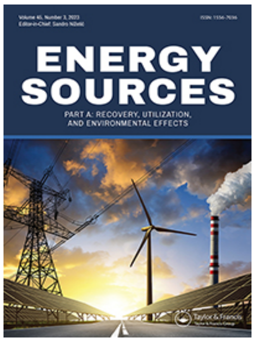

Energy Sources, Part A: Recovery, Utilization, and Environmental Effects

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# Experimental study on the performance of different photovoltaic thermal collectors with nano-technology

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**ABSTRACT**

The process of cooling the photovoltaic cell effectively leads to improving the electrical efficiency of the cell. Herein, the current experimental study employed three different nanofluids (CuO, ZnO, and $TiO_2$) to cool the PV panel to produce a hybrid collector, also known as a photovoltaic thermal solar collector (PVT). The nanoparticle volume fraction was 0.1, 0.2, and 0.3 vol%. The process of cooling the PV panel was carried out using a copper tube on the back of the PV, which was placed to cover the largest possible area on the back of the PV. Three different flow cross sections – rectangular, square, and circular – were used to compare them. This experimental study was carried out under solar radiation conditions ranging from 450 W/m$^2$ to 750 W/m$^2$, and the flow rates of the nanofluid were 0.5, 1, 1.5, and 2 L/min. The results show the electrical and thermal efficiency of the PVT system at different conditions. The electrical efficiency increased as a result of adding nanofluid compared to normal water, where the cell with CuO/nanofluids gave the highest value of electrical efficiency at 450 W/m$^2$, equaling 11.8%, while it was equal to 11.6%, 11.5%, and 10.8% for ZnO/nanofluids, $TiO_2$ /nanofluids, and water, respectively. An increase in mass flow rate leads to increased thermal, electrical, and combined PVT efficiencies. As well. The high mass flow rate increases the heat transfer coefficients between the tube wall and flowing fluid, which in turn decreases the PV module's temperature. Finally, the rectangular section and the CuO/nanofluids gave the best value for the electrical power, which reached 83.17 W, and the highest electrical efficiency, which reached 11.5%.

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Electrical efficiency; nano-technology; photovoltaic collector; solar irradiance; thermal efficiency

## Introduction

As the world deals with the issues of global warming, energy shortages, and the degradation of the environment and energy sources, there is a need for alternative energy to generate power rather than using fossil fuels. Global energy consumption has been rising at an alarming rate, particularly in industrialized nations. Fossil fuels provide for 86% of the world's energy supply, which contributes to global warming (Mohammed Hussein et al. 2022 and Ajeel, Sopian, and Zulkifli 2021). Numerous studies have employed photovoltaic (PV) systems as one of the renewable sources of electricity. A photovoltaic (PV) system's performance is influenced by a number of factors in addition to its fundamental electrical characteristics, such as its maximum power, maximum power voltage, maximum power current, maximum system voltage, open-circuit voltage (Voc), and short-circuit current (Isc) (Ajeel, Salim, and Hasnan 2019 and Kazemian et al. 2022). Also, this system is hindered by things like the ambient temperature, dust storms, airborne suspension, and the intensity, spectrum, and angle

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of irradiance of global solar radiation. Flat-plate photovoltaic thermal (PVT) systems, which use solar energy to generate heat and electricity concurrently, have improved in efficiency, as demonstrated by Lee et al (Lee, Hwang, and Lee 2019). Henein and Abdel-Rehim (Henein and Abdel-Rehim 2022) experimentally investigated the effect of using a hybrid magnesium oxide/multi-walled carbon nanotube (MgO/MWCNT) nanofluid on the thermal performance of the evacuated tube solar collector. Four different weight ratios of (80:20), (70:30), (60:40), and (50:50) have been used for a hybrid of MgO with MWCNTs in a water base, respectively. The experiments were performed at a 0.02% particle concentration and at various volume flow rates ranging from 1 to 3 L/min. The results showed that increasing the weight ratios of MWCNT nanoparticles and volume flow rate improved energy and exergy efficiencies. The enhancement of the energy and exergy efficiencies of the collector were 55.83 and 77.14%, respectively, for MgO/MWCNT (50:50) hybrid nanofluid. It was also found that increasing the weight ratio of MWCNT nanoparticles from 20% to 30% achieved a significant increase in collector efficiency enhancement compared to other hybrid nanofluids. The results concluded that MgO/MWCNT (50:50) performed better than all other hybrid nanofluids at all volume flow rates and was closer to MWCNT/water nanofluid. Menon et al. (Menon et al. 2022) evaluated the electrical and thermal performance of an unglazed photovoltaic thermal (PVT) system integrated with a serpentine coil-configured sheet and tube thermal absorber setup using water and a copper oxide-based nanofluid. An uncooled PVT system reached a maximum panel temperature of 68.4 $^{\circ}C$ at noon and obtained an average electrical efficiency of 12.98%. Water and nanofluid cooling of the PVT system reduced the panel temperature by 15°C and 23.7°C at noontime, respectively. The average electrical efficiency of the water- and nanofluid-cooled PVT systems increased by 12.32% and 35.67%, respectively, resulting in 14.58% and 17.61%. The thermal efficiency of the nanofluid-cooled PVT system (71.17%) was significantly higher than water cooling (58.77%) due to the maximum heat absorption by nanoparticles. Besides, it was also observed that the overall efficiency of the nanofluid-cooled PVT system was 21% higher than the water-cooled system. Ajeel et al. [8] numerically studied the flow structure and heat transfer characteristics of the novel channel, namely, the curved-corrugated channel with using ZnO-water nanofluid and the presence of L-shaped baffles. Different geometrical parameters have been studied at different Reynolds numbers (8000–32000) and volume fractions of ZnO particles (0–4%). The authors confirmed that the nanofluid has a positive effect on heat transfer enhancement compared with base fluid.

By laminating a copper sheet directly to the silicon cell, Michael & Iniyan (Michael and Iniyan 2015) created a unique photovoltaic thermal collector that reduced thermal resistance and enhanced performance by employing CuO/$H_2O$ nanofluid. Their outcomes revealed that the nanofluid significantly outperformed water in terms of thermal performance. The usefulness of using air and CuO nanofluid simultaneously as dual-fluid coolants for the thermal control of a photovoltaic/thermal (PV/T) system was highlighted by Hussain et al (Hussain, Lee, and Kim 2021). Calculations were made to determine the differences between the results of the indoor and outdoor tests. Under steady-state test conditions, the dual-fluid PV/T system's thermal efficiency and electrical properties were examined. Henein et al. (Henein, Abdel-Rehim, and El-Nagar 2023) investigated experimentally the performance of the evacuated tube solar collector using hybrid nanofluids of magnesium oxide and multi-walled carbon nanotubes with a water base. The experiments were carried out at various weight ratios and at three flow rates ranging from 1 to 3 L/min. The results showed an improvement in the optical efficiency of the collector by up to 78.1% with the increase in the weight ratio of multi-walled carbon nanotube nanoparticles. Besides, the average heat energy gain has increased from 240 W to 495 W. In another respect, Naghdbishi et al. (Naghdbishi, Yazdi, and Akbari 2020) constructed a hybrid PVT/PCM system to experimentally examine the effect of water/glycol-based nanofluids as active cooling media and organic paraffin wax (PCM) as a passive cooling medium. Multi-wall carbon nanotubes (MWCNT) have been considered nanoparticles due to their high thermal conductivity, which allows using a lower concentration of these nanoparticles and reduces the flow pressure drop and pumping power consumption. The best performance of the PVT/PCM panel in terms of relative enhancement of the electrical and energetic efficiencies was obtained for the MWCNT/water nanofluid. When MWCNT nanoparticles were dispersed in a water-based fluid, the thermal and electrical energetic efficiencies increased by up to 23.58% and 4.21%, respectively, when compared to pure water as a coolant fluid.

The numerical model was created by Rajaee et al. (Rajaee et al. 2021) in the ANSYS CFX environment while taking into consideration the unit's energetic and exergetic performance. The major factors in this simulation are the Reynolds number and the volume fractions of the nanoparticles. By utilizing the hybrid nanofluids, the concentrator photovoltaic-thermal panel's energy efficiency is also noticeably improved. The study has recommended that hybrid nanofluids might possibly produce a desirable performance in solar systems. Bellos & Tzivanidis (Bellos and Tzivanidis 2020) developed a novel photovoltaic thermal collector by laminating a copper sheet directly to the silicon cell that lowered thermal resistance and improved performance by utilizing $CuO/H_2O$ nanofluid. According to their findings, water was greatly exceeded by the nanofluid in terms of thermal performance. The use of a heat exchanger with higher efficacy may be able to improve electrical performance, according to additional evidence.

Sultan & Tso (Sultan and Tso 2018) conducted an experimental investigation at the College of Technology, Tamilnadu, India, to evaluate the performance of the PV/T system using water and $TiO_2$/water nanofluid with a constant concentration of 0.2 wt%. With a mass flow rate of 0.02 kg/s, the ($TiO_2$/water) nanofluid had maximum thermal and electrical efficiencies of 20.14% and 13.29%, respectively. By comparing the efficacy of water, CuO-water, and $Al_2O_3$-water nanofluids as the PVT system's heat mediums, Mahmood Alsalame et al. (Mahmood Alsalame, Lee, and Lee 2021) considered the performance evaluation of a photovoltaic thermal (PVT) system employing nanofluids. The effectiveness of a flat plate solar collector was examined by Arıkan et al. (Arıkan, Abbasoğlu, and Gazi 2018) using two types of nanofluids with and without ethylene glycol (EG). The nanofluids with and without EG were tested simultaneously in two systems. A numerical and analytical model was created by Mustafa et al. (Mustafa, Othman, and Fudholi 2017) to evaluate the efficiency of a photovoltaic thermal nanofluid system. This study theoretically investigated a new PVT system configuration that uses a nanofluid as the working fluid to extract heat from a solar panel and a rectangular stainless-steel tube. The findings showed that the electrical and thermal efficiencies are proportional to mass flow rate, and the best results were obtained with lower volume concentrations. Similarly, Rawat & Sudhakar (Rawat and Sudhakar 2016) emphasized the importance of using air and CuO nanofluid as dual-fluid coolants for the thermal control of a photovoltaic/thermal (PV/T) system. Lari et al. (Lari and Sahin 2017) conducted an experimental study on the effects of various nanoparticles on PV/T systems. The findings unequivocally demonstrated that the addition of the nanofluid increased thermal efficiency without consuming additional energy. Khanjari et al. (Khanjari, Pourfayaz, and Kasaeian 2016) investigated the experimental and PVT implications of using metal-oxide/water nanofluids as a coolant system in a photovoltaic thermal system. Among the nanoparticles taken into account are $Al_2O_3$, $TiO_2$, and ZnO, which were spread by 0.2 weight percent in deionized water as the base fluid. The results showed that all tested models of photovoltaic units (PV) had higher total energy efficiencies when compared to PVs without collectors. Additionally, the PVT/$Al_2O_3$ system has a greater boost in entropy generation than the PV unit.

Currently, there has been a large trend toward using nanotechnology (e.g., nanofluids) as one of the alternatives to traditional fluids or as one of the factors that contributes to improving the performance of these systems. As a supplement, this work tried to extend the previous studies to the PVT collector family, which has a different structure. Therefore, the current study is part of a series of studies that use nanofluids as an alternative to traditional fluids to study the performance of PVT collectors with square, circular, and rectangular tubes and different nanofluids. Under modularity, the variations between the outcomes of the tests conducted indoors and outside were calculated. The thermal efficiency and electrical characteristics of the dual-fluid PV/T system were investigated under steady-state test circumstances. The main objective is to obtain the highest electrical and thermal efficiency by using different shapes of copper tubes, including rectangular, square, and circular tubes with different diameters, with different nanofluids (CuO, ZnO, and $TiO_2$) to cool the solar cell. Currently, there are two sections to the experimental investigation. First, an analysis of the PVT collectors' performance is carried out using water as the working fluid. Second, the first segment is examined and contrasted with the comparative examination of the nanofluids utilizing three different nanofluids. In a lab, CuO, ZnO, and $TiO_2$/water are synthesized at 0.1, 0.2, and 0.3%, respectively. Also, this study investigated the highest overall efficiency (thermal and electrical efficiency) from the cooling process of PVT by using the best shapes of copper tubes (circular, square, and rectangular) with the best diameter.

## Experimental setup

An experimental setup was designed and fabricated to investigate the thermal and electrical performances of the PVT system utilizing nanofluids. Figure 1 presents the photovoltaic panel, which represents the main part of the system. It receives solar energy from the sun and converts it into electrical and thermal energy. In this study, two units were used: the first unit was cooled with pure water, while the second unit was developed to be cooled by different nanoparticles (CuO, $TiO_2$, and ZnO) added to the water. So, the cooling process in this unit is achieved by mixing nanofluids (CuO, $TiO_2$, and ZnO) in different proportions (0.1, 0.2, and 0.3) with water at a volume flow rate. Photovoltaic panel specifications are shown in Table 1. Figure 2 depicts sections of tube shapes with dimensions. Pure water is pumped by an electric motor and plastic tubes into three distinct forms of tubes (circular, square, rectangular) with three different proportions of water (0.1, 0.2, 0.3), and the quantity is controlled by a flow meter in the second type of cooling. A polystyrene board (or foam, as it is known commercially) is fixed to the back side of the aluminum pocket to insulate the PVT panel thermally. The foam board has a thickness of 5 cm. Finally, a 1 mm thick metal sheet is used to cover it, and the shapes of the cooling tubes (a, b, c) and the insulation of PV/T and PV/TN (d) are shown in Figure 3.

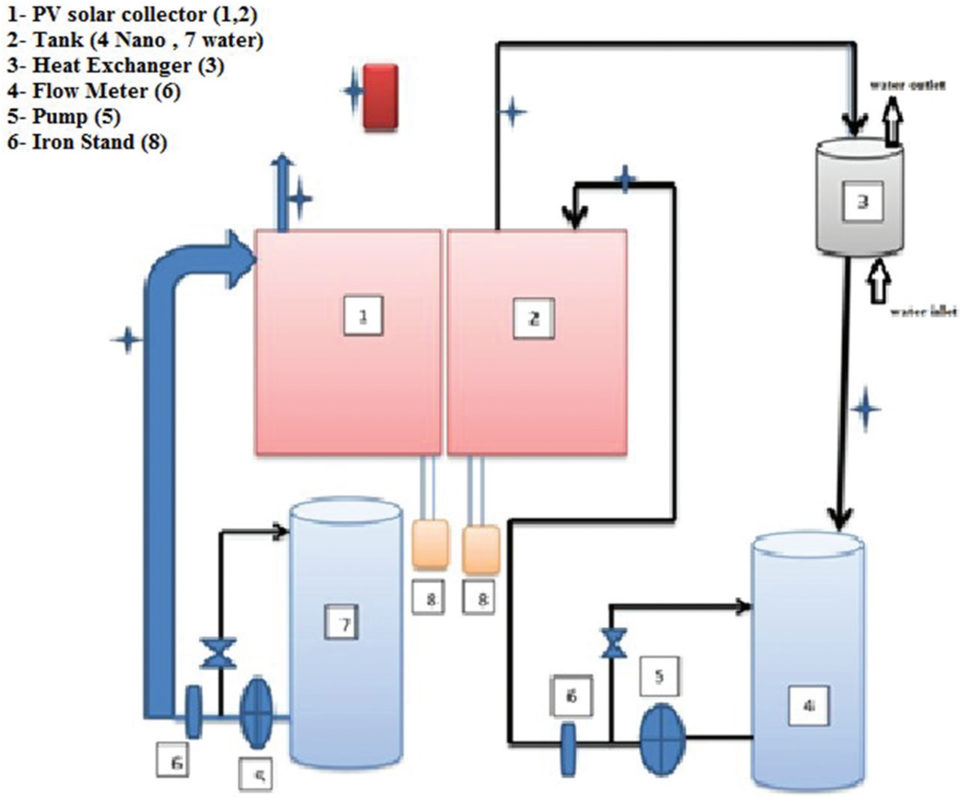

Figure 1. The schematic diagram of the photovoltaic thermal (PVT) experimental Setup.

**Table 1.** Specifications of used PV Units.

| ISTAR SOLAR IS100P, Italy | Module Model |
|---|---|
| 120 ± 3% W | Rated Maximum Power ($P_{max}$) |
| 21.90 V | Open- Circuit Voltage (voc) |
| 7.63A | Short -Circuit Current (Isc) |
| 17.90 V | Voltage at $P_{max}$ (Vmp) |
| 6.89A | Current at $P_{max}$ (Imp) |
| Up to 100% | Relative Humidity |
| 1200*540*30 mm | Dimensions(mm) |
| 7 kg | Weight |

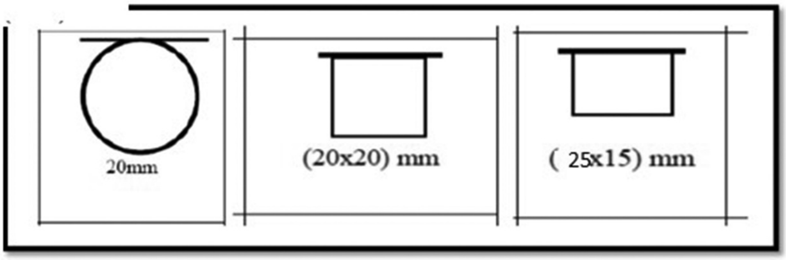

**Figure 2.** Shapes of Tubes with Dimensions under consideration.

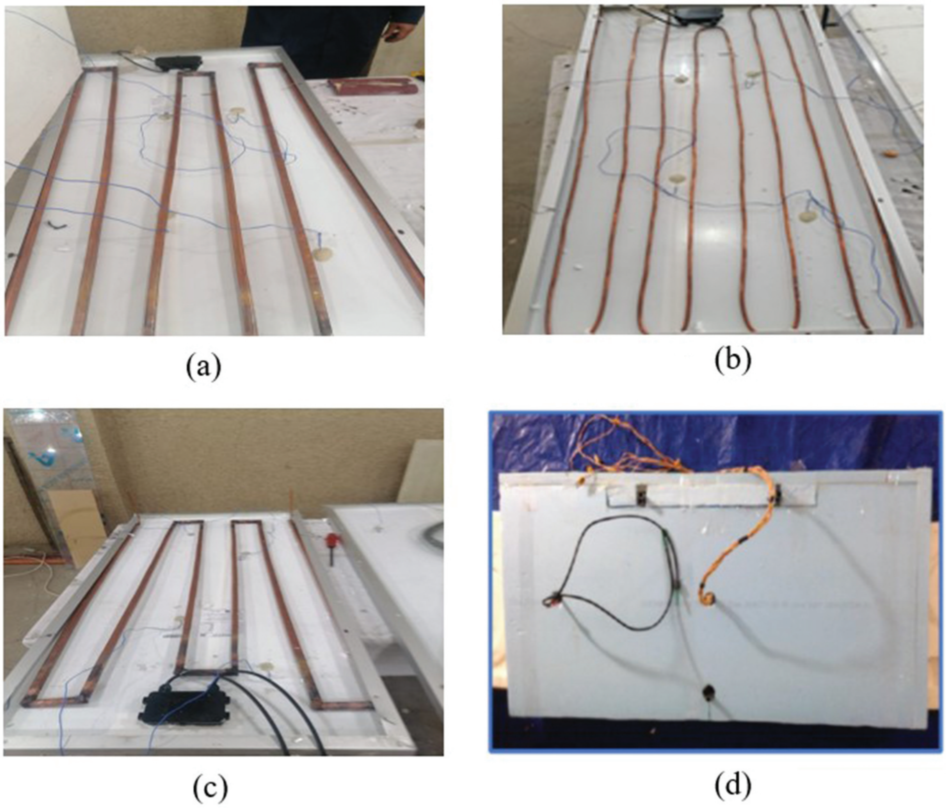
(a)
(b)
(c)
(d)

**Figure 3.** Shapes of Cooling Tubes: (a) Rectangle, (b) Circular, (c) Square, and (d) Insulation of PV/T and PV/TN.

**Figure 4.** (a) Helical coil, (b) Coil inside shell, and (c) Assembled heat exchanger.

The helical coil heat exchanger meets nanofluid-to-pure water heat transfer needs. LMTD designs the heat exchanger. EES software calculates design step equations using nanofluid and pure water thermal properties. The helical coil is made from a 12-mm-diameter, 1-mm-thick copper tube. The shell is 150 mm PVC tubing, and the helical coil has a mean diameter of 126 mm. 12 mm separates helical coil and shell wall. The cooling water entrance pipe is 1/2 inch below the shell, while the outflow pipe is 3/4 inch above. As shown in Figure 4, thermocouple extensions are attached to helical coil inlets and outlets and shell inlets and outlets.

Two 5 cm-thick rock wool-insulated water tanks provide pure water for cooling. 500 liters per tank. As seen in Figure 5a, iron supports elevate these tanks near the experimental rig for sufficient head. As shown in Figure 5b, K-type thermocouples measure temperatures on PV/TN, PV/T, and the heat exchanger's intake and exit.

## Theoretical approach and equations

### Preparation of the nano fluids

Due to the base fluid's strong thermal conductivity, nanoparticles improve the cooling fluid's thermal characteristics. This study uses nanoparticles (CuO, TiO2, ZnO). Sky Spring Nanomaterials, Inc. makes it. This nano fluid must be 99.99% pure and 40 nanometers spherical. This study employed 0.1, 0.3, and 0.5% mass concentrations. Each concentration mixed nanoparticles into deionized water. The Nano fluid unit, College of Engineering, University of Kufa, prepares nano fluid safely. Weigh the needed amount on a sensitive 99.9877% scale in the vacuum hood chamber, add deionized water, and stir with the magnetic stirrer in Figure 6. Stirring for 15 minutes creates a homogenous solution. Using US-made MTI sonication equipment, a 20-minute probe Sonication was accomplished. Ten liters, the minimum volume needed for continuous flow, is completed above. The University of Babylon's College of Engineering's sonication equipment completes the three-hour sonication bath process (Figure 7). A clean, dry container held Cuo, Zno, and TiO2 nanoparticles. An analytical balance (AND-EJ610) was used to weigh an empty glass container, add nanoparticles, and measure the total weight. Eq. (1) calculated the nanoparticle volume fraction ($\phi$) (Ajeel et al. 2019):

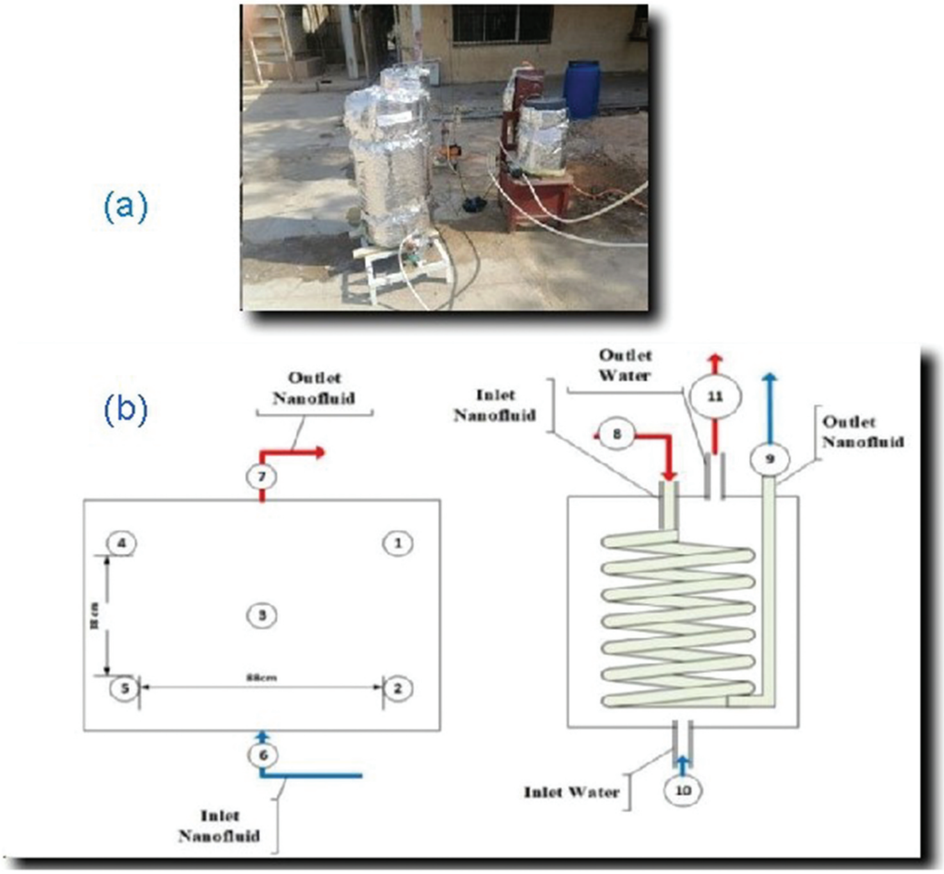

**Figure 5.** (a) Water Tanks, and (b) Positions of Thermocouples in PV/TN and Heat Exchanger.

$$\phi = \frac{m_{np}/\rho_p}{m_{np}/\rho_p + m_{nf}/\rho_f} \tag{1}$$

Where, ($\phi$) is the nanoparticle volume fraction (%); $m_{np}$ and $m_{nf}$ are the weight of nanoparticles and the base fluid, respectively, while $\rho_p$ and $\rho_f$ are the density of nanoparticles and base fluid, respectively. The (FESEM) picture was also utilized to estimate the size of the nanoparticles before they were dispersed in a base fluid. Transmission electron microscopy was used to examine a 50 mL nanofluid sample (TEM). It's a technique in which an ultra-thin specimen transmits a beam of electrons that reacts with it as it travels through it.

## *Thermo-physical properties of the nano fluids*

Thermal conductivity, density, and viscosity of Nano fluids were all measured. This was necessary in order to establish the Nano fluids' heat transfer coefficient. The thermal conductivity of Nano fluids was measured using a KD2-Pro thermal properties analyzer (made by Decagon, USA) as shown in Figure 8a, the density of the Nano fluid was measured using a DH300L Leading Factory Liquid Density Tester as shown in Figure 8a, and the viscosity was determined using a Brookfield (LVDV III ultra-programmable) viscometer as shown in Figure 8a. Table 2 presents thermo-physical properties of nanofluid (0.5%) at 25°C.

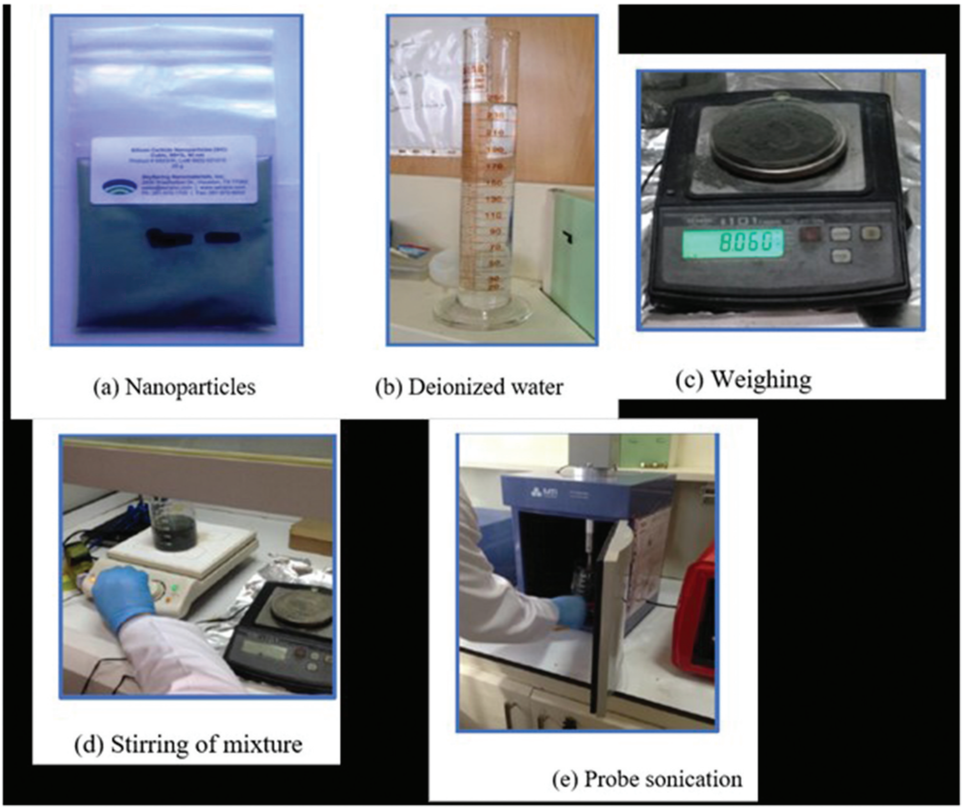

**Figure 6.** Preparing of CuO, $TiO_2$, and ZnO/water nanofluid.

**Figure 7.** (a) Sonication bath, (b) Adding water to bath.

**Figure 8.** (a) Measurement devices for thermophysical properties, and (b) Measurement devices for experimental work.

**Table 2.** Thermo-Physical Properties of Nanofluid (0.5%) at 25°C.

| Properties | Water | CuO/Nano fluid | $TiO_2$/Nano fluid | ZnO/Nano fluid |
|---|---|---|---|---|
| density (kg/m3) | 0.998 | 1.005 | 1.003 | 1.011 |
| Thermal conductivity (W/m.K) | 0.600 | 0.66 | 0.610 | 0.6450 |
| viscosity (Pa.s) | 1.010 | 0.9102 | 1.240 | 1.1340 |

## Measurement device

The solar meter model TES132 is used to measure the intensity of incident radiation, as shown in Figure 8b. The PROVA 200A-Solar Module Analyzer instrument is used to measure the performance of the photovoltaic cell, as shown in Figure 8b. The temperature recording device model BTM-420SD with 12-channels, is used It contains a secure data card (SD) to save the reading of the temperature over time. Three Rota meters, model ZYIA, with a range of 0.5–4 L/min are used to measure the flow rate of cooling water and Nano fluid. These flow meters are vertically installed with a regulating valve to control the required flow rate according to the experimental procedure, as shown in Figure 8b.

## Uncertainty

Error analysis examines measurement uncertainty. Error is the difference between measured and true values. The error is unknown since the true value is rarely known. The error is within a plus or minus range around the stated reading, according to the available information. Uncertainty is needed to determine if the results are sufficient and consistent with other similar results. Most measurements have many errors. Error propagation is combining errors. Eq. (2) estimates independent measurement uncertainty (Guarracino 2017).

$$U_R = \sqrt{(U_1)^2 + (u_2)^2 + \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(U_n)^2} \tag{2}$$

If the experimental result R represents a function of the independent variables x1, x2, x3. . ., xn, thus $R$ = f (x1, x2, x3. . ., x). The root-sum squares (RSS) approximation is a good estimate of the cumulative

Table 3. Accuracy, range, and resolution of measuring instruments.

| Instruments | Measurement | Resolution | Range | Accuracy |
|---|---|---|---|---|
| Thermometer type Lutron BTM-08SD | Temperature | 0.1°C | −50–999.9 °C | ∓ (0.4% +0.5) °C |
| Thermo-Anemometer | Air speed | 0.1 m/s | 0.2–20 m/s | ∓ (3%) m/s |
|  | Temperature | 0.1 °C | 0–50 °C | ∓ (0.2% +0.5) °C |
| Solar Module Analyzer type PROVA 200A. | Voltage | 0.01V | 10–60 V | ∓ (1%) V |
|  | Current | 0.001 A | 1–6 A | ∓ (1%) A |
| Solar Meter type TES 132 | Solar radiation | 0.1 W/m$^2$ | 0–2000 W/m$^2$ | ∓ (5%) W/m$^2$ ∓ 0.38 at 25 °C |
| Thermocouples k | Temperature | ................ | −50–999.9 °C | ∓ 0.25 °C |

effect of these errors. The uncertainty in the results (uR) can be written as Eq. (3), where u1, u2… to un are the uncertainties of independent variables (Guarracino 2017).

$$U_R = \sqrt{\left(\frac{\partial R}{\partial x_1} U_1\right)^2 + \left(\frac{\partial R}{\partial x_2} U_2\right)^2 + \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \left(\frac{\partial R}{\partial x_n} U_n\right)^2} \tag{3}$$

The accuracy of the instruments has a direct effect on the results of the experiments. The accuracy, range, and resolution of measuring instruments that are used in this study are shown in Table 3.

## Important definitions

During the experiments, electrical and thermal efficiencies, as well as combined efficiency, were calculated by the following equations (Othman et al. 2016):

$$(\eta_{el}) = \eta_r(1 - \beta(T_{pm} - T_r) \tag{4}$$

**Where** : $\eta_{el}$ :is the electrical efficiency, $\eta_r$ :is the reference efficiency of the PV module,($\eta_r = 0.14$ @ STC), β: is the temperature coefficient ($0.0045^{-1}$), $T_{pm}$ :is the temperature of the solar cells (°C), and $T_r$ :is the reference temperature.

Then,

$$Thermal\,Efficiency,\ (\eta_{th}) = \frac{\overset{\circ}{Q}_U}{GA_{PVT}} \tag{5}$$

The useful collected heat ($Q_U$) from water in the context of temperature increase can be expressed as:

$$Q_U = \overset{\circ}{m}\, c_p(T_{f,out} - T_{f,in}) \tag{6}$$

Also,

$$Combined\,efficiency,\ (\eta_{COmbined}) = \eta_{th} + \eta_{ele} \tag{7}$$

## Results and discussions

In this part, the experimental results will be discussed, which will be divided into two parts: in the first part, the results of cooling the photovoltaic cell using water are discussed, and in the second part, using Nano fluids, three different Nano fluids will be used and compared with the first part.

### PVC with water

Figure 9a shows the influence of changing the mass flow on the value of the highest capacity produced by the photovoltaic cell when the intensity of solar radiation was 750 W/m$^2$. Through the figure, a comparison was made between three different cross sections of the

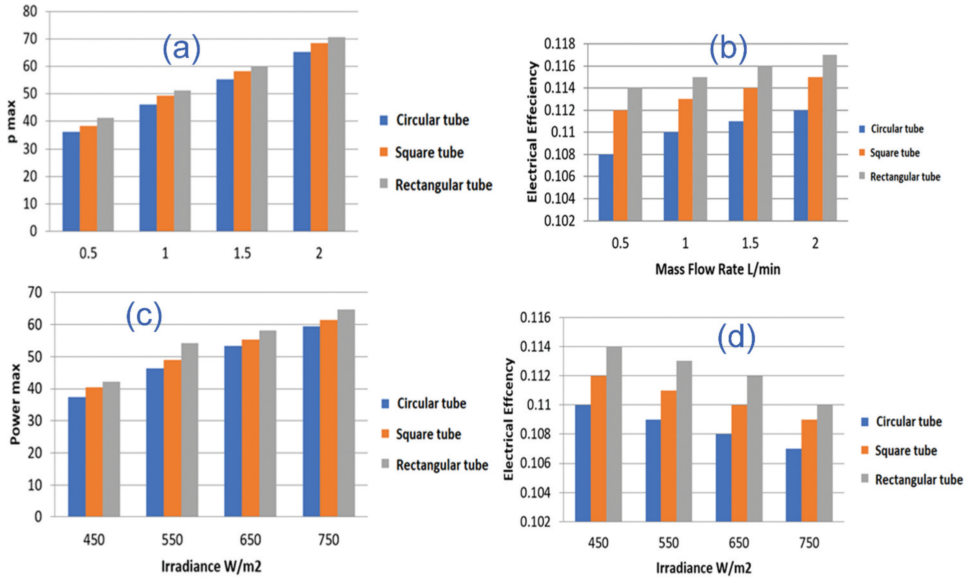

**Figure 9.** Influence of Flow Rate for Different Cross Section at Solar Intensity 750 W/m$^2$ on, (a) Maximum Power, and (b) Electrical efficiency; Influence of Solar Irradiance or Different cross Section at Flow Rate 2 L/min on (c) Maximum Power, and (d) Electrical efficiency.

three different cooling tubes (rectangular, square, and circular). It can be reported that the capacity boosts with an increase in the amount of mass flow, and this is due to the increase in the heat drawn by the water when the flow increases. Since the cross-sections are different, the amount of heat withdrawn was different as a result of the different surface areas of each of them. Therefore, we note that the highest value of the capacity reached 72.107 W at the highest value of the flow of 2 L/min (Ebaid, Al-Busoul, and Ghrair 2020). Results also indicate that the capacity produced by the photovoltaic cells generated by the three types of tubes under consideration increases with the flow rates due to better cooling of the PV module. Besides, the rectangular cross-section tubes achieved the highest capacity produced by the photovoltaic cells compared to round tubes and square tubes, due to the rise of the heat transfer surface. This can be attributed to a higher heat transfer rate at the rectangular tube, which means better electrical performance (power and efficiency) of PV cells. Figure 9b shows the influence of the flow on the value of electrical efficiency, since the increase in the flux will reduce the temperature of the cell. Besides, it was detected that the electrical efficiency increased by 2.67%, 2.60%, and 1.85% for the rectangular, square, and circular sections, respectively, when the flow rate was increased from 0.5 to 2 L/min. So, it can be concluded that the rectangular section gave the best results for electrical efficiency because, for the rectangular section, the surface area in contact with the cell is greater than the rest of the sections, so there will be a greater heat transfer, which leads to faster cooling of the cell (Ebaid, Al-Busoul, and Ghrair 2020). Figure 9c displays the influence of solar radiation on the value of the highest output power from the photovoltaic cell. As the power increases with increasing solar radiation, the power increased from 41.29 W to 70.63 W for the rectangular section. Figure 9d displays the impact of the intensity of solar radiation on the electrical efficiency of the PV cell. When the radiation intensity increases from 450 W/m$^2$ to 750 W/m$^2$ for the rectangular section, this is due to the increase in temperature when the solar radiation increases. Therefore, the electrical efficiency decreases despite the increase in production capacity. Figure 10 illustrations the influence of the mass flow rate on the thermal efficiency of the PV cell. When the mass flow

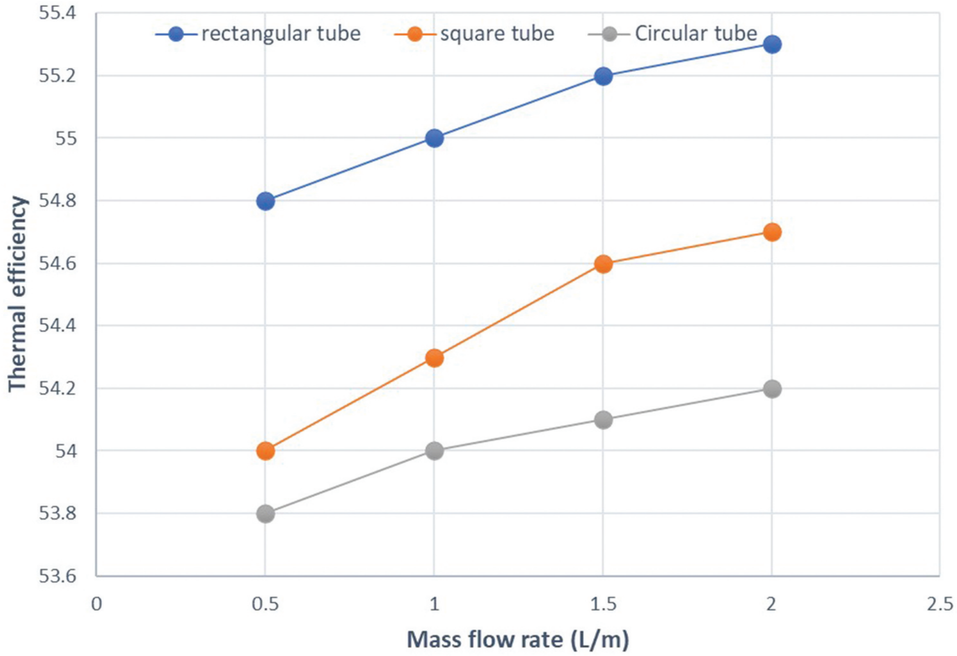

**Figure 10.** Influence of flow rate on Thermal efficiency for different cross section solar intensity 750 W/m$^2$.

rate increases from 0.5 L/min to 2 L/min for the rectangular section, thermal efficiency increases due to the decrease in temperature of the solar cell.

## PVC with nano fluid

Figure 11a exhibitions the influence of the intensity of solar radiation on the maximum power produced by a PVT cell that was cooled using nanofluids (0.1, 0.2, and 0.3 vol%). It can be seen when the radiation intensity is 450 W/m$^2$. CuO/nanofluids gave a power of 50 W, versus 47.6 W, 42.8 W, and 41 W for ZnO/nanofluids, $TiO_2$/nanofluids, and water, respectively. In some cases, the convergence between the results of CuO/nanofluids and ZnO/nanofluids can be observed, but in general, cooling using CuO/nanofluids gave the best electrical power due to the high thermal conductivity of CuO/nanofluids compared to others.

Figure 11b displays the difference in electrical efficiency for four different types of PVT cell cooling fluids, where it can be observed that the electrical efficiency augmented as a result of adding nanofluid compared to normal water, and the cell with CuO/nanofluids gave the highest value of electrical efficiency at 450 W/m$^2$, which is equal to 11.8%, while it is equal to 11.6%, 11.5%, and, 10.8% for ZnO/nanofluids, $TiO_2$ nanofluid, and, water, respectively. The decrease in the electrical efficiency can be observed as a result of the increase in the solar radiation, which is due to the rise in the temperature of the PV cell. As shown in Figure 11c, increasing the mass flow rate causes a growth in the heat transfer coefficient as well as an increase in the quantity of heat extracted from the back surface of the solar cell. For four different types of water-cooled PV, raising the mass flow rate increases the maximum power: CuO/nanofluids, ZnO/nanofluids, and $TiO_2$/nanofluids. When the mass flow rate increases from 0.5 to 2 L/min, the power increases from 77.45 W to 84.34 W for the cell cooled by CuO/nanofluids. This can be attributed to the fact that the effective thermal conductivity of CuO/nanofluids, thus resulting in a higher cooling effect on PV cells (i.e., lower surface temperature), which leads to an increase in the power and efficiency of

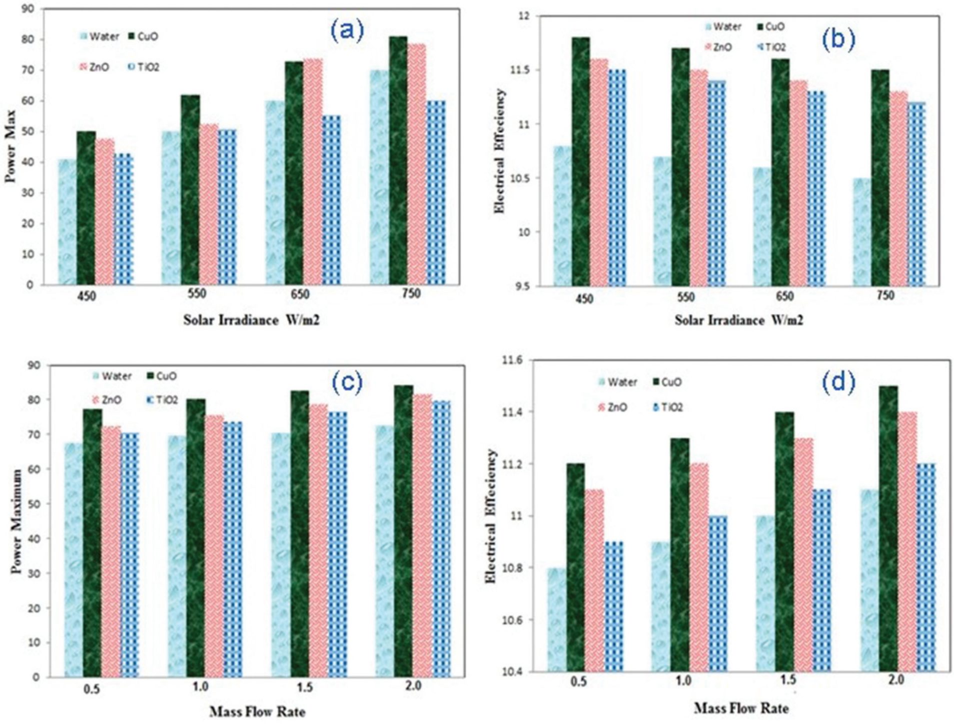

**Figure 11.** Influence of Solar Irradiance at Constant Mass Flow Rate for Rectangular Tube on (a) Maximum Power, and (b) Electrical Efficiency; Influence of Mass Flow Rate at Constant Solar Irradiance for Rectangular Tube (c) Maximum Power, and (d) Electrical Efficiency.

PV cells. Besides, by increasing the mass flow rate from 0.5 to 2 L/min, the electrical efficiency can be raised from 11.2% to 11.5% because the high mass flow rate will increase the heat transfer coefficients between the tube wall and flowing fluid, which will in turn decrease the PV module's temperature, as shown in Figure 11d.

Figure 12a depicts the influence of mass flow rate on PV cell temperature in order to compare the three distinct types of flow cross section areas used in this investigation. Where it can be seen that the flow, as previously described, reduces the temperature of the PV cell and that the rectangular portion gave the lowest temperature with a difference of 4 and 6 °C than the square and circular sections, respectively. This is due to the rectangular cross-lesser section's flow cross-sectional area when compared to other sections (Sangeetha et al. 2021). Figure 12b shows the influence of the mass flow on the electrical efficiency, where it can be observed that the electrical efficiency boosts with the growth in the mass flow due to a decrease in temperature. It can be seen that the square section gave the lowest electrical efficiency, and this is due to the larger cross-sectional area in the square section, and therefore the velocity is lower at the same amount of mass flow. However, this difference is not noticeable, as it can be noted that the highest difference in electrical efficiency is 0.78% between the circular and square section at 0.5 L/min. On the other hand, it can be shown that that the Rectangular tube [w = 25 mm, d = 15 mm] resulted in the highest efficiency compared to the Round tubes, due to the flat surface being in contact underneath the PV module [27].

Figure 13a illustrates the inverse relationship between the flow and the difference in temperatures between the inlet and outlet of the fluid. A decrease in the value of ΔT can be observed when the flow is increased for four different types of coolant fluids: water, CuO/nanofluids, ZnO/nanofluids, and $TiO_3$ /nanofluids, where ΔT decreased from 11.99 °C to 10.43°C when the flow was increased from 0.5 to 2

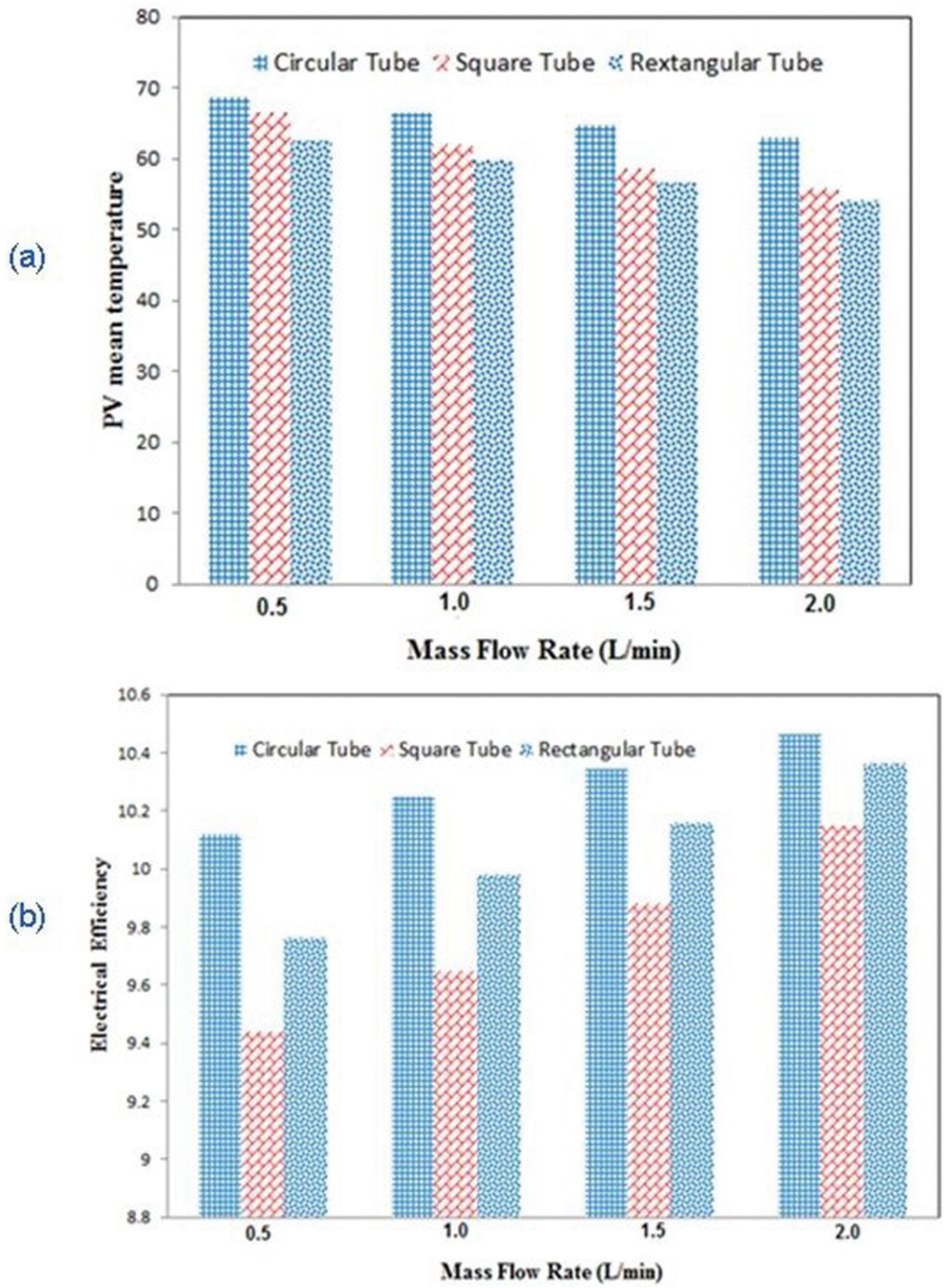

**Figure 12.** Influence of Mass Flow Rate at Constant Solar Irradiance for (Rectangular –Square – Circular) Tube on (a) Collector Temperature, and (b) Electrical Efficiency.

L/min of CuO/nanofluids due to Increment in water mass flow rate will result in more and more water entering the tubing to remove heat, which simultaneously reduces the PVT module's temperature. It can be seen that the CuO/nanofluids gave the highest temperature difference, followed, to a lesser degree, by ZnO/nanofluids, $TiO_2$/nanofluids, and then normal water due to Cuo nanofluid showed the best heat transfer rate, followed by $TiO_2$ and Zno (Ebaid, Ghrair, and Al-Busoul 2018). Figure 13b

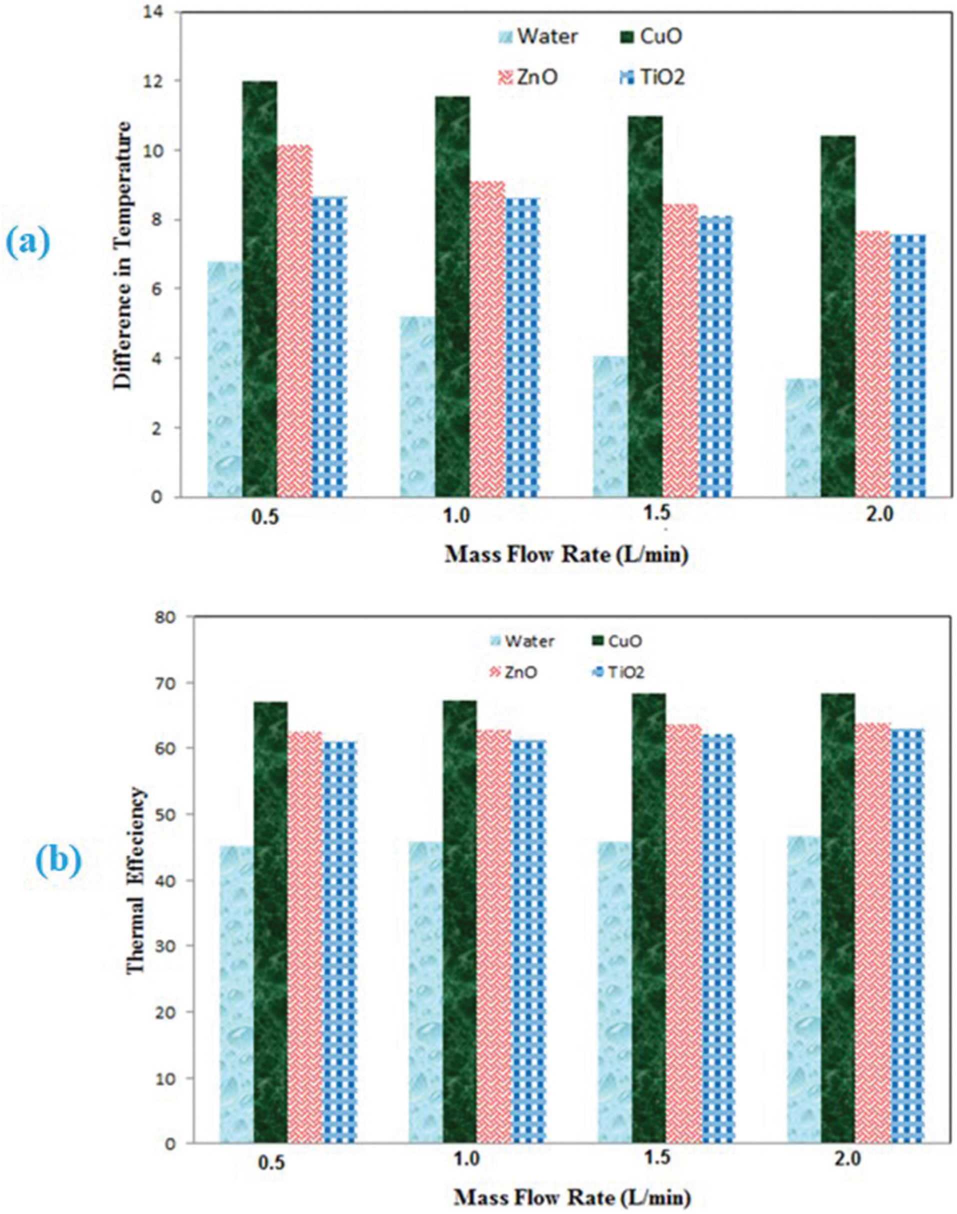

**Figure 13.** Influence of Mass Flow Rate of Rectangular Tube at Constant Solar Irradiance for water and Nano fluid on (a) Difference in Temperature, and (b) Thermal Efficiency.

depicts the change in thermal efficiency as the flow rate increases, revealing that there is a positive relationship between them and that the CuO/nanofluids provided the maximum thermal efficiency, reaching 68.43% at a flow rate of 2 L/min, while water provided 46.72% at the same flow rate. Based on the results, utilizing CuO/nanofluids increases thermal efficiency by roughly 46% when compared to using regular water due to the use of nanoparticles enhances the thermal conductivity, leading to an increase in the heat transfer coefficients (Choudhary, Sachdeva, and Kumar 2020).

Using the nanofluid, in general, increases the electrical power and electrical efficiency, as shown in Figure 14a,b where it is possible to choose the best used fluid with the best used

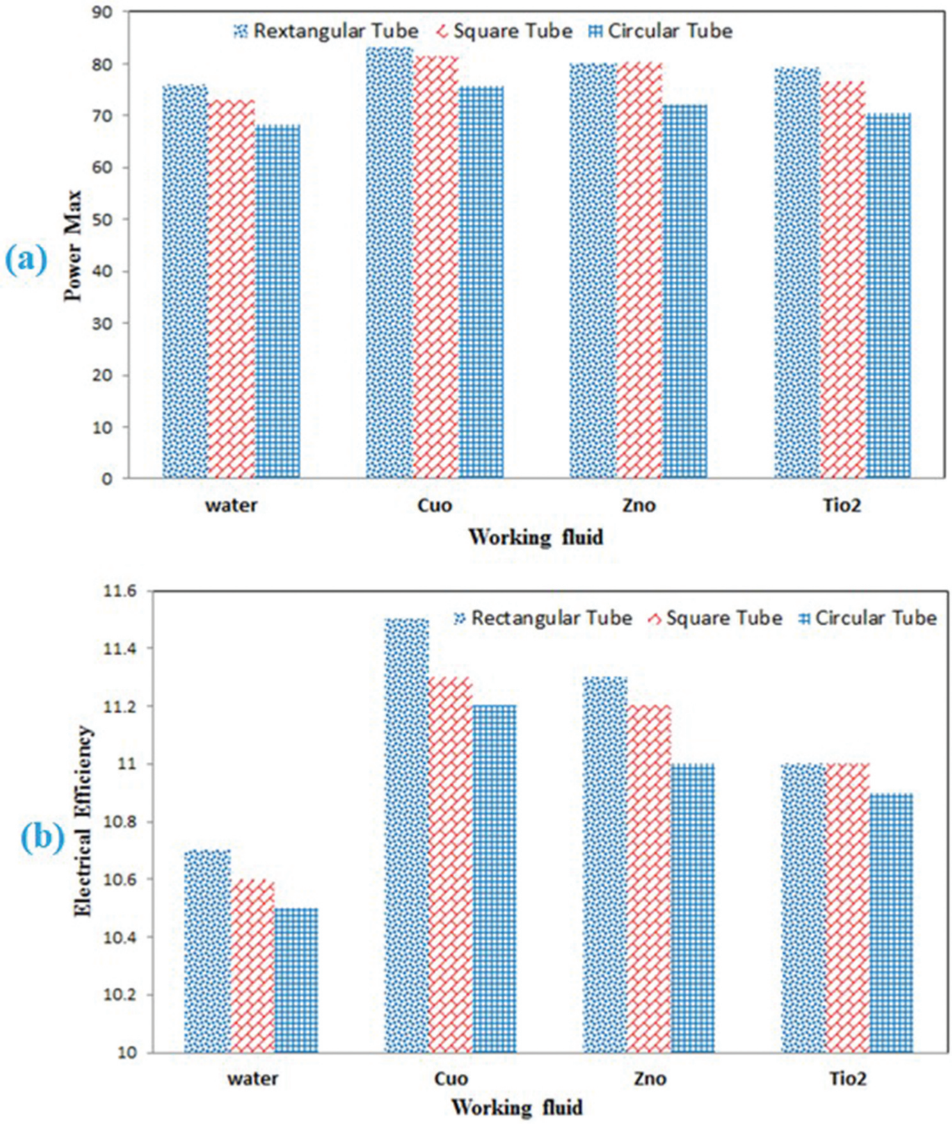

**Figure 14.** Influence of Nano fluid at Constant Solar Irradiance for (Rectangular –Square – Circular) Tubes on (a) Maximum Power, and (b) Electrical Efficiency.

cross-sectional area. It can be noted that the rectangular section and the CuO/nanofluids gave the best value for the electrical power reached at 83.17 W and, to a lesser extent, the CuO/nanofluids in the rectangular section. It is possible to choose the nanofluid and the appropriate shape depending on the value of the electrical efficiency (see Figure 25). Besides, it can be noted that the CuO/nanofluids in the rectangular section gave the highest efficiency that reached 11.5%. Figure 15 shows the effect of different volume fractions of nanofluid (0.1, 0.2, and 0.3 vol %) on Electrical efficiency at 2 L/min and 750 w/m$^2$. It is noticed that the growth in the volume fraction of Nano fluid leads to an augment in electrical efficiency due to the decrease in the temperature of the photovoltaic cell and the use of nanoparticles enhances the thermal conductivity, leading to an increase in the heat transfer coefficients.

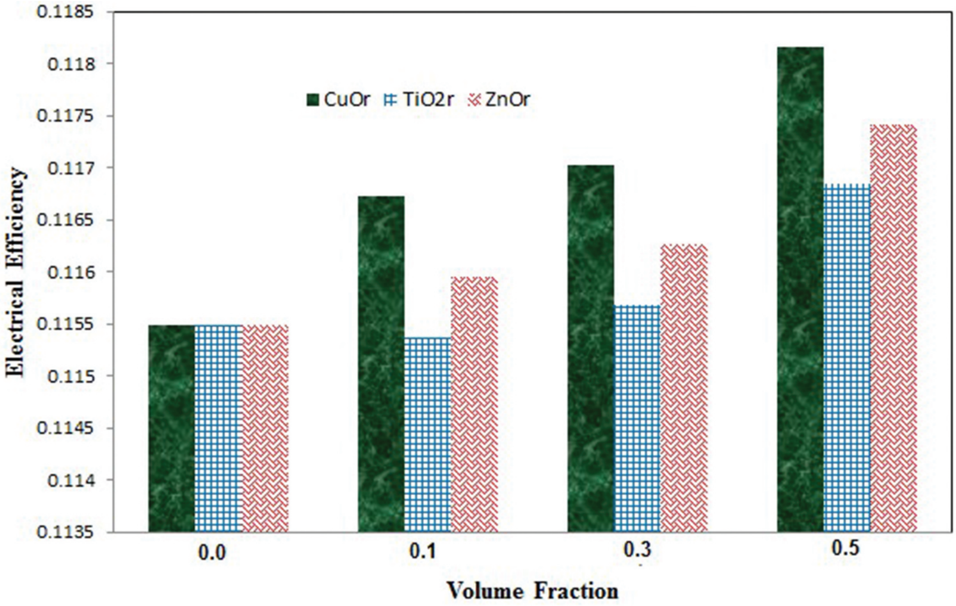

**Figure 15.** Influence of Different Volume Fraction of Nanofluid on Electrical Efficiency at (2L/min), (750 w/m$^2$).

## Conclusion

During this experimental study, three types of nanoparticles (CuO, ZnO, and $TiO_2$) were used and mixed in three different volume fractions (0.1, 0.2, and 0.3 vol %) with water. The resulting nanofluid was then used to cool the photovoltaic cell by passing the fluid through a copper tube placed on the back of the PVT. Moreover, three different flow sections were compared to find the best one. They are square, rectangular, and circular. Through this study, the following can be concluded:

(1) The nanofluids enhanced the electrical and thermal PVT efficiency compared to a water-based fluid. CuO nanofluid showed the best heat transfer rate, followed by ZnO and $TiO_2$. This phenomenon can be attributed to the fact that the thermo-physical properties of CuO-water were higher compared to the thermo-physical properties of the other nanofluids and pure water.

(2) It was observed that by combining the thermal and electrical aspects of solar panels, the electrical output increased due to the circulating nanofluids via the collector, decreasing the overall PV module temperatures.

(3) The used of rectangular tube resulted in higher electrical and thermal efficiency compared to round tubes and square tubes, due to the rise of the heat transfer surface. Where the electrical efficiency for rectangular, square, and circular tubes with water as the base fluid is 0.117, 0.115, and 0.112, increasing by about 5%. Also, the thermal efficiency of rectangular, square, and circular tubes filled with water (0.553, 0.545, and 0.542) increased by about 9%. So, the combination efficiencies for rectangular, square, and circular tubes with nanofluid are 0.67, 0.66, and 0.654, respectively.

(4) Overall, it was found that the rectangular tube [w = 25 mm, d = 15 mm] resulted in the highest efficiency compared to other ones, which is due to a higher decrease in the PV temperature.

(5) The high mass flow rate will increase the heat transfer coefficients between the tube wall and flowing fluid, which will in turn decrease the PV module's temperature.

(6) In the future, researchers may be able to mix different types of nanofluid to test hybrid nanofluids with the same shapes as copper tubes to improve the process of absorbing heat from the surface of a solar cell and get better results.

## Nomenclature

| | |
|---|---|
| Ac | Area of collector ($m^2$) |
| $C_p$ | Specific heat capacity of fluid (J/Kg. ℃) |
| G | Solar radiation ($W/m^2$) |
| Q | Heat transfer rate (J/s) |
| $T_a$ | Temperature of standard condition (25°C) |
| $T_i$ | Inlet temperatures of fluid in PVT (℃) |
| $T_o$ | Outlet temperatures of fluid In PVT (℃) |
| PVT | Photovoltaic thermal |
| β | Temperature coefficient of silicon cell ($\beta = 0.0045°C$) |
| Ø | Nanoparticles volume fraction |
| $\eta_{PVT}$ | Efficiency of solar collector |
| $\mu_{nf}$ | Nano fluid viscosity (kg/m. s). |
| $\mu_w$ | Water viscosity (kg/m. s). |
| $\rho_f$ | Density of the base fluid ($kg/m^3$). |
| $\rho_{nf}$ | Density of the Nanofluid ($kg/m^3$). |

## List of symbols

| | |
|---|---|
| Ac | Function of the collector area (m2) |
| Cb | Conductance of the bond between the fin and tube |
| Cp | Specific heat of the collector cooling medium (J/kg K) |
| Dh | Hydraulic diameter |
| EAC | AC energy output at time *t*(min), *h*(hour), *d*(day), *m*(month) |
| EDC,d | Daily net DC energy output (kWh/d) |
| F | Fin efficiency factor |
| $F^{-}$ | Corrected fin efficiency |
| $F_R$ | Heat removal efficiency factor |
| I(t) | Solar irradiance ($w/m^2$) |
| $h_{fi}$ | Heat transfer coefficient of fluid (W/m2 K) |
| $H_t$ | Plane-of-Array (POA), solar irradiation ($kwh/m^2$) |
| $K_{abs}$ | Absorber thermal conductivity |
| $K_{pv}$ | Photovoltaic module conductivity |
| $L_{abc}$ | Absorber thickness |
| LPV | Photovoltaic module thickness |
| m• | Mass flow rate (kg/s) |
| $P_{PV}$,rated | PV array rated power (kw) |
| $Q_u$ | Actual useful heat gain (W) |
| S | Absorbed solar energy (W) |
| $T_p$ | Photovoltaic collector temperature ($C^{o}$) |
| $T_a$ | Ambient temperature ($C^{o}$) |

## Disclosure statement

No potential conflict of interest was reported by the authors.

## Notes on contributor

*Ebrahim Hajidavalloo* is Professor of Mechanical Engineering, Department of Engineering, Shahid Chamran University. Dr. Hajidavaloo's research covers a wide range of topics in heat transfer thermodynamics, multiphase flow, advanced numerical methods, thermal power plants, refrigeration, fluid mechanics, and convection.

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## References

Ajeel, R. K., W. I. Salim, and K. Hasnan. 2019. Design characteristics of symmetrical semicircle-corrugated channel on heat transfer enhancement with nanofluid. *International Journal of Mechanical Sciences* 151:236–50. doi:10.1016/j.ijmecsci.2018.11.022.

Ajeel, R. K., W. I. Salim, K. Sopian, M. Z. Yusoff, K. Hasnan, A. Ibrahim, and A. H. Al-Waeli. 2019. Turbulent convective heat transfer of silica oxide nanofluid through corrugated channels: an experimental and numerical study. *International Journal of Heat and Mass Transfer* 145:118806. doi:10.1016/j.ijheatmasstransfer.2019.118806.

Ajeel, R. K., K. Sopian, and R. Zulkifli. 2021. Thermal-hydraulic performance and design parameters in a curved-corrugated channel with L-shaped baffles and nanofluid. *Journal of Energy Storage* 34:101996. doi:10.1016/j.est.2020.101996.

Arıkan, E., S. Abbasoğlu, and M. Gazi. 2018. Experimental performance analysis of flat plate solar collectors using different nanofluids. *Sustainability* 10 (6):1794. doi:10.3390/su10061794.

Bellos, E., and C. Tzivanidis. 2020. Yearly performance of a hybrid PV operating with nanofluid (vol 133, pg 867, 2017). *Renewable Energy* 155:1444–1444. doi:10.1016/j.renene.2019.12.028.

Choudhary, S., A. Sachdeva, and P. Kumar. 2020. Influence of stable zinc oxide nanofluid on thermal characteristics of flat plate solar collector. *Renewable Energy* 152:1160–70. doi:10.1016/j.renene.2020.01.142.

Ebaid, M. S., M. Al-Busoul, and A. M. Ghrair. 2020. Performance enhancement of photovoltaic panels using two types of nanofluids. *Heat Transfer* 49 (5):2789–812. doi:10.1002/htj.21745.

Ebaid, M. S., A. M. Ghrair, and M. Al-Busoul. 2018. Experimental investigation of cooling photovoltaic (PV) panels using (TiO2) nanofluid in water-polyethylene glycol mixture and (Al2o3) nanofluid in water-cetyltrimethylammonium bromide mixture. *Energy Conversion and Management* 155:324–43. doi:10.1016/j.enconman.2017.10.074.

Guarracino, I. 2017. Hybrid photovoltaic and solar thermal (PVT) systems for solar combined heat and power.

Henein, S. M., and A. A. Abdel-Rehim. 2022. The performance response of a heat pipe evacuated tube solar collector using MgO/MWCNT hybrid nanofluid as a working fluid. *Case Studies in Thermal Engineering* 33:101957. doi:10.1016/j.csite.2022.101957.

Henein, S. M., A. A. Abdel-Rehim, and K. El-Nagar. 2023. Energy, economic and environmental analysis of an evacuated tube solar collector using hybrid nanofluid. *Applied Thermal Engineering* 219:119671. doi:10.1016/j.applthermaleng.2022.119671.

Hussain, M. I., G. H. Lee, and J. T. Kim. 2021. A comprehensive performance characterization of a nanofluid-powered dual-fluid pv/t system under outdoor steady state conditions. *Sustainability* 13 (23):13134. doi:10.3390/su132313134.

Kazemian, A., A. Salari, T. Ma, and H. Lu. 2022. Application of hybrid nanofluids in a novel combined photovoltaic/thermal and solar collector system. *Solar Energy* 239:102–16. doi:10.1016/j.solener.2022.04.016.

Khanjari, Y., F. Pourfayaz, and A. B. Kasaeian. 2016. Numerical investigation on using of nanofluid in a water-cooled photovoltaic thermal system. *Energy Conversion and Management* 122:263–78. doi:10.1016/j.enconman.2016.05.083.

Lari, M. O., and A. Z. Sahin. 2017. Design, performance and economic analysis of a nanofluid-based photovoltaic/thermal system for residential applications. *Energy Conversion and Management* 149:467–84. doi:10.1016/j.enconman.2017.07.045.

Lee, J. H., S. G. Hwang, and G. H. Lee. 2019. Efficiency improvement of a photovoltaic thermal (PVT) system using nanofluids. *Energies* 12 (16):3063. doi:10.3390/en12163063.

Mahmood Alsalame, H. A., J. H. Lee, and G. H. Lee. 2021. Performance evaluation of a Photovoltaic Thermal (PVT) system using nanofluids. *Energies* 14 (2):301. doi:10.3390/en14020301.

Menon, G. S., S. Murali, J. Elias, D. A. Delfiya, P. V. Alfiya, and M. P. Samuel. 2022. Experimental investigations on unglazed photovoltaic-thermal (PVT) system using water and nanofluid cooling medium. *Renewable Energy* 188:986–96. doi:10.1016/j.renene.2022.02.080.

Michael, J. J., and S. Iniyan. 2015. Performance analysis of a copper sheet laminated photovoltaic thermal collector using copper oxide–water nanofluid. *Solar Energy* 119:439–51. doi:10.1016/j.solener.2015.06.028.

Mohammed Hussein, H. A., R. Zulkifli, W. M. F. B. W. Mahmood, and R. K. Ajeel. 2022. Structure parameters and designs and their impact on performance of different heat exchangers: A review. *Renewable and Sustainable Energy Reviews* 154:111842. doi:10.1016/j.rser.2021.111842.

Mustafa, W., M. Y. Othman, and A. Fudholi. 2017. Numerical investigation for performance study of photovoltaic thermal nanofluids system. *International Journal of Applied Engineering Research* 12 (24):14596–602.

Naghdbishi, A., M. E. Yazdi, and G. Akbari. 2020. Experimental investigation of the effect of multi-wall carbon nanotube–water/glycol based nanofluids on a PVT system integrated with PCM-covered collector. *Applied Thermal Engineering* 178:115556. doi:10.1016/j.applthermaleng.2020.115556.

Othman, M. Y., S. A. Hamid, M. A. S. Tabook, K. Sopian, M. H. Roslan, and Z. Ibarahim. 2016. Performance analysis of PV/T Combi with water and air heating system: an experimental study. *Renewable Energy* 86:716–22. doi:10.1016/j.renene.2015.08.061.

Rajaee, F., A. Kasaeian, M. A. V. Rad, and K. Aliyon. 2021. Energetic and exergetic evaluation of a photovoltaic thermal module cooled by hybrid nanofluids in the microchannel. *Solar Energy Advances* 1:100005. doi:10.1016/j.seja.2021.100005.

Rawat, P., and K. Sudhakar. 2016. Performance analysis of partially covered photovoltaic thermal (PVT) water collector. *International Journal of Research in Engineering and Technology* 5 (1):15–20. doi:10.15623/ijret.2016.0501003.

Sangeetha, M., S. Manigandan, B. Ashok, K. Brindhadevi, and A. Pugazhendhi. 2021. Experimental investigation of nanofluid based photovoltaic thermal (PV/T) system for superior electrical efficiency and hydrogen production. *Fuel* 286:119422. doi:10.1016/j.fuel.2020.119422.

Sultan, S. M., & C. P. Tso (2018, November). A thermal performance study for different glazed water based photovoltaic thermal collectors. In *AIP Conference Proceedings*, Ho Chi Minh, Vietnam (Vol. 2030, No. 1, p. 020307). AIP Publishing LLC.