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Optimizing MWCNT-Based Nanofluids for Photovoltaic/Thermal Cooling through Preparation Parameters

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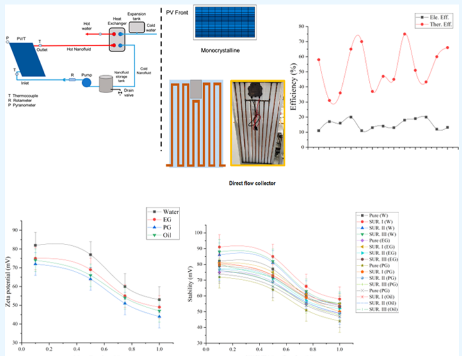
ABSTRACT: Multiwalled carbon nanotubes (MWCNTs) were employed as added particles for nanofluids in this practical investigation. To identify the most appropriate nanofluid for cooling PVT systems that are functional in the extreme summer environment of Baghdad, the parameters of base fluid, surfactant, and sonication time used for mixing were examined. Water was chosen as the base fluid instead of other potential candidates such as ethylene glycol (EG), propylene glycol (PG), and heat transfer oil (HTO). Thermal conductivity and stability were important thermophysical qualities that were impacted by the chosen parameters. The nanofluid tested in Baghdad city (consisting of 0.5% MWCNTs, water, and CTAB with a sonication period of three and a quarter hours) resulted in a 119.5, 308, and 210% enhancement of thermal conductivity (TC) for water compared with EG, PG, and oil, respectively. In addition, the nanofluid-cooled PVT system had an electrical efficiency that was 88.85% higher than standalone PV technology and 44% higher than water-cooled PVT systems. Moreover, the thermal efficiency of the nanofluid-cooled PVT system was 20% higher than the water-cooled PVT system. Finally, the nanofluid-cooled PVT system displayed the least decrease in electrical efficiency and a greater thermal efficiency even when the PV panel was at its hottest at noon.



1. INTRODUCTION

The transfer of heat from warmer to colder regions is an integral and important factor in a myriad of power generation, industrial, production, and chemical processes and micro-electronic, vehicular, and food industry applications. Optimizing the heat exchange performance of any of these applications, in terms of reducing the amount of time needed for the heat to be transferred, can lead to shorter processing times, improved equipment lifetime, and a decrease in energy consumption.[1] A great example of this is the radiator in cars. Improving heat transfer through the use of smaller heat exchangers to cool engine water can lead to a decrease in the vehicle's weight, which in turn can reduce fuel usage and lower emissions.[2,3]

For many years, traditional liquids such as water, oil, ethylene glycol, and others have been used for heat transfer in industrial and commercial applications. However, their low thermal conductivity has impeded rapid heat transfer and disposal. This has restricted their use in dynamic transfer processes.[4,5] To address this, microparticles with high conductivity were added to these liquids, increasing their thermal conductivity. The particles were either metals or metal oxides, but the fluids still suffered from low stability, causing the particles to gather and deposit at the bottom of the container, leading to corrosion of components, blockage of narrow passages, and low pressure of the flowing fluid.[6,7]

The development of nanofluids with high thermal conductivity has become a focus of manufacturers and researchers due to the introduction of nanoparticles. By adding these particles to the base fluid at a low concentration, the thermophysical properties of the mixture are changed significantly, leading to an increase in heat transfer properties without a decrease in flow pressure.[8−10] It is essential to create nanofluids that are stable over extended periods of time in order to use them in heat transfer applications and maximize the efficiency of the equipment.[11]

The physical traits of the emulsion, such as its color, density, and viscosity, as well as its thermal conductivity and heat capacity, all shift when nanoparticles are added to the base liquid.[12] These changes are due to the many properties of the nanoparticles, such as the molecule crystal structure, surface-

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to-volume ratio, surface curvature, diffusivity, catalytic activity, and electrical resistance.[13−15] The characteristics of the base liquid also have an effect on the thermophysical properties of the emulsion.[3] Numerous studies have been done to identify the ideal nanofluid for a particular application, yet there still is no consensus on the type of additive or base fluid to use. The thermal conductivity of the nanosuspension and its stability are two of the most important features when determining if a nanofluid is an ideal candidate or not.[16,17]

Ever since the discovery of nanoparticles, scientists have been using ones made of metals such as gold, silver, and copper for nanofluids due to their high thermal conductivity. It was later found that metal oxide nanoparticles were cheaper and had conductivity similar to the original set. Carbon nanotubes have also been used for nanofluids, as they have unique thermal properties and superior thermal capabilities.[18−20] These nanotubes come in two types, single-walled and multiwalled, and can have diameters ranging from one nanometer to several nanometers with a cylinder length of several micrometers.[21] Their thermal conductivity (2000−6000 W/m^2 K) is much higher than that of the metallic or metal oxide nanoparticles.[22−24] Nanofluids made up of carbon nanotubes can disperse and raise the thermal conductivity of the base fluid.[25] There has been much research done on nanofluids and CNT nanofluids to improve their effectiveness in industrial and civil applications, such as improved bubble adsorption in heat-driven absorption systems, enhanced heat transfers in heat exchangers and solar thermal collectors, and reducing the Leidenfrost effect in cooling processes.[26−33]

The thermal conductivity of any nanofluid is dependent on the properties of the base fluid and the nanoparticles that are included in it. Such characteristics include the crystal structure, shape, and size of the nanoparticles suspended in the base fluid. Furthermore, the formation of the nanofluid can be affected by its mass or volume fractions, surfactant concentrations, and the interactions between the nanomaterials and the base liquid, among other factors.[34,35]

The thermal conductivity and stability of carbon nanofluids are affected in distinct ways by a variety of factors. There has been a great deal of research on the usage of SWNTs and MWNTs to create nanoemulsions using several base liquids. These two kinds of nanofluids have been employed in many heat transfer processes, and the development of photovoltaic thermal (PVT) systems has further increased enthusiasm for them.

Photovoltaic cells are increasingly being used as an option for creating renewable energy. The desire to have a cleaner environment has caused a rise in the number of PV systems being set up around the world, which are powered by the sun's rays. Nevertheless, these cells can be impacted by many external factors such as shadow,[36] temperature,[37] humidity,[38] and dust.[39] In theory, the more the solar radiation, the more the electricity generated by the PV module. In reality, this is not the case. Most of the radiation is taken in by the cell to raise its temperature, with only a small portion being used to produce electricity. An increase in cell temperature results in a reduction in energy production and a decline in the electrical efficiency of the system.[37] The researchers proposed the use of PVT systems as the ideal solution to diminish the adverse consequences of this tricky problem (as the optimum spot for establishing PV fields in deserts with high solar radiation). PVT systems consist of a photovoltaic panel linked to a thermal solar storage tank. This setup is designed to transfer the thermal energy collected by the PV module, cooling it to enhance its electrical efficiency. Additionally, the heat taken away can be used in thermal applications.[40] A rise in the temperature of the solar panel leads to a decrease in the electrical energy it produces, whereas cooling it down brings about an enhancement of its energy production. Water or various nanofluids can be used to cool PVT systems, with numerous experiments having already been conducted.[41]

In their 2015 study, Xing and Wang[42] investigated the effects of adding three kinds of carbon nanotubes to water on the thermal conductivity of the resulting liquids. The emulsions had a greater thermal conductivity than the base liquid, and as the amount of CNT particles was raised, the conductivity also increased. The results showed that the addition of SWCNT particles with short and long cylinder lengths and MWCNT particles at a concentration of 0.48% (by volume) increased the thermal conductivity of the emulsions by 8.1, 16.2, and 5.0%, respectively, when the fluid temperature was 60 °C. The researchers concluded that using long SWCNT particles in water gave the highest thermal conductivity. Additionally, the increase in the thermal conductivity of the produced nanofluid and the concentration of carbon nanotubes and the operating temperature were in an almost linear relationship.

Sangeetha et al.[43] conducted an experiment to examine the effect of nanofluids with varying quantities of nanoparticles (Al_2O_3, CuO, MWCNT) in water on the performance of PVT systems. The concentrations they selected were 0, 0.5, 1, 1.5, and 2.0 (by volume %). The results revealed that using the manufactured nanoemulsions boosted the performance of the PVT system, as the efficiency of the systems rose when compared to cooling them with only water. The data showed that MWCNTs provided more efficient cooling for PV/T systems than CuO and Al_2O_3 particles.

A study conducted by Kazem et al.[44] examined the efficiency of a cooling PVT system when nanofluids consisting of water and ethylene glycol in a 75.0 and 25.0% volume ratio, respectively, were mixed with SWCNTs at varying weight ratios of 0.1, 0.5, 1.0, and 2.0%. The scientists conducted several experiments to evaluate the thermophysical properties of a nanofluid created by adding 0.5% (SWCNTs) to a PVT system. The results of the camera images and ζ potential tests showed that the nanoemulsion had a high thermal conductivity of 103% and remarkable stability of over 109 days. As a result of this addition, the generated electric power rose by 11.7% and the electrical efficiency improved by 25.2% relative to a separate PV system.

The stability of nanofluids is key in ensuring a secure and reliable heat transfer process in their application. To maintain the dispersion and distribution and prevent agglomeration of the nanoparticles, different methods and techniques have been developed and employed, such as the use of surfactants and the implementation of ultrasonic vibration technology. These two approaches have been widely adopted and have been utilized in a multitude of studies.[45,46]

Duangthongsuk and Wongwises[47] suggested that a nanofluid (consisting of water and TiO_2 nanoparticles) be subjected to ultrasonic vibrations for a period of 2 h. According to Wang et al.,[48] this procedure was employed to combine nano-Al_2O_3 and water for an interval of 15 min. Al-Waeli et al.[49] conducted the same protocol for a period of 6 h to obtain an effective combination of nano-SiC and water that achieved stability of over six months. Ultrasound therapy can be used to break

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down the connection between nanoparticles and disperse them evenly throughout the container, thereby increasing the stability of nanofluids.

Sonication time has a significant effect on the end result of a prepared suspension. Prolonged sonication times allow for complete and stable nanofluid production, which improves heat transfer and decreases remixing costs. However, too much sonication can lead to a change in nanoparticle diffusion and the possibility for them to cluster and agglomerate, leading to a lower quality of the final suspension. Moreover, a longer sonication time can result in an increased deposition of nanoparticles and reduce the quality of the final product. Finding the perfect sonication time for a given sample is important to ensure a high-quality end product.[50,51] No consensus has been reached among researchers on the ideal moment to implement sonication to spread nanoparticles in the underlying liquid. Lee et al.[52] conducted an experiment in which they exposed an Al_2O_3-water fluid to ultrasonic treatment for over 5 h. The results of this study revealed that when sonication is extended for too long, the thermal conductivity and stability of the nanofluid are adversely affected. Mahbubul et al.[53] investigated the impact of sonication on the stability of the nanofluid and determined that extending the sonication time beyond 1 h did not result in the betterment of the nanofluid's stability. Dhahad and Chaichan[54] investigated the effects of mixing 50 and 100 ppm of nano-Al_2O_3 and nano-ZnO into diesel in an ultrasonic container. Results indicated that the stability of the fluids produced when nano-ZnO was included at a concentration of 50 ppm was 76 days, while adding nano-Al_2O_3 at the same level yielded 81-day stability. When the concentration was upped to 100 ppm, the stability of the emulsions decreased to 68 days for nano-ZnO and 72 days for nano-Al_2O_3. Habib et al.[55] combined 0.1, 0.5, 1, 3, and 5% (in terms of weight %) of SWCNT particles with molten paraffin wax (at 80 °C to avoid hardening of the wax) by employing ultrasonic shaking over a two-hour period. The suspensions were then put in a special furnace and sonicated at 65 °C for a duration of 24 h in order to maintain the stability of the SWCNT and paraffin mixture.

The thermal conductivity and stability of nanofluids are essential for efficient heat transfer. Studies have shown that SWCNTs and MWCNTs possess much higher thermal conductivities than metallic or metal oxide nanoparticles. Usually, researchers will use the same preparation procedure for all nanofluids, regardless of the type of nanoparticles or the mass fraction added. This approach overlooks the fact that each nanofluid needs to be prepared differently depending on the type and amount of nanoparticles used. This study will investigate multiple mass fractions of MWCNTs added to a base fluid to demonstrate the importance of proper preparation. This study will evaluate a variety of base fluids such as water, ethylene glycol, propylene glycol, and oil. Additionally, different surfactants will be added to the base fluids. Subsequently, the optimal sonication time for water-based additives will be identified. Ultimately, the best ratio of MWCNTs to the most effective base fluid for PVT systems will be determined based on stability and thermal conductivity. It is worth mentioning that Al-Waeli et al.[4] and Sangeetha et al.[43] confirmed that when MWCNTs were added to the base fluid (water, EG, and PG) in amounts lower than 3%, the density and viscosity of the resulting nanofluid did not significantly rise. Following the results of the two studies, these two variables were not measured in this study. The chosen nanofluid will be put to the test in a practical cooling PVT system that works in extreme weather conditions. This study aims to give special attention to the various methods of producing nanofluids and to determine the most suitable fluid for a given application based on its ability to increase both thermal conductivity and stability. In particular, the focus is on determining which fluids are best able to enhance the thermal conductivity and stability of a system and then selecting the optimal fluid for specific applications. Additionally, the study will also look at the effects of the nanofluids on the environment and the potential for long-term sustainability. Furthermore, the study will also examine the potential for nanofluids to be used in the development of renewable energy sources, such as photovoltaic/thermal systems, and the possibility of creating a more efficient and cost-effective method of harnessing the power of the sun.

2. EXPERIMENTAL SETUP AND MATERIALS

2.1. Base Fluids. In the present investigation, four different base fluids (water, ethylene glycol, propylene glycol, and oil) with different thermophysical properties were selected for study due to their availability and affordability. These fluids were observed to have low thermal conductivity as per the data specified in Table 1, with water having the highest TC among them. For viscosity, water was the least viscous and ethylene glycol had the highest. With regards to specific heat, water proved to be the most superior compared to the other liquids, followed by ethylene glycol. Moreover, water's surface tension was seen to be the greatest of all of the liquids listed, which is a significant factor when adding a surfactant. All of the measurements of the fluid properties were done in the Chemical Engineering Department of the University of Technology, Iraq.

Table 1. Specifications of the Base Fluids Used

specifications	water	ethylene glycol	propylene glycol	heat transfer oil (HTO)
viscosity (mPa·s) at 25 °C	1.002	1.161	0.09	1.5
density (kg/m^3)	1000	998	1036	855
thermal conductivity (W/m·K)	0.57	0.258	0.147	0.134
specific heat (J/(kg K))	4.2	2.433	0.895	2.097
surface tension (mN/m)	76.5	48.6	45.6	35

2.2. Surfactants. A surfactant is a surface-active agent, which means it reduces the surface tension of a liquid it is dissolved in, making it easier to absorb. This happens because the amphiphilic molecules that make up the surfactant line up on the air side (hydrophobic) and the water side (hydrophilic) of the liquid's surface. As a result, the surface tension decreases.[56−58] In the experiments, three types of surfactants (Table 2) were used due to their availability in the local markets at a reasonable cost and the fact that they are some of the most commonly used surfactants in research involving nanofluids. Table 2 presents information regarding the type of surfactants, their chemical structure, TCs, and other relevant specifications supplied by the various manufacturers.

The agglomeration of nanoparticles in nanosuspensions is a result of the high surface energy of these particles.[5] When the particles agglomerate and deposit, the thermal conductivity of

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Table 2. Specifications of the Surfactants Used

specifications	SUR. I cetyltrimethylammonium bromide (CTAB)	SUR. II sodium dodecyl sulfate (SDS)	SUR. III dodecylbenzenesulfonate (SDBS)
manufacturer	Fisher Scientific UK	Fisher Scientific UK	Fisher Scientific UK
chemical structure	C19H42BrN	C12H25NaO4S	C18H29NaO3S
electrical conductivity (μs cm^{-1})	94.9	65	68
turbidity (NTU)	0.095	0.045	0.030
pH	6.13	9.1	8.5
molecular weight (g/mole)	464.45	288.5	348.48
density (g/cm^3)	0.5	1.01	0.18

the nanofluid is decreased, which negatively affects the heat transfer process. This is known as a decrease in the stability of the nanofluid, so it is essential to look into it thoroughly to assess the stability of any given nanofluid. The use of surfactants is to create feeble electrical attractions with the desired nanoparticles,[48] thus keeping the nonbinding communication in the suspension steady.[59] An amount of surfactant is added to the nanofluid, which is thought to enhance its stability. The concentration of the surfactant factors into how much the stability of the product will either increase or decrease.[60] Research has demonstrated that the most secure level of equilibrium is at a pH of 4, while the least secure is at a pH of 10.[61−63] The kind of surfactant used is significant here. Ionic surfactants weaken the stability of the nanofluid, while cationic and nonionic surfactants improve it.[64] Hence, the inclusion of an alkaline surfactant leads to a dramatic decrease in the nanosuspension stability. The surfactants used in this study were labeled as SUR I (CTAB), SUR II (SDS), and SUR III (SDBS). Table 2 demonstrates that SUR I has a more acidic pH than the other two types, which will make it the most effective in terms of the stability of the formed nanofluids.

2.3. MWCNTs. MWCNTs with a long cylinder shape were used,[42,43] and their characteristics are provided in Table 3.

Table 3. Specifications of the MWCNTs Used

manufacturer	carbon nanomaterial technology (South Korea)
diameter (external) (nm)	8−30
diameter (internal) (nm)	5−15
tube length (μm)	≥20
number of walls	3−10
assay	≥95 wt %
form	powder
amount of impurities (wt %)	≥5
bulk density (g/cm^3)	0.25−0.35
surface area (m^2/g)	≥270
melting point (°C)	3670
thermal conductivity (W/m K)	3000
thermal stability in air (°C)	≥600

MWCNTs can be seen as a long, coiled graphene sheet with a length-to-diameter ratio of 1000. Generally, the interior of these tubes is less than 5−15 nm in diameter and the exterior is 8−30 nm. The length of these nanotubes is ≥20 μm, so they are seen as one-dimensional structures. In comparison to metal nanoparticles and metal oxides, MWCNTs possess different attributes. They are known for their superior thermal conductivity of around 2000 to 4000 W/m K.[65−67] The MWCNTs (whose specifications are illustrated in Table 3) are responsible for the fact that production costs are still high, and people are working to find ways to make them more affordable. In Iraq, MWCNTs come at the cost of approximately 5 US dollars per gram. Though more expensive than many metal oxide nanofluids, the thermal conductivity (TC) that MWCNTs offer is far superior. Because of this, a smaller amount of MWCNTs is needed to achieve the same results as metal oxide nanofluids, which ultimately makes the cost of the nanofluid comparable to that of metal oxide nanofluids.

2.4. Nanoemulsion Preparation. The method of ultrasonic vibrations was employed for the making of all nanoemulsions. At the start of the trials, the base fluid was combined with nanoparticles in predecided proportions of 0.1, 0.5, 0.75, and 1.0%. The predetermined addition ratios were chosen to evaluate how nanoparticles affect the physical and chemical properties of the prepared suspensions, such as viscosity, surface tension, and thermal conductivity. The proportion of nanoparticles present has a direct impact on the density and viscosity of the suspension, which in turn determines its stability. A lower ratio of nanoparticles results in a higher level of stability. Testing different concentrations of nanoparticles allows us to determine the optimal concentration that should be added to the base fluid, which could improve the performance of the nanofluid produced.

The thermal conductivity and stability of the premade emulsions were examined, while the other thermophysical properties such as density and viscosity were not taken into account, as it was assumed that any changes in them would be insignificant, as indicated in references.[40,43,49] For the second trial, 0.5% by weight of surfactants were incorporated into the premade emulsions, following the protocol in the results of ref 49. The TC and ST of the emulsions were evaluated, and the most effective nanoemulsion was chosen. The third set of nanoemulsions was created using the same base fluid and surfactant as before but with a different period of sonication. The samples were then examined at intervals of 1.5, 2.0, 2.5, 3.0, 3.15, 3.5, and 4.0 h. Tests were conducted using six different sonication timings to observe the changes in the nanoemulsion with increasing sonication time. The results of these tests can be used to identify the optimal sonication time required to produce the desired properties of the nanoemulsion. The researchers had differing opinions about the optimal sonication time, with Ruan et al.[68] suggesting 30 min and Mahbubul et al.[69] and Hwangbo et al.[70] proposing a full hour, while Al-Waeli et al.[49] required about 6 h of sonication to reach a highly stable emulsion. In light of this, six timings were adopted in the study to find the ideal sonication time for the preparation of nanofluids. The results showed that no more than these timings were needed to attain satisfactory stability. The tests for TC and ST were conducted on the prepared emulsions to discover the optimal sonication duration for the materials. After selecting the correct base fluid, surfactant, and

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sonication period and incorporating the MWCNT mass fraction, this nanofluid will be used to cool a PVT system to assess its performance and compare the results to other studies in the literature.

2.5. Instrumentations. For this study, the most precise and accurate results were obtained through the use of an ultrasonic vibrating mixer (TELSONIC ULTRASONICS CT-I2). The weights were then checked with a METTLER TOLEDO (US-made) digital scale, which can measure up to 1 in 10,000 of a gram. To measure the thermal conductivity of the nanofluids, a KD2 Pro analyzer scale (ICT International, India) was used. In order to determine the stability of the fluids, a Nano Zeta-Sizer (ZSN) (GmbH) was utilized. To ensure accuracy, each experiment and measurement was conducted three times to ensure repetition and minimize any errors. Each instrument was precalibrated to ensure its accuracy, and these values were used to calculate the uncertainty, as seen in Table 4. The following equation displays the uncertainty of the experiments[42]

$$e_R = \left[\left(\frac{\partial R}{\partial V_1}e_1\right)^2 + \left(\frac{\partial R}{\partial V_2}e_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial V_n}e_n\right)^2\right]^{0.5} \quad (1)$$

The resulting uncertainty is represented by e_R, while R indicates the independent variable's function and e_i is the uncertainty interval in the nth variable and $\frac{\partial R}{\partial V_1}$ is the and single variable measured result sensitivity. In Table 4, the used instrument's uncertainty is detailed. The overall accuracy of the instruments was assessed to be 1.933, which is satisfactory. A DC electronic load 3711A was used to measure the short-circuit current, open-circuit voltage, and maximum power. To authenticate the device readings, they were compared to the measurements from the meter.

$$e_r = [(0.78)^2 + (0.47)^2 + (0.55)^2 + (0.032)^2 + (0.79)^2 + (1.26)^2 + (0.54)^2]^{0.5} = \pm 1.933 \quad (2)$$

Table 4. Uncertainties of the Used Instruments

equipment	parameter	experimental uncertainty
KD2 Pro analyzer	thermal conductivity	±0.78%
nano zeta-sizer	ζ potential	±0.47
multimeter	voltage	±0.55%
multimeter	current	±0.032%
luminous intensity meter	irradiance	±0.79%
thermocouples	temperature (PV module, PVT collector, inlet, outlet, and ambient)	±1.26%
flow meter	coolants' flow rate (kg/s)	±0.54%

2.6. PVT System Description. Once the experiments to decide the most fitting nanofluid for utilization in PVT systems had been done, the fluid was circulated in a system designed for this purpose. The direct flow collector was selected because of its simplicity of manufacture and cost-effectiveness compared to other types of collectors for nanofluid circulation. Figure 1 displays a schematic representation of the system applied. The PVT system involves a PV module mounted on the rear by a single-channel direct flow absorbent to circulate the picked nanoemulsion. Two PVT systems were utilized; one cooled with water and the other cooled with the prepared

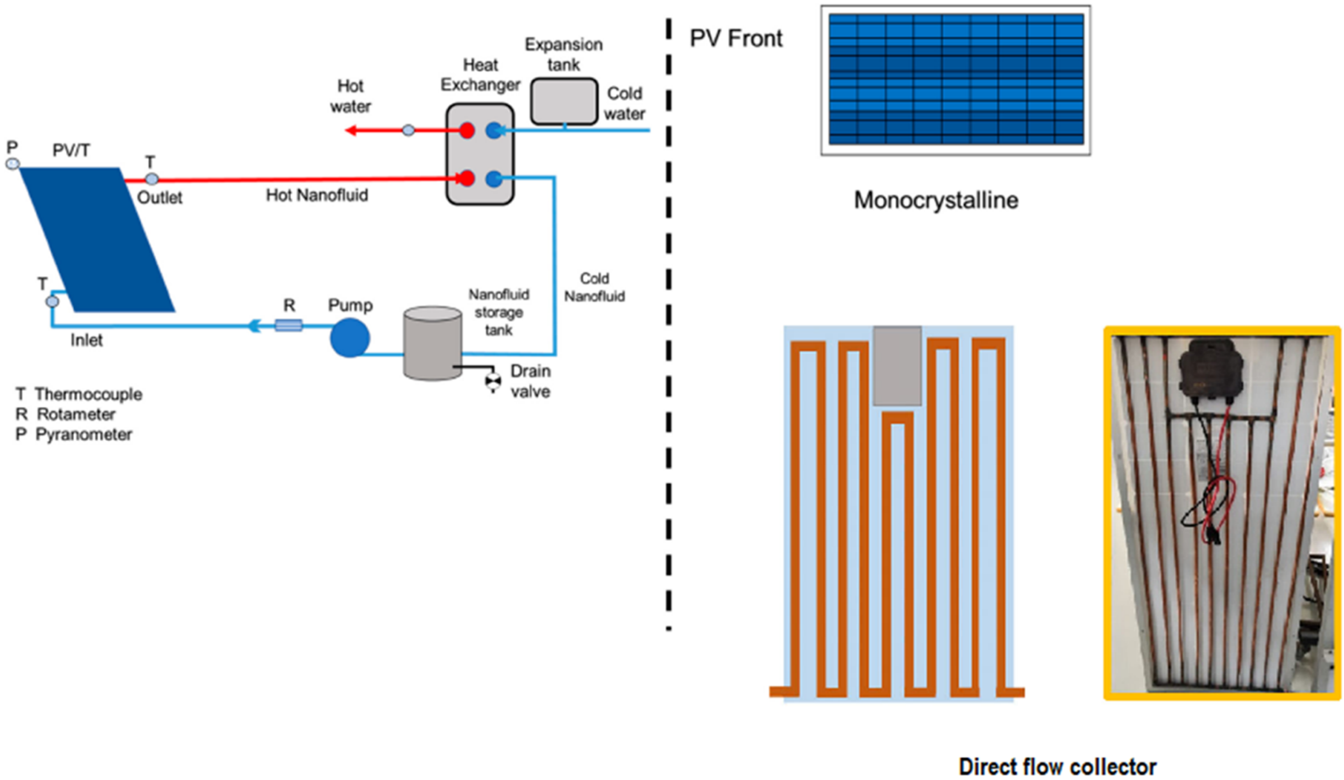

Figure 1. Schematic of the PVT system tested with a direct flow heat exchanger.

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nanofluid. Three monocrystalline-type PV modules were employed; their specifications are listed in Table 5. The width of the module is 0.65 m, and its length is 1 m.

Table 5. Specifications of the Used Modules

solar module type	Nutu Tech Fzco
peak power	100 W
max. power voltage	17.96 V
max. power current	5.57 A
open-circuit voltage	22.6 V
short-circuit current	5.76 A
weight	11.4 kg
dimensions	1010 × 660 × 34
operating temperature	−40 to 90 °C
wind resistance	2400 Pa

The practical tests were conducted outdoors in the city of Baghdad, Iraq's capital, which is known for its extreme weather conditions on summer days. Temperatures in the summer can reach over 60 °C in direct sunlight, while in the winter, the daytime temperature is typically no lower than 14 °C. In addition, Baghdad has seen a drop in rainfall in the last 30 years, with dust and dust storms becoming more common. To maximize efficiency, the PV panels were oriented southward at an angle of 33°. Table 6 displays the average weather conditions for Baghdad in July and August 2021, the hottest months of the year. During this period, the voltage and current of the three studied modules were monitored from morning until sunset. To reduce the number of tests, a mass flow rate of 0.015 kg/s was chosen following the results of ref 73. A tank with a circulating nanofluid and a TOPSFLO-China type pump was employed for the circulation process. The nanofluid system was a closed loop, with valves that controlled the movement of the coolant.

Table 6. Average Weather Conditions for July and August 2021 for Baghdad City

parameters	Jul	Aug
max. temp (°C)	51	47
min. temp. (°C)	35	34
shinning hours (h/day)	14.5	13
precipitation (mm)	0	0
rainy days	0	0
humidity (%)	44	31
wind speed (m/s)	3	2.5

The electrical and thermal efficacies of the examined systems, as well as the two PVT systems, were ascertained by utilizing the accompanying equations[49,74]

$$\text{the electrical power is:}\quad P_{max} = I_{mp} \times V_{mp} \tag{3}$$

$$\text{the useful collected heat } (W) \text{ is:}\quad Q_u = \dot{m}C_p(T_o - T_i) \tag{4}$$

$$\text{the electrical efficiency}(\eta_e) \text{ is:}\quad \eta_e = \frac{P_{max}}{I_s \times A_{panel}} \tag{5}$$

$$\text{the system's thermal efficiency is:}\quad \eta_{th} = \frac{Q_u}{I_s \times A_c} \tag{6}$$

$$\text{thetotal efficiency}(\eta_t) = \eta_t = \eta_{th} + \eta_e = \frac{Q_u + P_{max}}{I_s \times A_t} \tag{7}$$

3. RESULTS AND DISCUSSION

Several experiments were conducted to determine the ideal nanofluid to be used in PVT cooling systems. It is important to note that further testing is still necessary to ultimately settle on this nanofluid, but the present research has narrowed down the number of tests that need to be done in the future.

3.1. Base Fluid Type Effect. The experiments started with the combination of the base liquid and nanoparticles at 0.1, 0.5, 0.75, and 1.0 wt % mass fractions. As Table 1 and Figure 2 show, water had a larger thermal conductivity (TC) compared

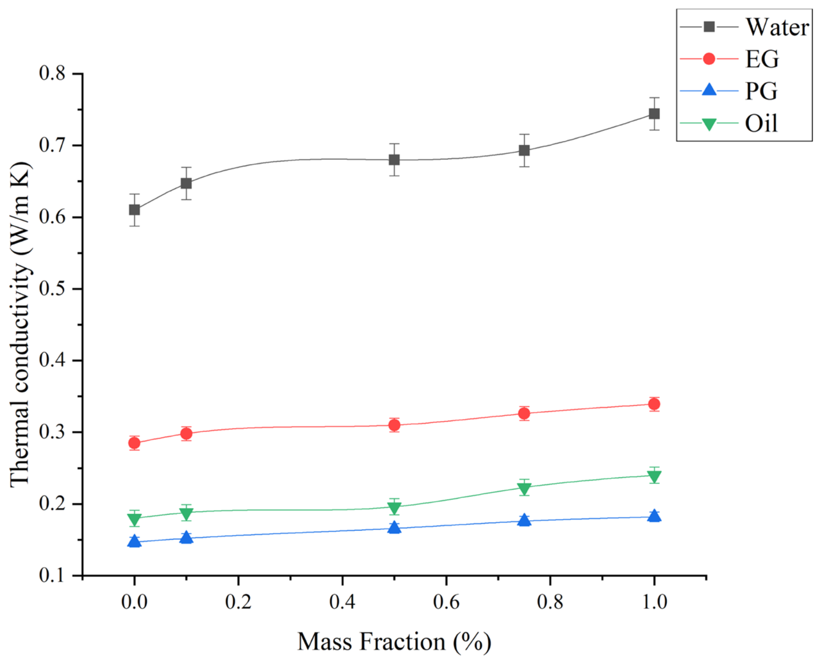

Figure 2. Type of base fluid and the mass fraction of MWCNTs used influence the TC of the nanofluid created.

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to the other bases. The TC was increased when MWCNTs were added, with the aqueous origin nanofluid demonstrating the highest performance. With a 1% MWCNT addition, the improvement values for water, EG, PG, and HTO were 21.90, 18.94, 23.80, and 33.33%, respectively. At this mass fraction, water had a TC that was 119.5, 308, and 210% higher than EG, PG, and HTO, respectively. These results illustrate the superiority of water as a base fluid. The exchange of thermal energy between the nanoparticles and the base fluid is the mechanism that caused the results mentioned in the paragraph. The nanoparticles have a higher thermal conductivity than the base fluid, so when they are added to the base fluid, the thermal energy is efficiently transferred from the nanoparticles to the base fluid, leading to an increase in the thermal conductivity of the nanofluid.

The data presented in Figure 3 demonstrates the influence of the base fluid type and mass fraction of added SWCNTs on

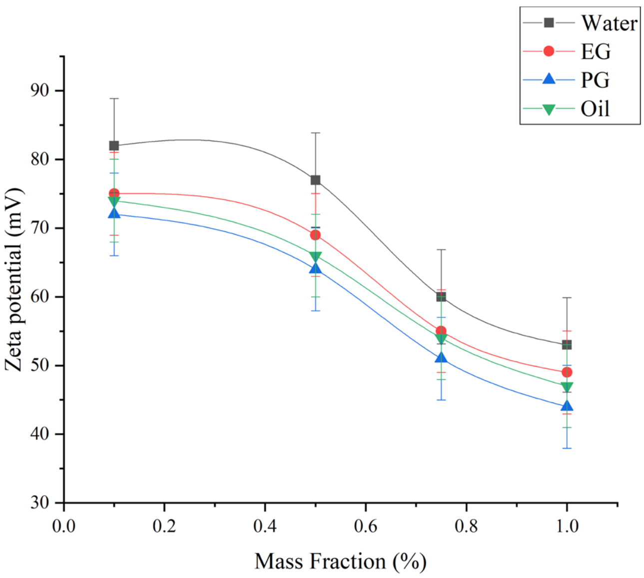

Figure 3. Type of base fluid and the mass fraction of MWCNTs used influence the ζ potential of the nanofluid created.

the stability (ST) of the nanofluids. The ζ potential of all of the prepared fluids was observed to be more than 40 mV, which indicates good stability. When 0.1% MWCNT was added, the ζ potential was more than 70 mV, which is an excellent result. For all tested mass fractions, nanofluids made with water had the highest stability, even at high addition rates (1%). When the MWCNTs were added at a mass fraction of 0.5%, the water-based nanofluid stability was greater than that of the ethylene glycol, propylene glycol, and oil-based nanofluids by 11.6, 20.3, and 16.66%, respectively. All of the nanofluids were characterized by high ζ potentials (greater than 60 mV).

Al-Waeli et al.[4] observed that both EG and PG can act as a lubricant for nanoparticles, thus allowing them to become redistributed if they settle and collect at the bottom of the tank when the liquid is recirculated. Generally, it can be advantageous to combine the trait with the higher thermal conductivity of water by mixing it with the liquids mentioned, such as refs 15, 44, 75, which has led to many investigations.

3.2. Surfactant Type Effect. For the second set, 0.5% (by volume) of surfactants were added to the base liquid, as determined by Mohd Saidi et al.[76] These surfactants can be seen in Table 2. The influence of the additional surfactant was minor on the thermal conductivity produced, as Figure 4 revealed a minimal increase. SUR I had a significant impact when included in the oil, but the effects on the remaining fluids were not conspicuous. The TC of the aqueous nanofluid increased by 0.64, 1.5, 1.6, and 0.14% when 0.1, 0.5, 0.75, and 1.0% of MWCNTs were added, respectively (Figure 5).

The results of the tests indicated that CTAB had a greater effect on the stability of the nanofluids than the other surfactants. This was evident from the measured ζ potential values for all of the tested nanofluids, which showed an increase in varying proportions depending on the base fluid and the surfactant added. For instance, when 0.5% MWCNT was added to water, the ζ potential increased by 10.3, 5.2, and 6.5% for the addition of SUR I, SUR II, and SUR III, respectively. Similarly, when 1% MWCNT was added to nano-EG, the ζ potential increased by 5.7 and 3.77% for the addition of SUR I and SUR III, respectively. In addition, when PG was used, the ζ potential increased by 2 and 4.15% for the addition of SUR II and SUR III, respectively. Lastly, when HTO was used, the ζ potential increased by 10.2% and decreased by 1.5% for the addition of SUR II and SUR III, respectively. SUR I's (CTAB) superiority is beneficial because it has a higher solubility in water than the other surfactants and it is more effective at reducing surface tension, which helps increase the stability of the solution. It also has relatively low toxicity, which makes it safer to use than some other surfactants. Finally, CTAB is more effective than many other surfactants in its ability to form micelles, which helps to stabilize the solution. The findings from the previous two sections indicate that combining water with CTAB as a surfactant produces the highest TC and ST values.

3.3. Sonication Time Effect. In this investigation, past findings were looked at to decide how many experiments and measurements should be done, and the most effective ones were then selected for use in the following trials. In this set of experiments, 0.5 wt % MWCNT was blended with water and CTAB was utilized as a surfactant. Six different sonication times were examined (1:30, 2:00, 2:30, 3:00, 3:15, 3:30, and 4:00). The prepared nanofluids were then tested through TC and ST tests to determine the best sonication time. Figure 6 displays the effect of sonication time on the TC of the tested nanoemulsions. To ensure precision in the outcomes, the TC was measured at a typical lab temperature of 25 °C. When 0.1% MWCNT was mixed in, the thermal conductivity went up after two and a half hours of sonication (0.635 W/m K). When the sonication was increased to three and a quarter hours, the TC dropped to (0.634 W/m K). With 0.5% MWCNT, the highest thermal conductivity was observed at three and a quarter hours and three and a half hours (0.67 W/m K). A slight decrease to 0.65 W/m K was seen when sonication time was extended to 4 h. The most effective thermal conductivity with 0.75% MWCNT was recorded at three and a half hours. The results demonstrate that each mixture has an optimal sonication duration, which should be tested in small samples prior to carrying out the quantitative production of nanofluid. When a small amount of particles is added, it needs less time compared to a large proportion of nanoparticles. This is a common phenomenon since particles with a small mass fraction are more likely to disintegrate and disperse faster than those with a large mass fraction due to the short distances between them. Going over the appropriate sonication time can lead to a decrease in TC, as well as an increase in expenses, as the effect of the process is reversed.

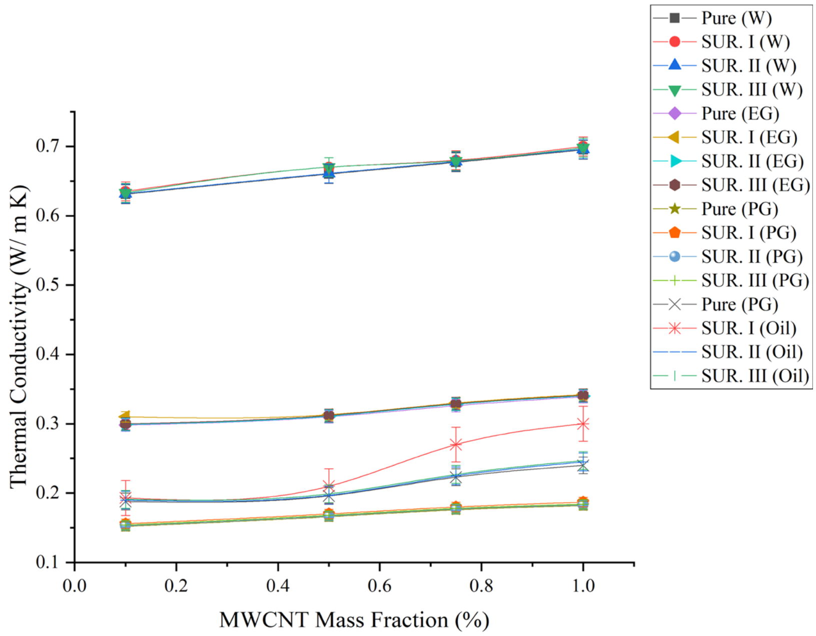

Figure 4. Type of base fluid and surfactant type and MWCNTs used influence the TC of the nanofluid created.

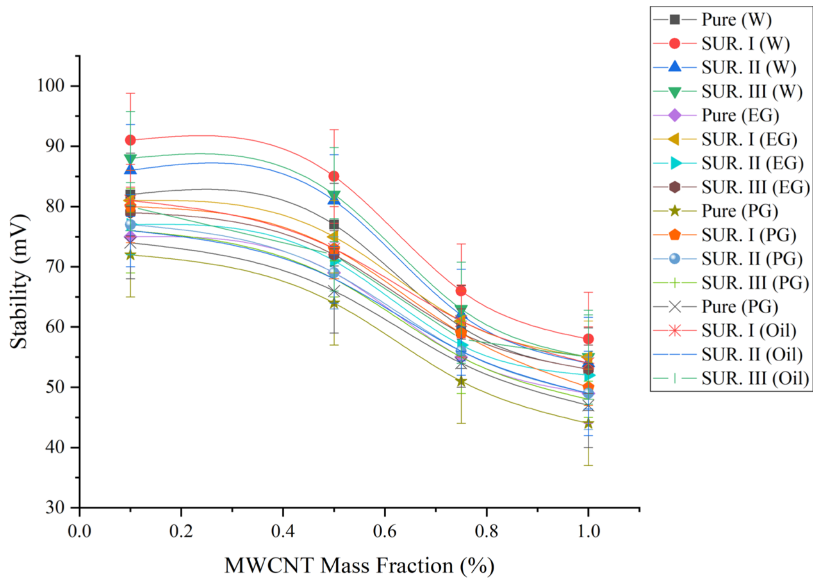

Figure 5. Type of base fluid and surfactant type and MWCNTs used influence the ST of the nanofluid created.

In this study, the researchers adopted six timings to determine the appropriate sonication time for producing a suspension with high stability. However, the results showed that there is no need to exceed these timings. However, further research is needed to explore the effects of multiple factors on the process simultaneously and to determine the ideal sonication time for the preparation of nanofluids with the studied base fluids.

Figure 7 displays the influence that the duration of sonication has on the fabricated nanofluid's ST. The ST rose when the sonication time was amplified, reaching its highest point at three and a quarter hours for the 0.1 and 0.5% additions. When it came to 0.75 and 1%, the greatest ST was obtained after 4 h. It is clear that there is a connection between ST and TC, as the ST decreased after the specified sonication time was reached, which was in agreement with the TC outcome.

The most suitable base fluid for providing the best TC and ST is water. In addition, CTAB was found to give the best TC and ST, so it is preferable to use it. With regards to the mass fraction of MWCNT to be added, it has been decided to use 0.5% in order to reduce the cost of nanoparticles and sonication. This 0.5% mass fraction nanofluid provides an excellent ST, and the difference in TC compared to the 1% mass fraction is relatively small. So, in the next set of tests, the used nanofluid consisted of 0.5% MWCNT, water, and 0.5 wt % CTAB.

3.4. Outdoor Test Environmental Conditions. This study was conducted in Baghdad, Iraq, in order to investigate the effectiveness of using a nanofluid to cool a PVT system in the most extreme weather conditions. July and August were

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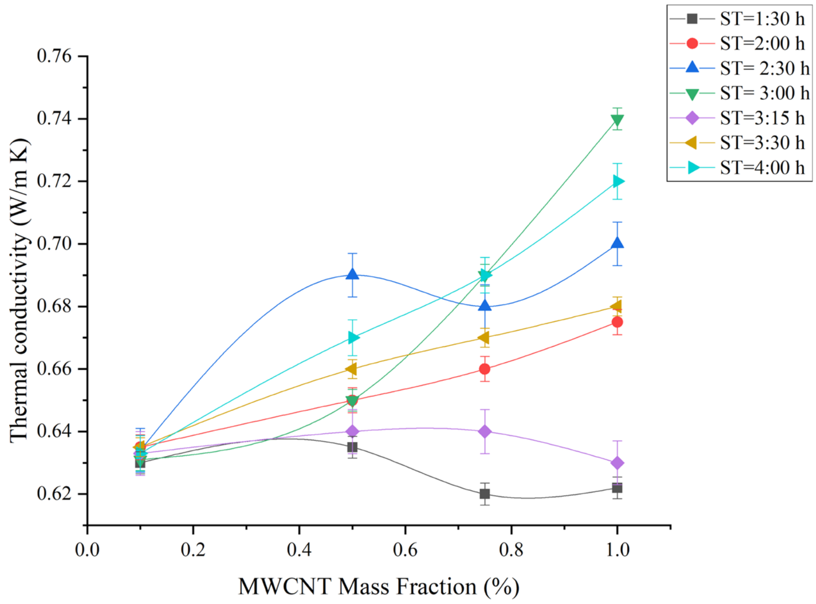

Figure 6. Effect of sonication time on the TC of the prepared nanofluids (MWCNT + Water + CTAB).

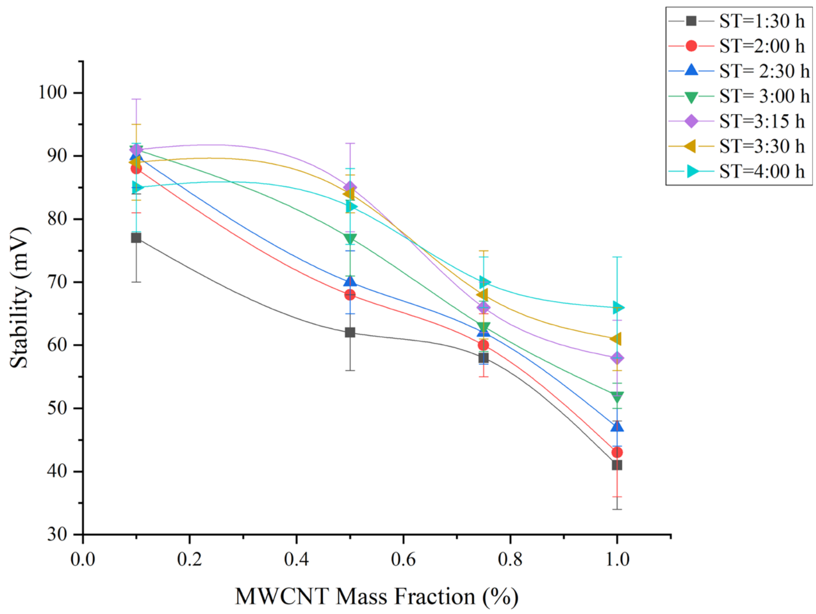

Figure 7. Effect of sonication time on the ST of the prepared nanofluids (MWCNT + Water + CTAB).

selected as the time period of examination because these months of the year are known to have the highest temperatures. During the study, noon temperatures exceeded 50 °C and solar radiation intensity was observed to be greater than 1000 W/m^2. Figure 8 in the study displays the measurements of solar radiation, atmospheric temperatures, and surface temperature of the PV panels for a single module and two PVT systems cooled with water and nanofluid. At 2:15 PM, the temperature of the standalone PV panels increased to 78 °C, despite the ambient temperature only being 50 °C. It is important to note that the ambient temperature is read in the shade, while the PV panel surface temperature is under direct sunlight exposure. Figure 8 shows that the PV panel temperature was decreased when cooled with water and nanofluid, and the cooling effect is greater with the nanofluid. This result was echoed in all studies that employed nanofluids in cooling PVT systems. The efficiency of cooling for nanofluids varies. It is estimated that the temperature decrease of the nanofluid-cooled PVT system over the course of a full day's operation is 57.5% higher than that of the PV module and 17% higher than the water-cooled PVT system.

3.5. PVT System Efficiencies. Figure 9 illustrates how the efficiencies (electricity, thermal, and overall) of the three systems tested changed over time. The electrical efficiency of the standalone PV system was at its highest, 10%, at 8:00 AM but then began to decline until it hit its lowest point of 4.5% at midday. This is likely because the solar intensity at 8:00 AM was only 119 W/m^2, not enough to bring the PV panel to its maximum efficiency. When the intensity peaked at 1:30 PM, the temperature of the panel had risen to 70 °C, which caused the efficiency to deteriorate. At midday, the water-cooled PVT

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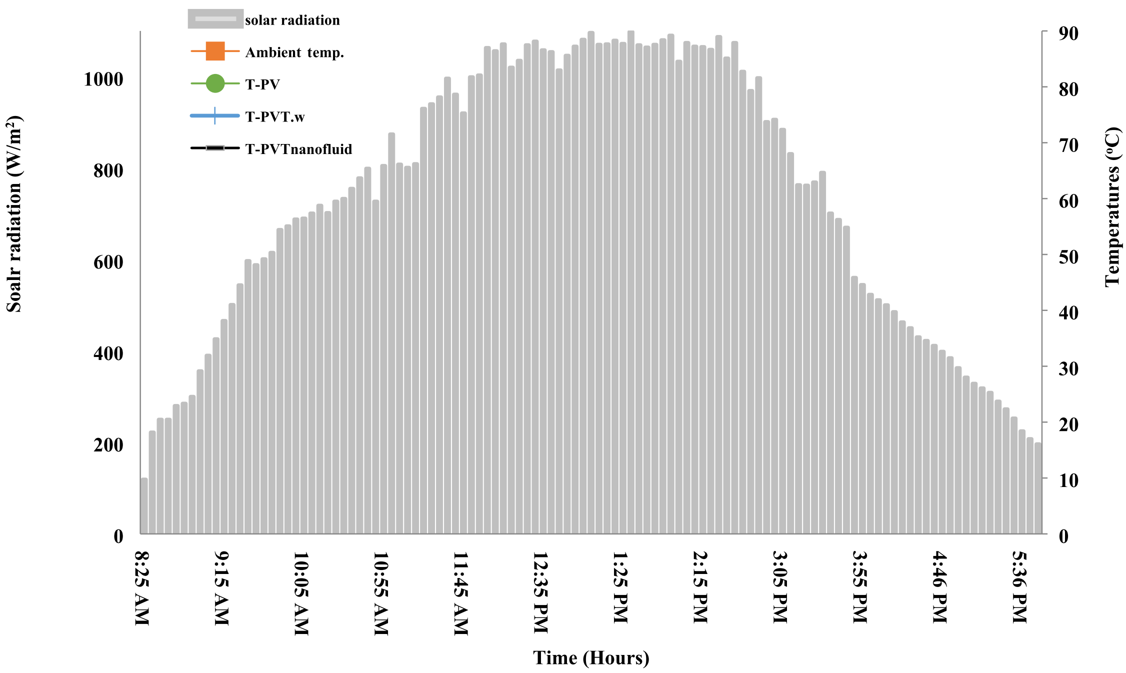

Figure 8. Solar radiation and temperature measured for the tested systems.

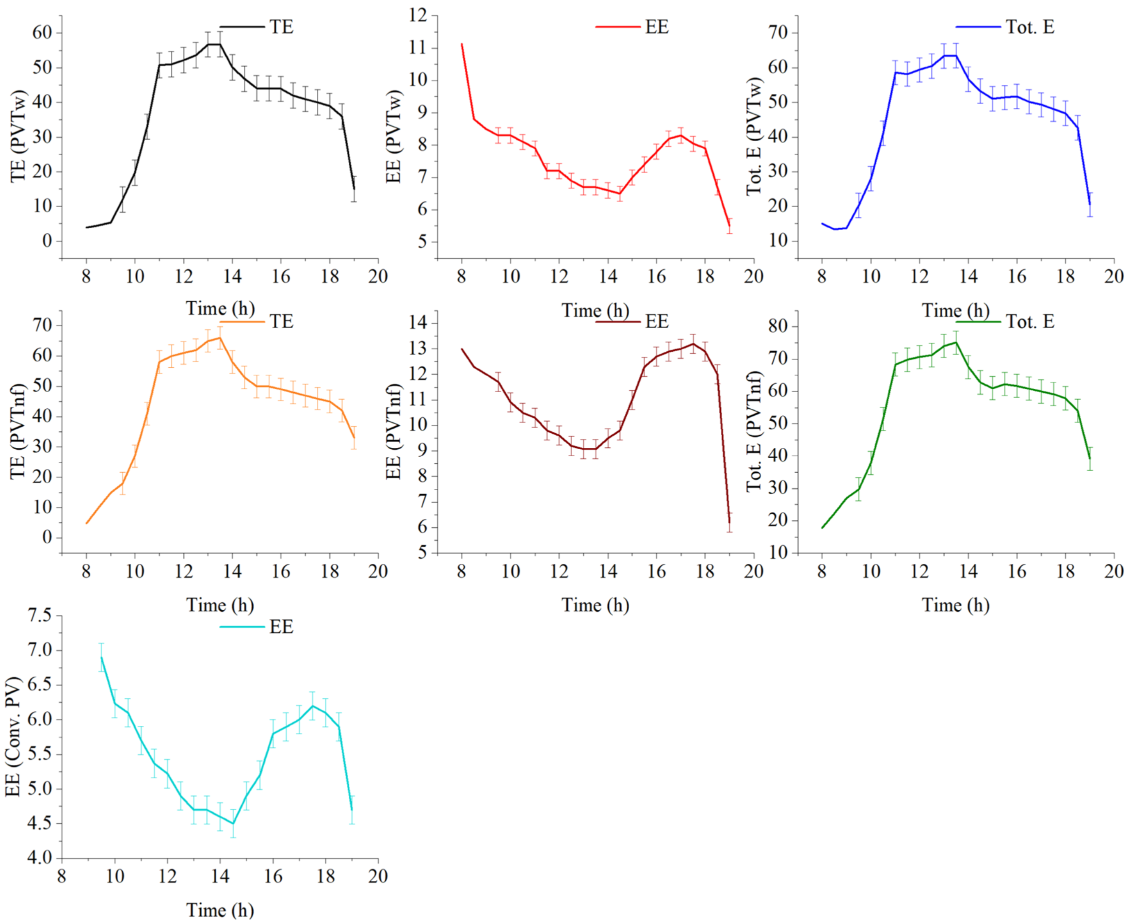

Figure 9. Efficiencies of the tested system vary with time.

(PVTw) system had the lowest electrical efficiency of 6.5%. The lowest efficiency attained using the nanofluid (PVTnf) to cool the PVT system was 9.07%. This is significantly higher than the electrical efficiency of the standalone PV and water-cooled PVT systems, which were 88.85 and 44%, respectively. The thermal efficiency of the nanofluid-cooled PVT system is also higher, with an increase of around 20% over the water-cooled system. The electrical efficiency of all systems decreased

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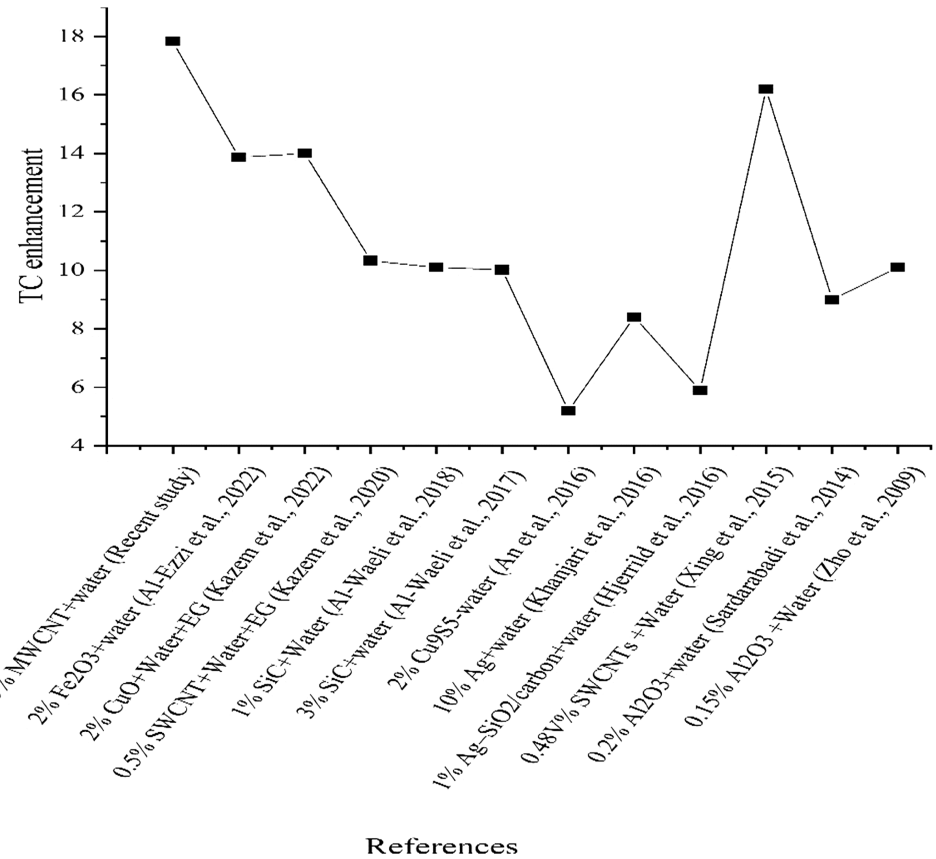

Figure 10. Comparison of the TC enhancement rate for the current study nanofluid and others from the literature.

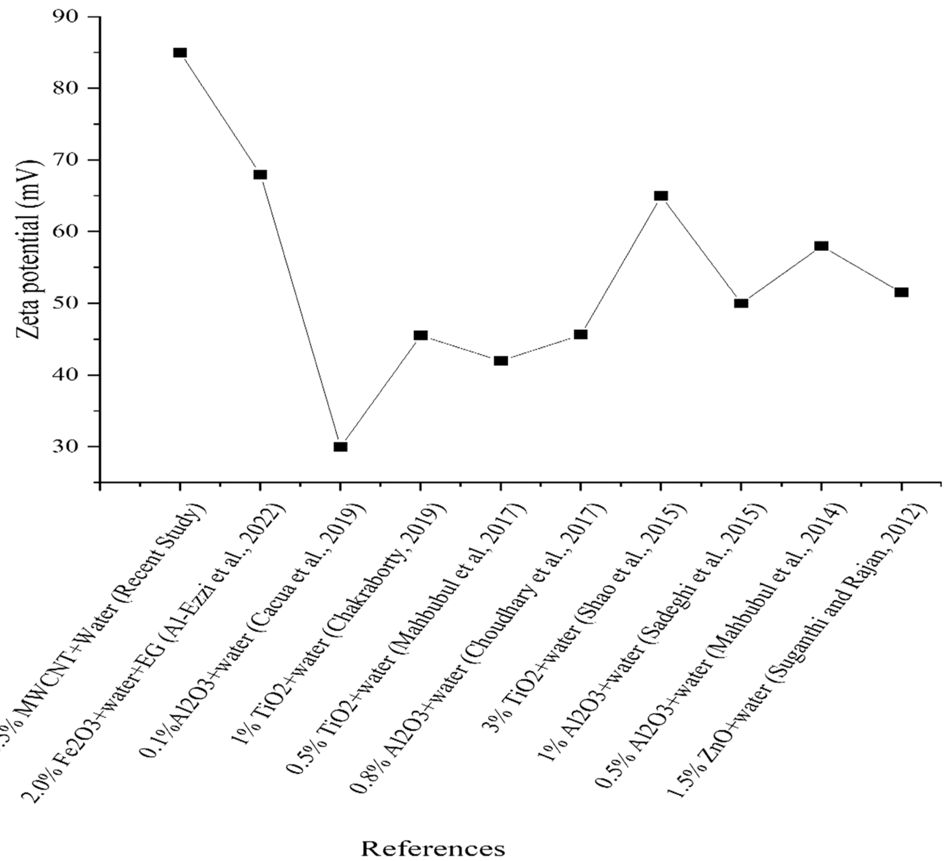

Figure 11. Comparison of ST for the current study nanofluid and others from the literature.

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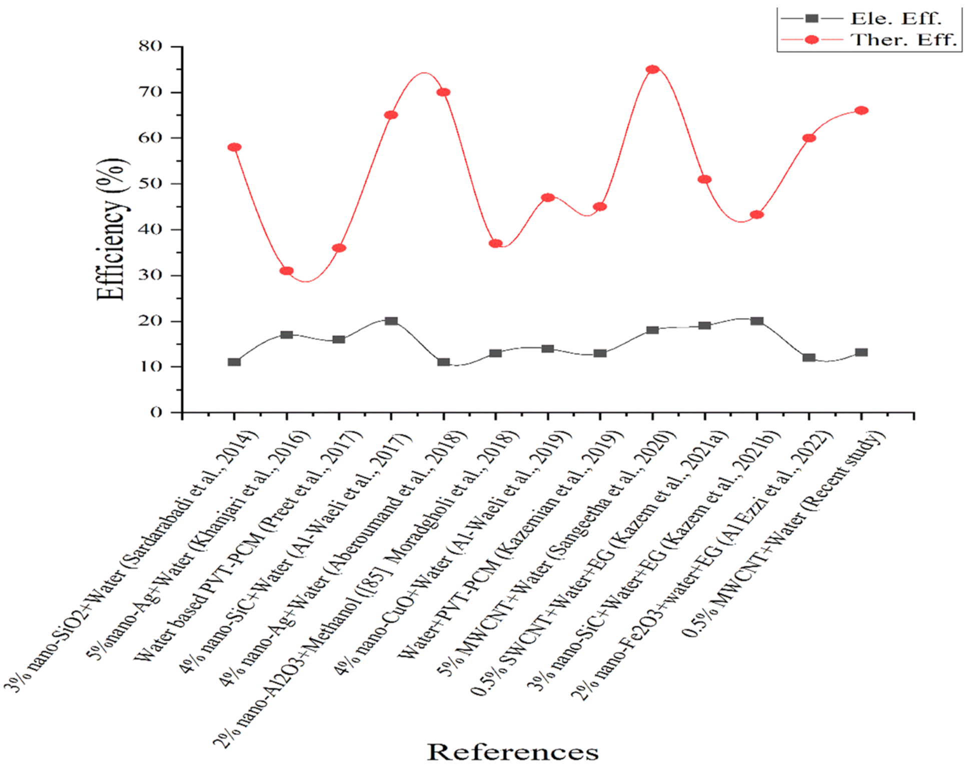

Figure 12. Comparison of electrical and thermal efficiencies for the current PVT system study and others from the literature.

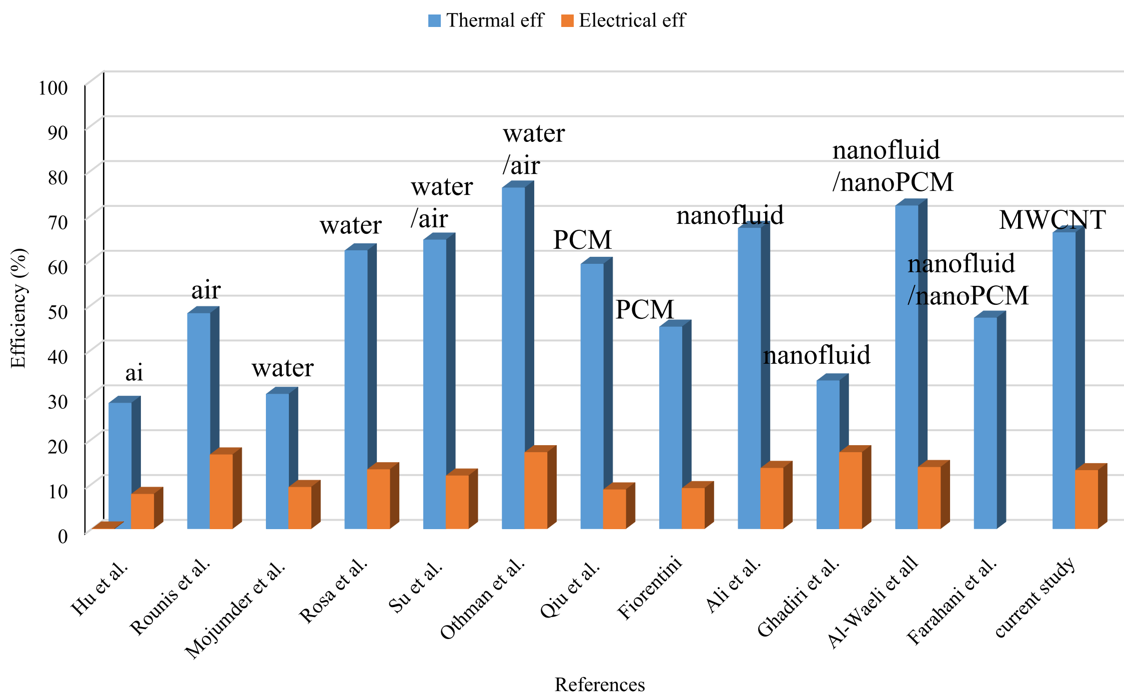

Figure 13. Comparison of the performance of the proposed cooling nanofluid to the existing and conventional cooling methods for PVT applications.

at midday; however, the thermal efficiency of the nanofluid-cooled PVT system rose due to its high TC. The total efficiency of the nanofluid-cooled PVT system peaked at 75.08%, surpassing the maximum total efficiency of the water-cooled PVT system, which was limited to 63.5%.

3.6. Comparison with the Literature. In this section, the results of the TC and ST of the prepared nanofluids will be compared to other fluids from the literature. Additionally, the performance of the proposed cooling nanofluid will be compared to existing and conventional cooling methods for PVT applications. Figure 10 shows the rate of TC enhancement. It is noteworthy that such comparisons may not be entirely accurate since there are discrepancies between the type of nanoparticles added, leading to differences in TC and the

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base fluid used, thus having an effect on the TC of the nanofluid that is produced. However, these figures offer evidence of the validity of the results. Analyzing the outcome of the present investigation against the output from refs 17, 42, 44, 49, 74, 77−81 displays that the advancement in the TC of the current study is greater than what has been seen in the other studies (Figure 10). This is attributed to the TC of the MWCNTs chosen and the judicious selection of the base fluid, surfactant, and sonication time. The optimal blending yields an outstanding outcome, validating the proper research strategy.

Comparison of the ST of the nanofluids prepared in this study with those from other studies[63,69,81−86,88] reveals that the current study nanofluid has a higher ST (Figure 11). This high ST affirms the validity of the methods used during the tests and the success of the accurate measurements taken. The results of both Figures 10 and 11 indicate the suitability of the nanoemulsion made of water (base fluid), CTAB (surfactant), and MWCNTs (additive nanoparticles) for use in cooling PV/T systems that need nanofluids with both high ST and TC.

In Figure 12, a comparison is made between the electrical and thermal efficiencies of various systems taken from the literature and the results of the current research. However, this comparison is not entirely fair as the systems used involve multiple PV panels with varying efficiencies. The research of the[4,12,43,44,49,71,72,79,81,87−92] were all undertaken in different environmental conditions to that of the current study. Even so, this comparison provides an idea of how valid the current study's methodology is and how much the outcomes are in line with those of other studies. The electrical output generated by the system under investigation is in line with what is documented in the literature. This result is heavily dependent on the type of photovoltaic panel used, the amount of solar radiation, and the temperature of the panels, and as previously mentioned, the environmental conditions of this study were the most difficult of any in the world. Despite the fact that the current PVT study system has high thermal efficiency, the systems in studies 43, 90 were able to surpass it. Sangeetha et al.[43] included a greater amount of MWCNTs (5%) compared to the amount used in this study (0.5%), leading to a reduction in the cost of the current study fluid production. Aberoumand et al.[90] revealed that adding expensive nanosilver was 4%, leading to high costs. This is in contrast to the findings of the current study. Despite the severe weather conditions in which the tests were carried out, the PVT system in the current study was effective and efficient.

The comparison of PVT electrical and thermal efficiency with regard to different cooling methods is illustrated in Figure 13. It is seen that the thermal efficiency is relatively high and in line with the findings reported in the literature. In terms of efficiency, air cooling yielded the least favorable results, with ηe and ηth measuring 7.7 and 28%, respectively, while nanofluid cooling produced the highest efficiencies at 13.14 and 68.22%. All cost factors, such as civil and installation works, pump, heat exchanger, nanofluid, and mount, were taken into consideration when performing the economic analysis. It is clear that air, water, and air/water cooling methods have the lowest efficiency compared with nanofluid and/or nano-PCM cooling methods. For economic analysis, the same procedure in Al-Waeli et al.[75] was adopted to calculate the cost of energy, COE, and yield. The costs for the system components were based on their local price, where the cost of the PV system was 200$ (priced at $2/Wp), the pump was $40, the heat exchanger was $80, the nanofluid costed $24 ($80/liter), the pipe costed $20 ($1/m), and the insulation costed $5. The proposed system costs about $169 more than the conventional PV system. However, when analyzing the cost of energy, COE (which is the life cycle cost of the system divided by the annual energy yield), we found that cooling using the proposed system results in a COE of $0.027/kWh while the conventional PV yields a $0.0338/kWh. This analysis is made using the simple life cycle cost and COE model, also assuming only a 10% and 20% decrease in system yields in the years 10−20 and 20−25, respectively.

4. CONCLUSIONS

This study involved the testing of MWCNT nanoparticles as a nanofluid in four base fluids (water, ethylene glycol, propylene glycol, and heat transfer oil) and three surfactants to assess the most suitable combination for thermal conductivity and stability. Results showed that the most thermally conductive base liquid was water, and the addition of 1% MWCNT increased its thermal conductivity by 119.5, 308, and 210%, respectively, compared to EG, PG, and HTO. The surfactant CTAB provided the most stability for the nanofluid. Sonication time was adjusted according to the mass fraction of nanoparticles used, with 0.1% MWCNT needing two and a half hours and 0.5% MWCNT needing three and a quarter hours of sonication. The nanofluid was tested in Baghdad under the harshest weather conditions and achieved satisfactory electrical and thermal efficiencies of 13.2 and 63%, respectively. These results validate the effectiveness of the nanofluid in extreme conditions; however, further studies are needed to find the ideal nanofluid for photovoltaic thermal (PVT) systems.

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Notes

The authors declare no competing financial interest.

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■ NOMENCLATURE

AC & A_{module}	collector and PV areas (m^2)
Cp	water heat capacity (J/(kg K))
G	solar irradiance (W/m^2)
GS	global solar radiation (W/m^2)
I_{SC} & I_{mp}	short-circuit and maximum point currents (A)
MF	mass flow (kg/h)
PV	photovoltaic
PVT	photovoltaic/thermal
P_{rated} & P_{mp}	rated and maximum point powers (W)
$T_{ambient}$	ambient temperature (°C)
TC	cell temperature (°C)
T_{in} and T_{out}	inlet and outlet temperature (°C)
V_{OC} & V_{mp}	open-circuit and maximum point voltages (V)
W_R	uncertainty
$\eta_{electrical}$ & $\eta_{thermal}$	electrical and thermal efficiencies (%)

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