricants, nano greases, nano refrigerants, and nanofluids. Intriguingly, some of these nanofluids were first created by introducing CNTs into them, as exemplified by the introduction of "nano grease" by Hong et al. [2]. Their work demonstrated improved thermal conductivity and lubricity in nano lubricants and nano greases containing MWCNTs dispersed in commercial oils. Furthermore, a distinct category of base fluid comprises molten salts characterized by unique physical attributes such as high heat storage capacity, excellent thermal stability, and high viscosity.

Integrating nanoparticles into ionic liquids results in nanofluids, a concept pioneered. Consequently, nanofluids containing these CNTs have become attractive alternatives for thermal medium operating fluids. CNTs possess favorable optical properties, making them well-suited for solar applications. When CNTs are dispersed in different fluids, they modify spectral absorptivity across the solar spectrum.

Studies have indicated that the presence of CNTs in nanofluids reduces transmittance. Notably, the presence of SWCNTs in water at a 0.5% volume fraction significantly increased its absorption, enabling the nanofluid to absorb nearly all emitted light. Increasing the volume fraction of SWCNTs had a relatively minor impact on the absorption characteristics of the nanofluid. It was demonstrated that increasing the nanofluid's temperature led to a reduction in radiation absorption levels. These higher absorption properties of nanofluids containing CNTs make them particularly advantageous for solar applications. Carbon nanotubes (CNTs) boast many enticing qualities, ranging from their remarkable aspect ratio to their outstanding mechanical, thermal, and optical attributes. These characteristics position them as up-and-coming candidates for application in many mediums and devices. Notably, CNTs exhibit an exceptionally high thermal conductivity, typically ranging from 2000 to 6000 $\frac{W}{m.K}$. An enlightening study by Liu et al. [3] provides valuable insights into this enhancement. Numerous investigations have delved into the influence of employing nanofluids that include solid-phase carbon-based particles in thermal devices. Tanshen et al. [4] implemented a pulsating heat pipe charged with water functionalized with multi-walled carbon nanotubes at various concentrations, spanning from 0 to 0.3% wt. This caused a significant decrease in thermal resistance.

Qu et al. [5] examined how adding MWCNTs to water affected transmittance. They observed that the tiny increase in MWCNTs resulted in a considerable decrease in transmittance. For instance, compared to pure water, a nanofluid containing 0.0015% weight of MWCNTs in water had a 40% lower transmittance throughout wavelengths between 200 and 880 nm. The concentration of nanostructures in the water was increased to reduce transmission further. Additionally, a study found that the 0.5% volume fraction of SWCNTs in water caused a noticeably higher absorption rate. This led to the nanofluid absorbing almost all the light being released. Contrary to expectations, additional increases in the volume fraction of SWCNTs did not appreciably change its absorption rate.

3 Durability of CNT Nanofluid

Mechanical treatment involves physically mixing nanoparticles in a solvent through ultrasonication, irrespective of whether the CNTs have been functionalized. Qualitative observation of nanofluids in static conditions and quantitative measurements like zeta potential provide insights into colloidal stability. Zeta potential, representing the degree of repulsion between charged particles on CNTs and the base fluid, is a crucial parameter. Positive or negative values indicate repulsion, with higher values signifying better stability. Both functionalization and the addition of surfactants can alter the iso-electric point, where nanoparticles carry no net electrical charge, impacting stability. Regarding the electrostatic charge on particle surfaces, pH measurement is critical in determining stability.

The interplay of these forces determines the stability of the nanofluid. High attractive forces, dependent on interparticle distances and nanoparticle shape, lead to aggregation. The shape of nanoparticles impacts the attractive forces, with larger contact areas favoring stronger attraction and aggregate formation aggregation, resulting in increased particle size, promoting settling, and affecting dispersive behavior. Conversely, high repulsive forces maintain suspension stability.

Nanofluids subjected to repeated heating and cooling cycles in heat exchangers suffer processes that promote nanoparticle aggregation. Brownian motion is accelerated by high temperatures, which increases the likelihood of nanoparticle collisions and encourages aggregation formation. A dragging force and a reduced fluid viscosity also support aggregation. The coordinated, directed movement of nanoparticles encourages aggregation and interferes with homogenous dispersion due to CNTs' proclivity for irreversible aggregation over time, fueled by strong-interactions; CNT nanofluids, particularly, encounter difficulties.

Depending on interparticle distances and nanoparticle shape, high attractive forces lead to aggregation. Aggregation results in increased particle size, promoting settling and affecting dispersive behavior. Conversely, high repulsive forces maintain suspension stability.

In heat exchangers, nanofluids undergoing repeated heating and cooling cycles experience phenomena that enhance nanoparticle aggregation. Elevated temperatures accelerate Brownian motion, increasing nanoparticle collision probability and favoring aggregate formation. Reduced fluid viscosity and dragging force further support aggregation. The collective directional movement of nanoparticles disrupts homogeneous dispersion and promotes aggregation. The quest for harnessing the full potential of CNT nanofluids requires addressing challenges related to dispersion and stability. Chemical and mechanical treatments offer promising avenues, and researchers continue to explore novel functionalization techniques and stability assessment methods.

4 Heat-Conducting Properties of CNT Nanofluids

A distinguishing quality of carbon nanotube CNT-nanofluids over base fluids is their excellent conductivity. The transient hot-wire method is one of several methods that can be used to evaluate the conductivity of nanofluids. The thermal conductivity enhancement observed in nanofluids varies depending on factors. A dual-phase procedure is typically utilized for synthesizing CNT nanofluids, involving the dispersion of CNTs in a base fluid followed by stabilization through chemical and physical treatments. One of the most straightforward techniques for stabilizing CNT nanofluids is homogenization using an ultrasonication device. An effective procedure commonly used involves chemicals. They are altering the surfaces of CNTs by treating them with acids before achieving homogeneous dispersion in base fluids through ultrasonication. Another way involves dispersing CNTs into the foundational fluid and adding a surfactant before homogenization using ultrasonication.

Covalent functionalization, which utilizes a combination of acids, constitutes one of the chemical treatments applied to CNTs to enhance their thermal conductivity.

In a study conducted in 2009, investigating the consequences of covalently functionalizing multi-walled carbon nanotubes using nitric and sulfuric acids on the thermal conductive characteristics of water-based nanofluids were examined. Specifically, a 16% enhancement was recorded for f-MWCNT nanofluids at 0.5% of MWCNTs, compared to a 4.6% enhancement for pristine MWCNT nanofluids. A similar outcome was observed in another study involving water-based nanofluids.

Non-covalent alteration, in contrast to covalent functionalization, involves using surfactants to modify the surface of CNTs. This process aims to make the CNTs hydrophilic, allowing them to interact favorably in conjunction with the foundational fluid and repel alternative CNTs, thus preventing aggregation. Researchers have conducted studies to identify the most effective concentration of different surfactants for achieving the most stability and the highest thermal conductivity of nanofluids. The outcomes revealed that all surfactants enhanced thermal conductivity generally rise in higher surfactant concentrations, except in the case of SDS (sodium dodecyl sulfate), which led to a decrease in thermal conductivity enhancement. Maintaining the homogeneity of nanoparticles in the solvent is crucial for achieving high thermal conductivity in nanofluid suspensions. Ultrasonication, especially at elevated power levels, supplies ample energy to disperse particle clusters, fostering the creation of uniform suspensions. Moreover, the duration of ultrasonication was found to significantly impact thermal conductivity, with longer ultrasonication times leading to increased thermal conductivity, especially at higher concentrations of nanoparticles.

Han et al. [6] conducted experiments on water-based SWCNT nanofluids with varying SWCNT concentrations (0.05–0.25 vol%) in the presence of SDS surface-active agents at temperatures ranging from 40 °C.

Furthermore, higher temperatures provide the suspended nanoparticles with increased energy, enhancing their random movement and collision frequency, which is essential to the mechanics of heat conduction.

The diameter and length of CNTs have been investigated for their impact on CNT nanofluids' thermal conductivity. The diameter of CNTs is mainly associated with the number of layers and affects their thermal properties. In a work by Lee et al. [7], the minor Functionalized Multi-Walled Carbon Nanotubes (f-MWCNT) diameter, 10 nm, was found to boost thermal conductivity in a water-based nanofluid by up to 16% when compared to larger f-MWCNT width sizes at a concentration of 0.5 vol%. Wu et al. [8] investigated the thermal conductivity of nanofluids based on water, incorporating distinct types of CNTs, such as SWCNTs measuring 1–2 nm in diameter and MWCNTs with an 8 nm diameter.

They found that SWCNTs exhibited a more substantial enhancement in thermal conductivity, reaching approximately 40%, while MWCNTs showed a lower enhancement of only 10% at a concentration of 0.38 vol%. This suggests that SWCNTs, with their smaller diameter, are more effective in enhancing thermal conductivity in this study. Glory et al. [9] investigated the effect of ultrasonication time on conductivity enhancement. They found that longer CNTs (5 μm in length) led to a noticeable increase in thermal conductivity enhancement to 45% compared to shorter CNTs (0.5 μm in length) when the sonication time was reduced from 700 to 50 min. The diameter and length of CNTs can impact the thermal conductivity enhancement of CNT nanofluids, with smaller-diameter CNTs and longer CNTs generally leading to higher enhancements. However, the relationship between CNT properties and thermal conductivity can be influenced by various factors, including the type of base fluid and experimental conditions.

The adjustment of MWCNT lengths was achieved through a controlled process of ball milling, yielding a noteworthy enhancement in thermal conductivity of approximately 29.5% and a temperature of 63.9 °C. In a parallel investigation, the same research group, Chen and Xie [10], delved deeper into the impact of varying CNT lengths achieved through ball milling on the silicon oil-based nanofluids thermal conductivity, which incorporated functionalized MWCNTs (f-MWCNTs). Notably, at a concentration of 0.05 vol% and a temperature of 65 °C, they recorded a peak enhancement of 27.5% after 20 h of ball milling. However, the enhancement began diminishing as the ball milling treatment extended beyond this point. Regarding the impact of CNT length, they discerned no significant alterations in thermal conductivity when the temperature was near room temperature. However, beyond 310 K, nanofluids with shorter MWCNTs exhibited higher thermal conductivity than those with longer counterparts. This observation led to the hypothesis that shorter MWCNTs are more mobile and capable of faster movement at elevated temperatures. In contrast, longer MWCNTs may tend to entangle to a greater extent. Numerous studies have highlighted the potential for achieving more excellent thermal conductivity enhancements in CNT nanofluids when employing lower inherent thermal conductivity base fluids. For instance, A notable 46% improvement in thermal conductivity was observed by Jiang et al. [11] for a nano-refrigerant containing MWCNTs distributed in R113. The 13% improvement attained in a water-based nanofluid at an analogous nanoparticle volume fraction of 0.2% was significantly outperformed by this improvement. In contrast, hybrid nanofluids featuring CNTs yielded opposing effects compared to their base fluids regarding thermal conductivity enhancement. In some instances, water-based hybrid nanofluids exhibited more remarkable thermal conductivity enhancements than their EG-based counterparts despite EG having lower inherent thermal conductivity than water [12, 13].

5 Utilization of CNT Nanofluids in Solar Applications

Over the past decade, substantial research efforts have been directed toward understanding nanofluids' fundamental principles and practicality, explicitly focusing on carbon nanotube (CNT) nanofluids within solar collector applications. This discussion will provide an extensive overview of solar thermal technology, emphasizing the potential enhancements achieved by employing CNT nanofluids as heat-absorbing fluid. Solar collectors, designed to harness solar energy, have a rich history dating back centuries.

Research efforts have also extended to evaluating the evacuated tube's thermal performance using nanofluids. Sabiha et al. [14] conducted experiments to assess the improved heat transfer by employing water-based nanofluids, including SWCNTs, as capturing media. Their study considered varying nanoparticle concentrations and mass flow. They reported that both nanoparticle concentration and mass flow significantly contributed to the application of evacuated tube solar collectors. Notably, they achieved a peak collector 93.43% efficiency with 0.2 vol% Nanofluid of SWCNT and a flow rate of 0.025 kg/s, representing a remarkable 71.84% improvement over pure water. Moreover, they observed that on cloudy days, the collector's efficiency utilizing 0.2 vol% SWCNT nanofluid surpassed water on sunny days, underlining the advantages of nanofluid-based systems in diverse weather conditions.

Theoretical investigations have also delved into the application of enclosed-type, nanofluid-using evacuated U-tube collectors. Tong et al. [15] performed a comprehensive review of U-tube collectors equipped in the U-tube with a copper fin, analyzing varying Reynold's ratios (ranging from 400 to 2000) with constant heat flux and utilizing MWCNT/water nanofluids with varying MWCNT concentrations (up to 0.24 vol%). Their results revealed an average 8% relative rise in pure water's heat transfer coefficient ratio.

Collector efficiency rapidly increased with rising radiation levels under low-radiation conditions, leveling off under high-radiation exposure. In recent research, the heating capacity and energy efficiency potential of a U-tube collector for sunlight using nanofluids have been studied by Kim et al. [16]. They investigated nanofluids containing MWCNTs spread among a combination of 20% propylene glycol and water. They also emphasized the environmental and economic benefits, estimating a reduction of coal usage by up to 131.3 kg annually and a savings of about 0.64 MW/ h of electricity annually when 50 solar collectors employing nanofluids as the absorbed substance were deployed. While evacuated tubes and flat plates have played a vital role in harnessing solar energy, they are not without limitations, particularly in terms of efficiency due to the conductive and convective absorbent surface and its impedance and the working fluid, resulting in significant heat losses. To address these challenges, a novel concept emerged in the 1970s aimed at minimizing heat losses while efficiently absorbing solar energy. This innovation led to the development of direct absorption solar collectors (DASCs), a unique category of solar collectors. DASCs directly absorb solar radiation and convert it into heat, offering a promising alternative to traditional collectors. Researchers have made significant strides in understanding the complex interplay of factors affecting nanofluid behavior within various collectors, including flat-plate, evacuated tube, and direct Absorption solar collectors. From pH adjustments to the addition of surfactants and careful consideration of nanoparticle concentrations and flow rates, these studies have provided valuable insights into optimizing nanofluid-based solar collector systems. Furthermore, theoretical analyses have underscored the advantages of CNT nanofluids, particularly SWCNT-based nanofluids, over other nanofluid types and pure water in terms of energy and exergy efficiencies, as well as reductions in entropy generation and enhancements in heat transfer coefficients. These findings can potentially revolutionize the field of solar thermal technology, offering more efficient and environmentally friendly solutions for harnessing solar energy. In particular, the remarkable performance enhancements achieved in evacuated tube solar collectors and U-tube solar collectors using CNT nanofluids have significant implications. The capability of carbon nanotube (CNT) nanofluids as absorbent media in direct absorption solar collectors offers an exciting avenue for further research and innovation in solar energy capture. As researchers continue to delve into optical characteristics and the long-term consistency of CNT with nanofluids within DASCs, the future of solar collector systems appears increasingly promising by harnessing the sun's energy more efficiently and sustainably. These developments open the door for a brighter and greener future powered by nanofluid-enhanced solar technology. The researchers prepared a nanofluid based on water with varying concentrations of MWCNTs, ranging from 0.0005 to 0.005 volume percent. They used Cetyltrimethylammonium Bromide (CTAB) as a surfactant and employed a self-assembled apparatus based on the Lambert–Beer law to measure the extinction coefficient. Surprisingly, they discovered that nanofluids with a volume fraction of 0.0005 and exceedingly low percent could completely absorb solar energy up to a depth of 10 cm. They conducted an analytical investigation to explore the impact of varying wavelengths from 200 to 2000 nm. Their findings highlighted the crucial role of MWCNT nanofluids in absorbing sunlight within the visible and near-infrared wavelength ranges, specifically from 200 to 1400 nm, a feat not achievable with pure water alone.

5.1 Photovoltaic-Thermal (PVT) Systems

Applying photovoltaic (PV) solar cells for electricity generation has seen significant growth. While PV cells are known for their low greenhouse gas emissions during electricity production, the commercial versions often suffer from relatively modest efficiencies. Moreover, these efficiencies tend to decrease as the operating temperature of the cells rises. To address this challenge, substantial efforts have been devoted to managing the thermal conditions of PV cells, ensuring they operate at optimal temperatures for peak performance. Various advanced techniques, such as Heat pipes, PCM, and active cooling techniques, have tackled this thermal management issue. One efficient approach in this sector is PV/T (Photovoltaic/Thermal) systems.

The heat produced by the PV cells in PV/T systems is used for focused thermal functions, such as heating water or air. Nanofluids have been used as the operating liquids in PV/T systems to increase their efficiency further their efficiency.

Alous et al. [17] conducted an experimental study on a Photovoltaic/Thermal (PV/T) system. This system incorporated a sheet and tube heat exchanger connected to the rear of a monocrystalline PV cell. Three different coolants were employed: water, graphene nanoplatelet/water, and MWCNT/water nanofluids, all at a concentration of 0.5% by weight. The results demonstrated energy efficiency enhancements of

53.4%, 57.2%, and 63.1% when using water, MWCNT/water, and graphene/water nanofluids, respectively. Researchers monitored PV cell temperatures at different times of the day. It was shown that using nanofluids during hours of higher solar irradiation was more advantageous since the temperature differential between the cooling conditions and the reference condition grew during these hours. Compared to water, the entropy generation in the system was reduced by 0.82%, 1.23%, and 2.88% when these nanofluids were used as coolants.

The efficiency of PVT systems, particularly in comparison to standalone PV systems, is a multifaceted aspect influenced by various factors. Beyond the intrinsic nature of the nanofluid used, the operational conditions play a pivotal role in determining the enhancement rate in PV/T systems, especially when juxtaposed with standalone PV systems. This intricate relationship was investigated by Sangeetha et al. [18], who explored the impact of three different nanofluids—CuO/water, Al2O3/water, and MWCNT/water—on a PV/T system. The study revealed that the highest efficiency improvement occurred around mid-day, aligning with peak solar irradiance. This finding underscores the significance of effective cooling mechanisms for PV panels, particularly in regions characterized by intense sunlight and elevated temperatures.

MWCNT/water nanofluids with concentrations ranging from 0% to 0.3% by volume were used in an inquiry by Abdallah et al. [19] in a PV/T system. Intriguingly, the study identified the concentration of 0.075% by volume as the maximum average efficiency enhancement point. This shows that there may be an ideal concentration where changes in specific heat, thermal conductivity, and viscosity change combine to produce the best outcomes. The study underscores the nuanced interplay between nanofluid composition and concentration in achieving optimal PV/T system efficiency. Moving beyond active cooling methods, passive thermal management strategies have garnered attention, particularly in the context of PV cell temperature control. Among these, using phase change materials (PCMs) is noteworthy. This suggests the promising potential of MWCNT-based nanofluids in passive thermal management strategies, presenting an avenue for improving the overall efficiency and longevity of PV/T systems.

In conclusion, the efficiency of PV/T systems is intricately linked to the interplay of nanofluid characteristics, operating conditions, and cooling strategies. As research in this field progresses, a comprehensive understanding of these factors will be crucial for advancing the efficiency and applicability of PV/T systems in diverse environmental contexts.

5.2 Solar Collector

To transform solar irradiance into helpful heat energy, solar collectors are essential. The thermophysical characteristics of the fluid being significantly used impact how well these collectors perform. Different nanofluids, including those comprising metallic, metal oxide, hybrid, and carbon-based nanoparticles, have been used to increase the efficiency of solar collectors. Carbon-based nanofluids have garnered considerable interest due to their exceptional heat transfer properties, making them popular for improving solar collector efficiency. Using MWCNT/water nanofluids in a U-tube solar collector was the subject of a significant study that tested different concentrations of MWCNTs in water, ranging from 0.06% to 0.24% by volume. It found that the highest enhancement in efficiency was achieved with a 0.24% concentration. Compared to using water as the operating fluid, employing the nanofluid resulted in an average heat transfer enhancement of 8% across various Reynolds numbers. Importantly, this transition to nanofluid usage also had positive environmental implications. A thorough environmental analysis revealed that when 50 such collectors were employed, replacing water with nanofluid led to annual reductions of 1600 kg and 5.3 kg in Carbon Dioxide and Sulfur Dioxide emissions, respectively. As previously mentioned, carbon-based nanofluids, particularly those containing Carbon Nanotubes (CNTs), exhibit superior optical properties compared to pure fluids. This makes them ideal for use in direct-absorption solar collectors.

However, it is worth noting that higher nanofluid concentrations result in more excellent Absorption of solar radiation at the collector's top, and the subsequent temperature rise can lead to higher heat losses. Interestingly, it has been observed that SWCNTs offer even more significant improvements in thermal conductivity compared to MWCNTs. Said et al. [20] used volume fractions of 0.1% to 0.3% of SWCNT/water nanofluid in a flat plate solar collector. The energy effectiveness of the collector was found to be 89.26% and 95.12%, respectively, when employing nanofluids with concentrations of 0.1% and 0.3% at a mass flow rate of 0.5 kg/min, compared to just 42.07% when using water. The effectiveness of an evacuated tube using SWCNT/water nanofluid at three distinct concentrations and varied mass flow rates was investigated by Sabiha et al. [21]. The highest collector efficiency observed was 93.43%, achieved at a mass flow rate of 0.025 kg/s and a volumetric nanofluid concentration of 0.2%.

A further inquiry by Mahbubul et al. [22] demonstrated the potential of SWCNT/water nanofluid in improving evacuated tube solar collecting' efficiency. Carbon nanotube-containing nanofluids have shown promise in high-temperature collectors. A linear Fresnel collector was numerically studied by Ghodbane et al. [23], employing MWCNT/diathermic oil (DW) nanofluid as the working fluid.

5.3 Solar Pond

Solar ponds featuring a layered salt solution structure are innovative systems that capture and preserve solar energy. These ponds typically consist of layers with varying salt concentrations, reaching saturation at 1–2 m. The Non-Convicting Zone (NCZ)'s upper layer contains water with lower salinity and density than the Lower Convicting Zone (LCZ) beneath it. The increased salt concentration in the LCZ inhibits free convection, effectively trapping and storing the energy from the sunlight hits over here. The ratio of the total energy collected from a solar pond to its predicted capacity is known as its efficiency, and it depends on several variables, including the heat recovery temperature and the specific layers from which energy is extracted. By harnessing nanofluids in solar pond tubes, it becomes possible to significantly enhance heat extraction efficiency from these innovative solar energy storage systems, thereby increasing their practicality and effectiveness in various applications.

5.4 Generation of Solar Steam

Solar energy holds great potential for various applications, including generating steam required for seawater desalination, waste sterilization, and power generation. Nanotechnology has played a pivotal role in significantly enhancing the performance of these solar steam generation systems. Using appropriate nanofluids in these systems can lead to substantial improvements in efficiency. Research findings from a study have demonstrated that using plasmonic nanofluids containing gold particles can result in an approximate 300% increase in system efficiency. Regarding solar steam generation, nanofluids containing Carbon Nanotubes (CNTs) are particularly promising choices. Wang et al. [24] conducted a study where they employed SWCNT-based nanofluids in direct gas creation from a solar energy setup. For instance, when using a nanofluid with a concentration of 19.04×10^{-4} vol% and solar power for lighting 10 Suns, this system achieved an impressive efficiency of 46.8%. In contrast, if pure water were employed in the system, the efficiency would not exceed 7.8%. This substantial improvement underscores the remarkable potential of nanofluids containing CNTs in enhancing the performance of solar power systems. The study concentrated on applying nanofluids with CNTs in solar energy systems, which has yielded significant modifications in system performance. The extent of enhancement depends on several elements, including the kind and concentration of CNTs used, the specific system under investigation, and the operating conditions employed.

6 Conclusion

According to our in-depth literature research, preserving a uniform dispersion and long-term stability are essential for the CNT nanofluids to keep their superior thermal characteristics. The goal of maintaining the conditions mentioned above is challenging due to the hydrophobic nature of the CNT against most fluids and the potent van der Waals interaction among CNT nanoparticles. Nevertheless, many scholars have made countless attempts to meet those requirements.

However, it should be highlighted that numerous obstacles must be found and overcome for various CNT nanofluid applications, particularly solar devices. Two significant barriers to its commercialization are the stability and production cost.

Because of this, it is necessary to redesign the majority of solar collectors to accommodate the practical usage of nanofluid in water heating systems used in home and industrial settings. By overcoming these obstacles, it is anticipated that nanofluids will have a significant impact on both the engineering and industrial sectors, as well as improve people's quality of life.

To attain good thermal characteristics of the CNT nanofluids for an extended period, homogeneous dispersion and long-term stability must be maintained. It isn't easy to uphold the criterion above because of the CNTs' hydrophobicity toward most fluids and their robust van der Waals interaction. Chemical treatments (covalent and non-covalent functionalization) and physical treatments are the two main ways to stabilize CNTs in any base fluid.

Depending on the base fluids, CNT concentrations, and CNT kinds utilized, each treatment results in varying stability periods, according to prior studies' findings. For comparing covalent functionalization to non-covalent functionalization, it was discovered that covalent functionalization was more effective at maintaining the stability of CNT nanofluids. Physical treatment is frequently applied following chemical treatment to produce homogeneous solutions. In this regard, deagglomerating CNTs in suspensions using ultrasonication was a successful technique. The long-term stability and homogeneity of CNT nanofluids were shown to be maintained by covalent functionalization and ultrasonication, respectively. Still, the effects of each method's prolonged treatment on these properties were adverse.

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