

Advances in Nano-Materials Used in Photovoltaic/Thermal Systems



Ali H. A. Al-Waeli and Hussein A. Kazem

Abstract The key step for using nanoparticles for heat transfer applications is to prepare nanofluids, either through the one-step or two-step method. Among applications of nanofluids in heat transfer are to use them as working fluid for hybrid photovoltaic thermal (PV/T) systems. PV/T systems combine photovoltaic modules and solar thermal collectors to produce hot water and electricity simultaneously. This chapter presents classifications of PV/T systems, principles, and performance. Moreover, detailed introduction to nano-material is used for PV/T systems and related parameters such as volume fraction (%) and mass flow rate. Furthermore, the chapter provides a case study of three different PV/T systems which are nanofluid and nano-phase change material (nano-PCM)-based PV/T, a water-based PV/T with a PCM tank, and water-based PV/T with water tank. The findings show an overall improvement in thermo-physical properties as nanoparticles are added to base fluid (water) and phase change material (PCM). Moreover, the highest performance is attributed to the nanofluid and nano-PCM-based PV/T system.

Keywords Nanofluid · Nano-SiC · Nano-PCM · PV/T · Collectors

1 Introduction

Human population growth is expected to peak at around 9 billion in 2050, according to the predictions of the United Nations' population division [1]. With this continuous rise in the population, so does the energy demand. This is because energy is simple a proactive agent in raising the standard of living and prompting change in the social conditions as well [2]. World energy use is projected to increase from its current value

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of 9000 million tonnes of oil equivalent to around 21,000 Mtoe/a as the population increase from 6 to 12 billion people in the twenty-second century.

Energy sources such as coal, oil, and gas or also known collectively as fossil fuels take up around 80% of global energy sources [3]. The remaining are renewable energy sources, except for uranium. The mass production and consumption of fossil fuels by human activity were known as contributor to climate change, making it a concern, as well as the depletion of fossil fuels [4]. On the other hand, renewable energy exhibits favorable characteristics as energy resources. Hence, many countries have shifted their energy policy to adopt renewable energy technologies investment and utilization for industrial, commercial, and residential purposes. Among these countries are China, the EU, and the USA.

Among renewable energy technologies is the solar cell, or photovoltaic (PV), which is the most commonly implemented by residential users. This is attributed to its relatively cheap cost, low weight, and zero noise during operation. The projected solar (PV) capacity growth from 2017 to 2022 is around 438 GW [5].

Photovoltaics are semiconductor devices that convert the sunlight into electricity by utilization of sunlight photon energy. Solar cells, PV, are made of different semiconductors including silicon such as CdS/CdTe and CIGS. PV does not utilize the infrared part of the solar spectrum; hence, the PV cell temperature increases across time of operation. Internal losses due to manufacturing and heat gained through surrounding environment lead to an increase in the cell temperature which results in a reduction in the open-circuit voltage. This means the electric power produced by this device will decrease as a result of the device heating up. Hence, every increase of 10 °C causes a decrease in PV efficiency of around 5% [6]. This is particularly the issue in hot climate and high solar irradiance areas. Moreover, this leads to shortening the lifetime of the device. Hence, several researchers and scientists have recommended the removal of the heat from the device using cooling fluids. This would involve a channel to carry a fluid which removes the temperature from the solar cell and utilize it in other applications. This design is known as photovoltaic/thermal (PV/T) hybrid collector. The heating of fluids is the function of the solar thermal collector. Hence, PV/T is essentially composed of a photovoltaic module and a solar thermal collector, attached for heat transfer purposes. The PV module will then be cooled, while fluid within the thermal collector will be heated. The type of fluid that runs through a PV/T collector is a critical factor. Given that, different fluids have different thermo-physical properties. PV/T collectors are usually classified depending on the type of base fluid [7]. Figure 1 shows the classifications of PV/T collectors.

According to Fig. 1, the types of PV/T include air-based, water-based, combi (air and water), phase change material (PCM)-based. The classifications are determined either with the number of passes within the collector, shape of pipe, type of concentrator or reflector used to maximize efficiency and working fluid.

The air-based design is considered the cheapest because of the simplicity of the system. Moreover, the use of air instead of a liquid leads to eliminate the risk of freezing, boiling, and damage (due to leak). On the other hand, the thermal performance of this type of collector is considered the lowest. This is because of its low

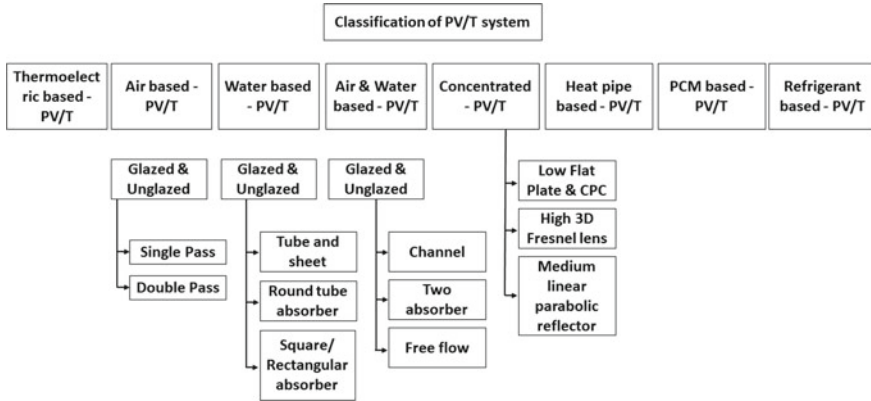


Fig. 1 Classifications of photovoltaic thermal (PV/T) collector

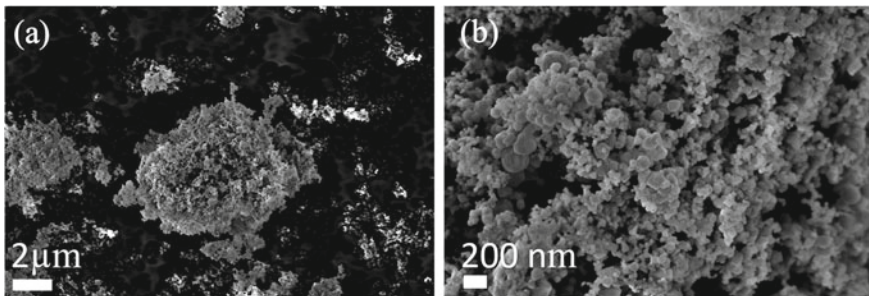


Fig. 2 a SiC image at 2 μm, b SiC image at 200 nm

heat capacity, which leads to a low heat transfer. On the other hand, water has better thermal capacity and hence better heat transfer. While water-based PV/T does exhibit better thermal performance, it is more expensive and with more risks. Water-type is most suitable for hot-water demand. Water circulates through the pipes and is supplied to the user [8]. Bi-fluid design which combines water and air is useful for cooling PV module and extracting heat. The design could be made to be thermally biased or electrically biased, depending on the consumer’s needs, and/or limitations. Different refrigerants could be used for the system, e.g. R134a, such as those employed for heat pump cycles. Heat pipes on the other hand use different base fluids according to the wall and wick of the heat pipe, which are designed to operate for longer periods and minimal maintenance.

Because of the effect of base fluid thermo-physical properties on heat transfer, nanofluid was introduced as a base fluid for PV/T collectors. Nanofluids are mixtures of base fluids and nano-material.

This chapter introduces nano-material’s used in PV/T collectors and provides the description of the advances of these nano-materials and PV/T collectors, mixing

process to produce nanofluids and their effect on thermal and electrical efficiencies of PV/T. Along with referenced works in the literature, actual experiments are carried out by the authors of this chapter to examine different types of nanofluids.

2 PV/T Principle and Performance

Photovoltaic component of PV/T produces electricity, while solar thermal component provides the function of cooling the PV and heating up the working fluid. Each device has an efficiency based on its output. Efficiency is a great indicator of the system's functionality and performance.

The PV efficiency is simply the ratio of its output electric energy to input solar energy. Equation (1) illustrates the electrical efficiency of PV cell [9]:

$$\eta_{el} = \frac{P_{max}}{A_c \times G} \quad (1)$$

where P_{max} is the maximum electrical power, A_c is the collector area, and G is the solar irradiance (W/m^2). On the other hand, the thermal efficiency of solar thermal collector is given in Eq. (2) [10].

$$\eta_{th} = \frac{Q_u}{A_c \times G} \quad (2)$$

where Q_u is the heat gain of solar collector.

The efficiency for a whole day can be calculated by integration of the solar irradiance and output power (both for electrical and thermal). As the hybrid PV/T combines both components, the efficiency of PV/T is given in Eq. 3 [11].

$$\eta_{tot} = \eta_{th} + \eta_{el} \quad (3)$$

where η_{tot} is the total efficiency of PV/T. The energy-saving efficiency offers a more accurate description of how much energy is actually produced by dividing electrical efficiency by the efficiency of the electric power generation of a conventional power plant. The power generation efficiency is usually taken as 40%.

The performance of the PV/T is affected by multiple factors including solar irradiance, ambient temperature, climate conditions, type of working fluid, mass flow rate of working fluid, and type of thermal collector material. Majority of these factors are displayed by the literature provided.

Shahsavari and Ameri [12] used air-based direct-coupled PV/T collector to investigate the effect of a thin aluminum sheet suspended at the middle of air channel. This sheet was employed to increase the heat transfer surface. The system was tested experimentally and validated with a theoretical model. Moreover, the system was tested for natural and forced convection. For the forced, various fans operating in the

model were used. The study concludes that there are an optimum number of fans to achieve maximum electrical efficiency and that increase in mass flow rate leads to better heat transfer. Finally, authors confirm that glazed PV/T has higher efficiency than unglazed. These findings are important for understanding the effect of mass flow rate, glazing, and heat transfer area has on PV/T performance.

Sopian et al. [13] performed a comparative study between double- and single-pass PV/T collectors. The study concludes that double pass exhibits higher efficiency than single. Moreover, the study affirms that increase of mass flow rate, up to a level, leads to electricity efficiency enhancement. Beyond the appropriate mass flow rate, the efficiency will in fact decline. Aside from mass flow rate, number of fluid channels has a significant effect on collector performance. Chow [14] also investigated the effect of PV/T parameters on its performance, e.g. flow rate. The investigation was carried out using an explicit dynamic model which allows for performance analysis. Chow believes that PV/T is dynamic, and that steady-state models are not favorable. Main concern for the authors is inability of steady-state model to predict PV working temperature, and heat-removal during fluctuations in irradiance and/or fluid flow.

PV/T is heavily influenced by its design. Certain design modifications could lead to higher heat transfer and hence overall total efficiency. Kumar and Rosen [15] added fins, vertical extension surfaces, to thermal collector of a double-pass PV/T system. Design, climate, and operation parameters were taken into consideration, as they have direct impact on device efficiency. Significant reduction in PV cell temperature, attributed to the addition of fins, was observed with around 16 °C drop. The design aspect is also investigated by Zondag et al. [16] where different designs were compared in terms of performance. Massive heat losses are observed for uncovered sheet and tube collector which caused the poorest performance among collectors. Fall of electrical efficiency of a sheet and tube with two covers, due to further reflection at the second cover. Authors state the importance of calculating optical efficiency as well as thermal. Hence, reducing heat losses to surroundings could be attributed to glass covers, but also reduction of energy absorption, by reflection, which is explained by Sandnes and Rekstad [17] as well. Authors see a 10% reduction in energy absorption, which is significant.

The configuration of the PV/T plays a role as well. It is important to do more research in that area. Dubey and Tiwari [18] analyzed water-based PV/T connected in series, using theoretical and analytical methods. They utilized energy balance equations to develop the analytical expression of N number of collectors. Changing the number of collectors connected in series and viewing its effect on exergy and also analyzing electrical and thermal energy, for five different cities in India. The electrical efficiency of four PV/T collectors connected in series was found to be higher than 10 connected in series.

A steady-state conditions model was used by Dupeyrat et al. [19] to study thermal and electrical performance of several glazed, water-based PV/T flat plates. The single package lamination method was used for the experiments. The focus of the experiments was on heat transfer and optical performance. With regard to optical tools, linear Fresnel concentrators are also investigated in the literature. With this type

of collectors, along with a 2D axis tracking, Rosell et al. [20] achieved an overall combined efficiency above 60% when the ratio of the concentration was above 6.

The literature in PV/T collectors is vast, and there are numerous works on the subject. This is attributed to the different fields this technology is linked to, and the number of factors associated with PV and solar thermal collectors. Table 1 shows a summary of the aforementioned research studies to provide an impression of general research in the area. It is very important for research in this field to be limited in scope. Considering, every aspect of the collector would cause too many complications to the study. It is noteworthy to mention that Table 1 does not reflect on the research field of PV/T, nor it is used as a sample representation.

Table 1 shows the year, location, type of investigated PV/T, method of investigation, investigated parameters, and the achieved maximum efficiency (theoretical or measured). The general trend in this table is the use of both experimental and theoretical modeling. Almost every single research includes investigation into mass flow rate, which is a critical factor in thermal performance of this collector. The highest thermal efficiency is around 75%, while the highest electrical efficiency 16%. These two values are merely mentioned to give an impression of the electrical and thermal outer range. Overall, the water-based PV/T designs exhibit higher thermal efficiency and better thermal performance. Optical efficiency seems to be a recurrent topic of discussion and consideration. The discussed literature proves the importance of each aspect of PV/T in terms of design, operation, and weather conditions. As explained in the introduction, nanofluids have better thermo-physical properties than water [21–25]. Hence, it is very reasonable to employ nanofluids in PV/T collector to enhance the heat transfer process. The next section provides introduction to nano-material, in-depth analysis of their thermo-physical properties and application in PV/T cooling.

3 Nano-Materials Used for PV/T Cooling

Nano-materials are nano-sized particles with a diameter between 10 and 100 nm (nano-scale). The origin of the word nano is Nanos which is Greek for dwarf, which historically implies small size. Hence, nano is commonly used as an abbreviation of nanotechnology. Nanoparticles are a product of this technology and are used for many purposes and exist in different types. Among these types are metals, alloys, semiconductors, ceramics, glasses, polymers, and inorganic carbon-based material. These nanoparticles exhibit better properties due to its high surface area-to-volume ratio, compared to large particles. This means that nano-materials will be more chemically reactive [26].

The applications of nano-materials, of different types, are immense. The following are different applications of nano-materials for different industries.

1. Template material
2. Electronics
3. Solar cells

Table 1 Summary of studies on photovoltaic thermal collectors

Reference	Year	Location	Type of investigated PV/T	Method of investigation	Investigated parameter	Max. Efficiencies
Shahsavari and Ameri [12]	2010	Iran	Direct-coupled air type	Experimental, and modeling	Glazing, mass flow rate, natural and forced convection	Thermal: around 60% Electrical: Around 10%
Sopian et al. [13]	1996	Malaysia	Single and double-pass air-based PV/T	Theoretical modeling	Packing factors, mass flow rate, absorber length, pass	Highest by double pass Electrical: 7.5% Thermal: 33%
Chow [14]	2003	China	Water-based PV/T with tube pipes	Experimental and Numerical	Mass flow rate, solar irradiance	Thermal: 60% Electrical: 10%
Kumar and Rosen [15]	2011	Canada	Double pass, air-based PV/T with/without fins	Theoretical modeling	Inlet air temperature, mass flow rate, Solar irradiance, fins, packing factor, depth of air channel	Electrical: 16% Thermal: 64%
Zondag et al. [16]	2003	The Netherlands	Free flow, two-absorber, channel, tube and sheet, PV/T designs	Theoretical, refers to some experimental studies	Collector design type, covers, insulation, opaque/transparent PV	Electrical: 7.9% (Tube and sheet) Thermal: 39% two-absorber insulated
Sandnes and Rekstad [17]	2002	Norway	Water-based PV/T	Experimental, and analytical model	Collector configuration, inlet fluid temperature	Electrical: 13.4% Thermal: 70%
Dubey and Tiwari [18]	2009	India	Water-based PV/T flat plate	Theoretical	Number of collectors series connection, solar intensity, mass flow rate	Electrical: 10.7% Thermal: 62% For 4 collector in series
Dupeyrat et al. [19]	2011	Germany	Glazed, water-based PV/T flat plate	2D theoretical model and experiments	Packing factor, inlet fluid and ambient temperatures	Thermal: 75% Electrical: 10.9%
Rosell et al. [20]	2005	Spain	linear Fresnel concentrator with a channel PV/T collector	Experiments, and theoretical model	Fresnel concentration, mass flow rate	Thermal: 65.8% Electrical: 13.5%

4. Biological sensors
5. Gas sensing nanoprobes.

There are many more applications to different nanoparticles. Heat transfer is a very important application in industry.

Nanofluids are suitable for heat transfer processes. Nanofluids are nanoparticles mixed with a base fluid. The synthesis of these nanoparticles is classified into two methods which are physical and chemical. The most popular physical method is the inter-gas evaporation technique [27]. Other physical methods include sputtering technique and mechanical deformation. The chemical method of synthesis can be divided into two:

1. Thermal and ultrasound decomposition methods.
2. Reduction methods.

However, the main issue associated with the chemical method is the chemical homogeneity of the final product.

On the other hand, the base fluid to mix with the nanoparticles is also important. There are different types of base fluid's depending on the application, final product intended. Most common base fluids used are (1) water and (2) ethylene glycol.

Water is common because it possesses the highest heat capacity per unit mass of all substances. Moreover, it is abundant and cheap. Ethylene glycol (EG) is a dihydric alcohol that is composed of two-hydroxyl-groups, making it highly soluble in water, and is connected to both sides of an aliphatic carbon chain. In addition, it can easily mix with many polar solvents. Both fluids, water and EG, are similar in being odorless, colorless, and clear [28].

Several mechanisms affect the nanoparticles as they travel through base fluid, including gravity, Brownian motion, and thermophoresis. In order to understand these concepts, it is important to understand what they affect, which is the thermo-physical properties of the produced nanofluid, or base fluid.

Thermo-physical properties are simply material properties which vary with temperature without altering the chemical identity of the material. This term is commonly used to describe the properties associated with transfer and storage of heat [29]. These properties will include thermal conductivity, viscosity, and density. Thermally, it also includes diffusivity, heat capacity, thermal expansion, and thermal radiative properties, as well as mass and thermal diffusion coefficients.

All properties are of interest in the field of nanofluids. This is because nanofluids are commonly used to transfer heat. Nanofluid-based PV/T collectors are effective due to the thermo-physical properties of the working fluid. Thermal conductivity is basically the property of a material to conduct heat. It is expressed with the general formula given by Eq. (4):

$$\vec{q} = -k \vec{\nabla} T \quad (4)$$

where \vec{q} is the heat flux, k is the thermal conductivity, and $\vec{\nabla} T$ is the temperature-gradient.

Viscosity of a fluid is a measure of its resistance to gradual deformation by shear stress or tensile stress. It can be tested using different types of viscometers and rheometers. The shear viscosity formula is expressed in Eq. (5).

$$\mu = \frac{Fy}{Au} \quad (5)$$

where μ is the dynamic viscosity, F and y are the applied force into the separation distance, respectively. A and u are the area of each plate and speed, respectively.

Density of a material is its ratio of mass per volume. Equation 6 describes the density.

$$\rho = \frac{m}{v} \quad (6)$$

where ρ is the density, m and v are the mass and volume, respectively.

The effect of these thermo-physical properties is immense for solar heaters and PV/T collectors. They can affect parameters such as the heat transfer coefficient, which is the constant of proportionality between the heat flux and the thermodynamic driving force for the flow of heat. The coefficient is expressed in Eq. (7):

$$h = \frac{q}{\Delta T} \quad (7)$$

where h is the heat transfer coefficient, and q is the heat flux.

An example of the effect of thermo-physical properties is thermal conductivity's effect on the heat transfer coefficient. This is expressed in Eq. (8):

$$h = \frac{k}{l} \quad (8)$$

where h is the heat transfer coefficient of an object, k is its thermal conductivity, and l is the thickness of that object. Nanofluids have higher thermal conductivity and viscosity than water [30]; Meaning, systems utilizing nanofluids will have a better heat transfer coefficient.

Nanofluid preparation can be classified into two methods: 1-step method and the 2-step method. The most common due to its relatively cheap price is the 2-step method. The nano-materials are imported in powder form and then mixed with the base fluid. The mixing process usually involves shaking, spinning, and applying temperature. Most researchers utilize ultrasonic baths when preparing nanofluids for PV/T systems. Type, size, and volume fraction of the nano-material play major role, along with type of base fluid, in the resultant nanofluid's thermo-physical properties.

Volume fraction (φ_i) is the volume of a constituent (V_i) divided by the volume of all constituents of the mixture V prior to mixing. This is expressed in Eq. (9) [31]:

$$\varphi_i = \frac{V_i}{\sum_j V_j} \quad (9)$$

Wang and Xu [32] studied the effective thermal conductivity of alumina (Al_2O_3) and copper oxide (CuO) nanofluids with diameters of 28 nm and 23 nm, respectively. This was done by mixing the nano-material with different base fluids and measuring the thermal conductivity using steady-state parallel-plate method. The authors [32] found an increase in thermal conductivity of all base fluid's as a resultant of mixing them with nanoparticles. Moreover, the authors [32] state the decrease in the nanoparticle size leads to increase in the thermal conductivity. Finally, the dispersion method is acknowledged as an important contributor to thermal conductivity. The authors [32] used three methods for mixing the nanoparticles and base fluids: mechanical blending, coating particles with polymers, and filtration. The blending was executed using an ultrasonic bath. The filtration method resulted in the highest increase in thermal conductivity, 12% with 3 vol% particles in water, for Al_2O_3 nanofluid. However, the thermal conductivity of the same nano-material mixed with ethylene glycol, at same volume fraction, is higher. From this research, done by the authors [32], the importance of volume fraction, type and size of nano-material is highlighted, along with importance of base fluid.

According to Prasher et al. [33], increase in the viscosity is greater than thermal conductivity enhancement for nanofluids which is observed in the literature. The letter reports increase in nanofluids viscosity corresponding to increase in its volume fraction, across different types of base fluids. Moreover, the authors [33] illustrated that relative viscosity does not vary significantly with temperature. Another element to consider in the preparation of nanofluids is the stability, which is heavily linked to the type of surfactant employed, and the quality of mixing process.

Drzazga et al. [34] prepared Al_2O_3 and CuO nanofluids using the two-step method, with different stabilizers, SHMP and acetic acid, to investigate the effect of the preparation method, and stabilizers on nanofluid stability for both types. Good stability of CuO -water nanofluid was obtained for 1% mass of SHMP while poor stability of $\gamma\text{-Al}_2\text{O}_3$ -water nanofluid was received for all investigated stabilizers.

The density of nanofluids decreases with the increase of the volume fraction, as illustrated by Prakash et al. [35]. The study investigated two types of nanofluids, CuO -water and TiO_2 -water. Density of TiO_2 nanofluid is significantly lower than that of CuO nanofluid, for the same volume fraction. Moreover, increase in viscosity and thermal conductivity was observed, corresponding to increase in nanofluid volume fraction, for both fluids.

A common method to understanding the nano-material implemented is to utilize different scanning methods such as field emission scanning electron microscope (FESEM), X-ray diffraction (XRD) or energy-dispersive X-ray spectroscopy (EDX). FESEM images a sample surface by raster scanning over it with a high-energy beam of electrons. It allows for the characterization of size, size distribution, and measurement of height and lateral dimensions. It provides a correlation between surface appearance and morphology. Figure 1 shows an FESEM image of SiC nanoparticles at the 2 μm

range and the 200 nm range. Among important information to surmise from FESEM is the uniformity of particles or observing change in the morphology of the particles.

X-ray diffraction is a technique that is used for the structural characterization of solid and fluid materials in different ranges including the nanometer (nm) range. This method can be used to test and identify the crystallite size, shape, lattice distortions, and faulting. Also, the composition variations, orientation and phase composition [36]. Figure 3 shows XRD results for the same nano-material, SiC, used in Fig. 2.

Various research works for nanofluid-based PV/T collectors were conducted in the past decade [37–41] which addressing the nanofluid-related parameters [42, 43], PV/T design and material parameters [44, 45], and the operational parameters [46, 47]. Different system designs of nanofluid-based PV/T collectors are proposed and tested [48, 49]. The different designs include flat plate [50], nanofluid impingement jet [51], and nanofluid spectral splitting filter [52].

Yousefi et al. [53] examined the viability of Al_2O_3 nanofluid as a heat absorber medium for a flat-plate solar collector. The study investigates the impact of mass flow rate and mass fraction of nanoparticles on thermal efficiency of the collector. The mass flow rate varies from 1 to 3 L per minute for two mass fractions, 0.2% and 0.4%, respectively. The results obtained showed increase in efficiency corresponding to increase of mass flow rate, at constant nanofluid concentration.

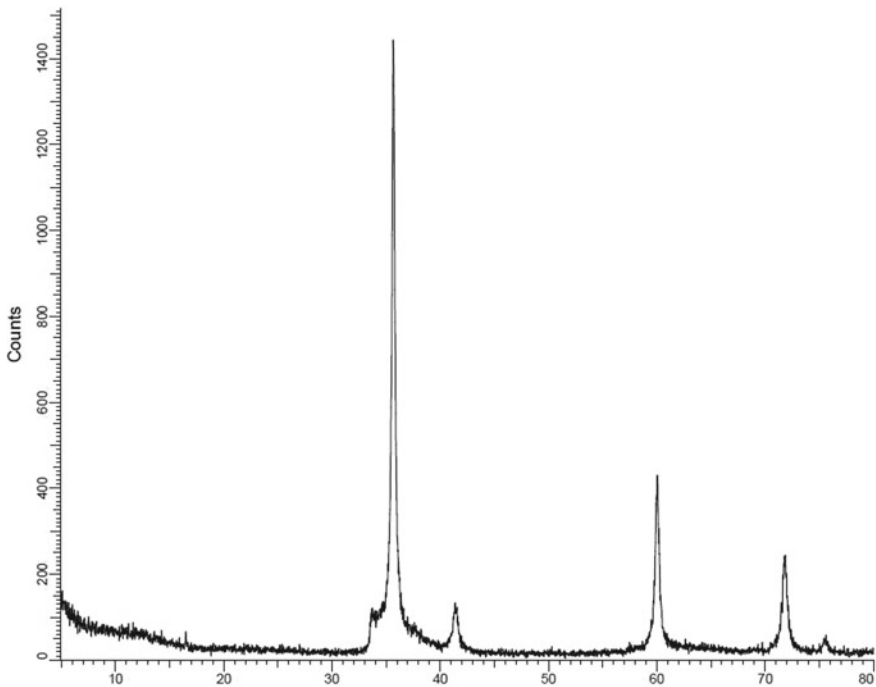


Fig. 3 X-ray diffraction of SiC

Zeinali Heris et al. [54] performed a numerical investigation on the convective heat transfer of three types of nanofluids. The channel of flow had a square cross section, with a laminar flow. The study focused on adjusting diameter and volume fraction of the nanoparticles and observing the effects on the fluid. The finds show an enhancement in heat transfer for two conditions. The first, when decreasing the nanoparticle size and fixing the volume fraction for all fluids. The second, when increasing nanoparticle volume fraction and keeping the particle size fixed.

Hwang et al. [55] also investigated multiple nanofluids in terms of conductivity. The nanofluids are multiwall carbon nanotubes (MWCNT), CuO, SiO₂. All with water is as the base fluid. The study reports a significant increase in fluid thermal conductivity (the conductivity increased more than 150% when small—about 1% of nanoparticles was added).

Sardarabadi et al. [56] experimentally studied an SiO₂ nanofluid-based PV/T. The study aimed to assess the impact different weight percentages, 1% and 3%, had on the electrical and thermal efficiencies. The authors [56] performed an uncertainty analysis to measure the inaccuracy. Adding 1% and 3% nanoparticles to water caused an increase in PV/T energy efficiency by 3.6% and 7.9%, respectively. This was done by converting produced electric power into equivalent thermal energy. As for thermal efficiency, it was increased by 7.6% and 12.8% for 1 wt% and 2 wt%, respectively. The total exergy was compared to a water-based PV/T and a conventional PV. Water-based PV/T, 1%-SiO₂-nanofluid, and 3%-SiO₂-nanofluid led to an increase in total exergy by 19.36%, 22.61%, and 24.31%, respectively.

Other methods of cooling or maintaining PV module temperature were introduced in this field. Among these methods is the use of phase change material (PCM). Organic PCM has been used to store and release temperature. PCMs are stable, non-toxic, recyclable, non-reactive, non-corrosive and available for wide phase change temperature selection. Simply, according to the required application, paraffin wax PCM is used for thermal storage to maximize thermal efficiency for PV/T collectors. PCM-based PVs and PV/Ts have massive potential for development. Ma et al. [57] presented a comprehensive review on PCM use in PV systems, for thermal regulation and electrical efficiency improvement. Various systems and emerging concepts were discussed in detail including aspects such as system development, performance evaluation, materials selection, heat transfer improvement, and numerical models. The study raises a concern on the economic-feasibility in enhancing PV efficiency only. PV/T systems utilizing PCM has a better potential, giving that the thermal storage could be extracted using a working fluid. Preet et al. [58] performed an outdoors experimental investigation of a water-based PV/T with and without PCM and compared the collectors to conventional PV system. The authors [58] integrated copper pipes to carry the water. Paraffin wax (RT-30) was used as the PCM. The study used three mass flow rates, which are 0.013 kg/s, 0.023 kg/s, 0.031 kg/s to investigate effect of mass flow rate on thermal and electrical efficiencies. The authors [58] found that overtime, the electrical efficiency of the PV/T with PCM becomes higher, while thermal efficiency of the PV/T without PCM becomes higher, which seems like a trade-off that must be taken into consideration. Nano-PCMs are preferred due to having higher heat release rates, compared to base fluids, which is attributed to

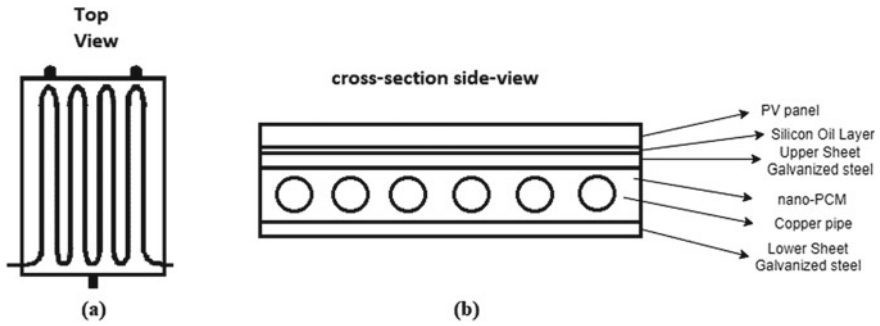


Fig. 4 a Top-view, b side-view drawings of the proposed PV/T

increase of thermal conductivity and reduction of latent heat. Fan and Khodadadi [59] performed both experimental and theoretical investigations to study freezing nano-PCM in container in vertical configuration. The experiments were used to validate the theoretical model established using a modified 1-D Stephan model. The solidification process was studied by Khodadadi and Hosseinizadeh [60] numerically using a square cavity which stores nano-PCM and is differentially heated. The results of the study show how higher rates of heat are released by the nano-PCM over the typical PCM medium and mainly attributed those outcomes to increase and reduction of thermal conductivity and latent heat, respectively.

The evolution of nano-material in PV/T systems continues to provide more innovative systems with better overall performance. In 2017, the authors of this work, Al-Waeli et al. [61], introduced a novel method and design of a hybrid nanofluid and nano-PCM-based PV/T. The collector was designed for maximum PV-cooling and thermal production. The concept was to increase the thermal conductivity of PCM by employing nanoparticles, or else known as nano-PCM. Nanofluids were added for optimum extraction of heat. The side-view and top-view drawings are given in Fig. 4.

The system was designed for optimum heat transfer. This was achieved by employing high thermal conductivity material such as nanofluids and nano-PCM. Moreover, as Fig. 4 shows, the system utilizes galvanized steel and copper as well. The copper pipes are emerged into a layer of nano-PCM which is stored at the back of PV module. The nanofluid will flow within these copper pipes. To ensure higher heat transfer, glass wool was implemented for thermal insulation. The system consisted of the proposed PV/T collector, a heat exchanger, a nanofluid tank, an expansion tank, the proper sensors, and control devices. In-between the PV and the nano-PCM tank, silicon oil was implemented to avoid air-gaps for better heat transfer. Moreover, the tank covered the whole area on the back of the PV for better cooling and heat transfer. Figure 5 shows the schematic diagram of the combined system.

The operation of the system is dependent on the nanofluid cycling through the PV/T, extracting heat, and the heat exchanger, transferring heat to water. By the start of every cycle, the nanofluid must be cooled-down for maximum heat transfer. The

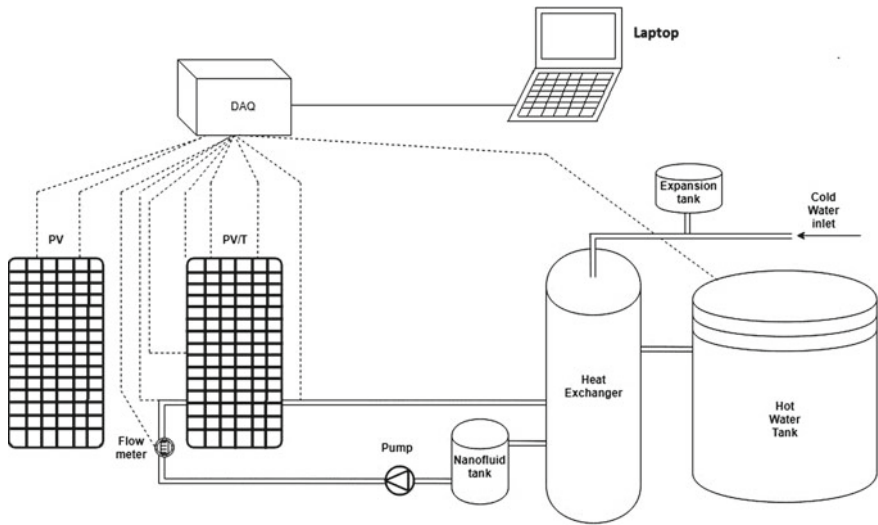


Fig. 5 Schematic diagram of the nanofluid and nano-PCM-based PV/T

nanofluid itself must be made so that it has high thermal conductivity and viscosity. This is done by performing accurate mixing and shaking of nanoparticles in the base fluid. The nano-PCM must be prepared effectively as well. Figure 6 shows the preparation of the nano-PCM.



Fig. 6 Preparation of nano-PCM using ultrasonic bath

Various mass flow rates were implemented ranging from 0.00833 to 0.0175 kg/s. The system was tested outdoors for Malaysia's tropical climate. The sensors used include flow meter, k-type thermocouples, pyranometer, and multimeter for nanofluid mass flow rate, surface temperature, solar irradiance, and electrical components—voltage and current, respectively. A data acquisition device was used to collect the data and transfer it to a portable computer. All pipes and containers were well isolated to avoid heat escape. Moreover, the proposed PV/T was compared to a water-based PV/T, a PCM-water-based PV/T, and a conventional PV.

The next section will present results from the outdoor experiments of the nano-PCM and nanofluid-based PV/T from our published works [61–64].

4 Results and Discussions

SiC nano-material was used for the nanofluid and the nano-PCM, while organic paraffin wax was used as PCM. The FESEM image and XRD analysis of the nano-PCM can be viewed in Fig. 7, while the EDS scan is provided in Fig. 8.

Figure 8 shows the map sum spectrum of the nano-PCM or SiC-Paraffin sample. It clearly shows traces of silicon (Si) and high content of carbon (C). Hydrogen (H) is not shown because it is a light element and cannot be routinely analyzed using EDX.

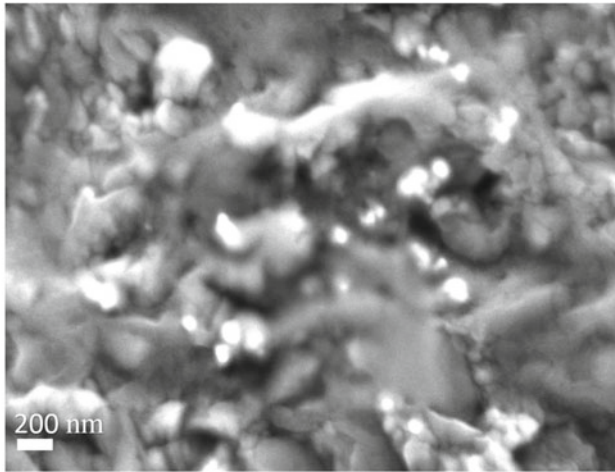
Four systems are considered in the results which are:

1. Nanofluid and nano-PCM-based PV/T/abbreviated (PVT cell.pcm.n.nf)
2. PCM tank, water-based PV/T/abbreviated (PVT cell.pcm.w)
3. Water tank, water-based PV/T/abbreviated (PVT cell.w)
4. Conventional PV.

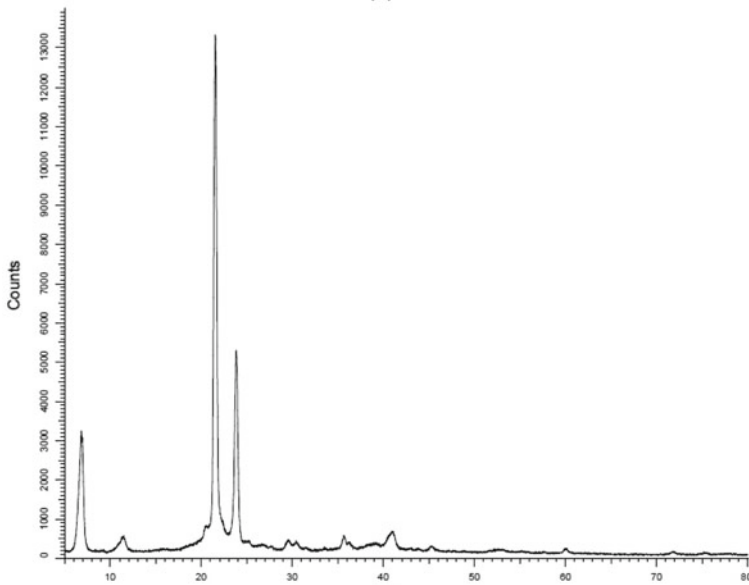
To reduce the number of tests required, the experiments began with an investigation of optimum mass flow rate by testing various nanofluid flow rates. Water-based PV/T with a PCM tank was used for these tests. Figure 9 shows the observed change in PV module temperature across various flow rates throughout the day.

To form a better understanding of the system, Fig. 9 shows the recorded temperature of the PV, the solar irradiance, and time. The solar irradiance and ambient temperature behaviors are displayed in the black (diamond marker) and orange lines (square marker), respectively.

From Fig. 9, it can be observed that temperature of the PV module has decreased with increase of mass flow rate from 0.0833 to 0.175 kg/s. These results agree with the theory and literature, where increase of mass flow rate causes increase in heat exchange and enhanced heat transfer from hot to cold mediums. More increase to mass flowrate could be made, but a vibration in the PV/T system was noticed. Hence, it is important that the mechanical design works well with operational parameters. Hence 0.175 kg/s shows better cooling and is suitable for the system, and it was used for the remaining experiments. The temperature distribution across the four systems investigated and is provided in Fig. 10.



(a)



(b)

Fig. 7 a FESEM of SiC-paraffin, b XRD of SiC-paraffin

It is noticeable that temperature of all modules starts higher than the ambient. This is because measurements were taken after sunrise. As expected, the conventional PV module had the highest temperature throughout the experiments; as no method of cooling or thermal regulation was implemented. The second highest in temperature was the water-based PV/T with a water tank, then the water-based PV/T with a PCM tank. The lowest PV temperature is clearly the nano-PCM and nanofluid-based

Fig. 8 EDS of SiC-paraffin sample

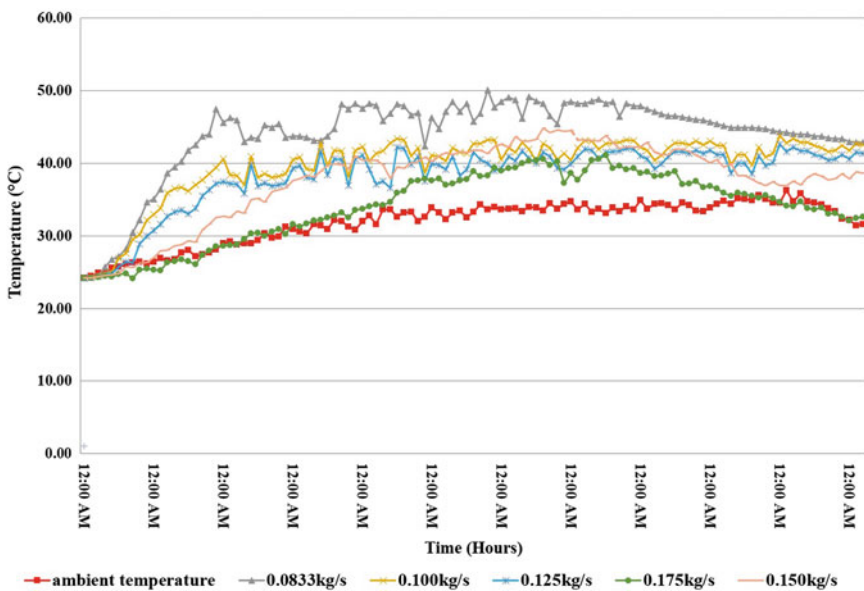
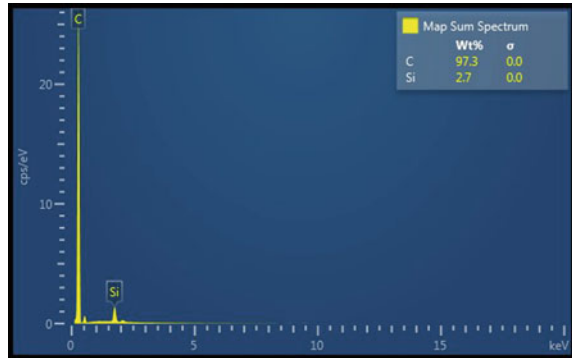


Fig. 9 Effect of mass flow rate on collector temperature for the tested systems

PV/T. Nanofluid has lower specific heat than water, but it does have higher thermal conductivity and so it led to higher reduction in PV module temperature. Using nano-PCM allowed for better utilization of PV temperature to produce more thermal energy. The nano-PCM has the advantage in heat storage as it acquired temperature and transferred it to the nanofluid more quickly. The thermal energy and thermal efficiency of the systems are provided in Figs. 11 and 12, respectively. The fourth collector, conventional PV, was excluded from these two figures given that it does not capitalize on thermal energy. Although the electricity produced can be converted into thermal energy for the sake of comparison, however, it would be counterproductive to do so, and employing a solar thermal collector would be more suitable. It is needless

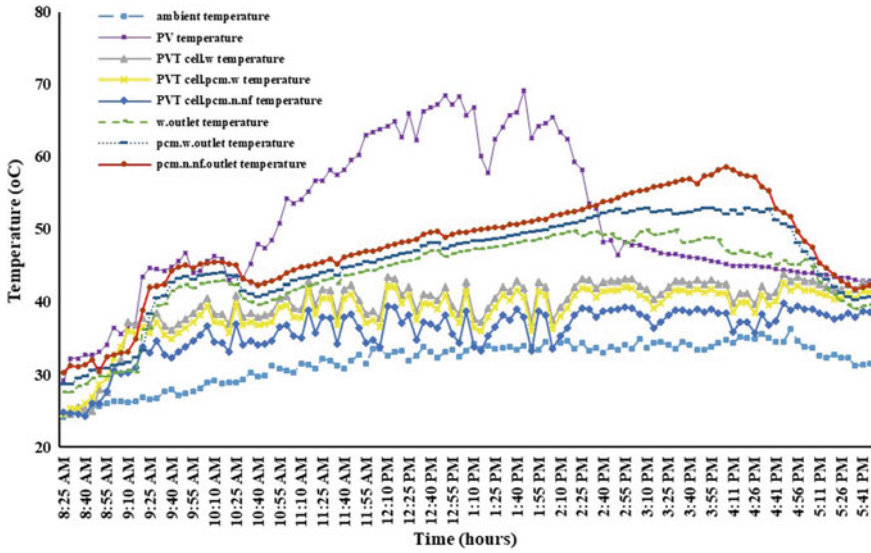


Fig. 10 Temperature distribution of all systems

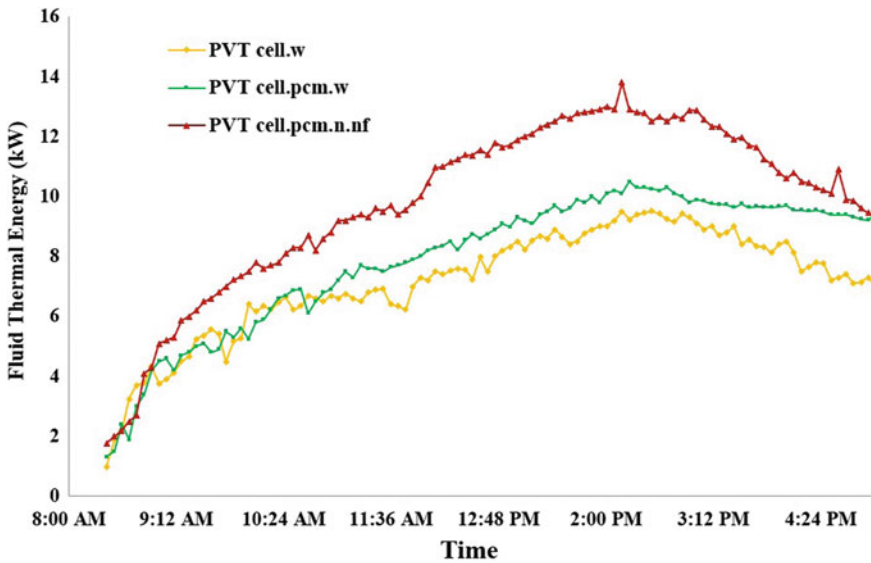


Fig. 11 Thermal energy of the PV/T collector

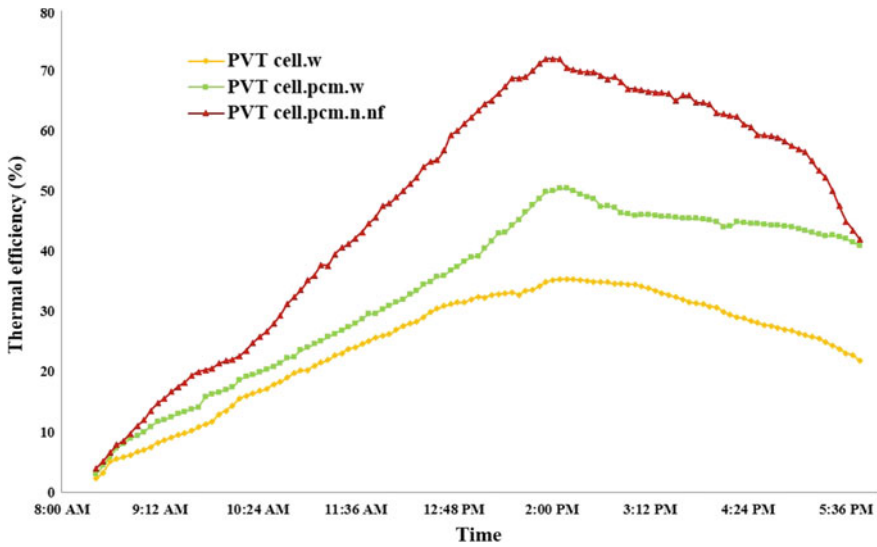


Fig. 12 Thermal efficiency of the PV/T collector

to say that other environmental variables have some effect on the performance of the module and may lead to some irregularities which are expected in tropical climate, for example, wind speed and direction, diffused and reflected solar irradiance, air mass and position of the sun.

Clearly, the highest thermal energy is produced by the nano-PCM and nanofluid-based PV/T which is mainly attributed to design material. Increase of heat transfer due to employing nano-material is the main key to this process. The better heat transfer occurs the better cooling of the module happens and hence maintaining electrical performance close to the standard conditions. It is important to note that instantaneous change of solar irradiance leads to temperature fluctuations which are dampened, or even eliminated, if PCM is used. The use of a nanofluid is particularly crucial at later time, throughout the day, typically 4–6 PM, where it is important to extract heat from the PCM or the nano-PCM as fast as possible to avoid heat returning to the module; given that module surface temperature begins to drop considerably. Because nano-PCM has higher thermal conductivity than water and PCM, it stores the heat for a longer time and hence discharges without acquiring new heat, which explains the thermal efficiency of the nanofluid and nano-PCM collector. As for thermal efficiency, Fig. 12 shows the efficiencies for the three proposed systems over time.

At the start of the testing, all three systems had similar efficiencies as not enough heat was transferred to the working fluids. Since the highest thermal efficiency is achieved by the nano-PCM and nanofluid-based PV/T, it is clear that it causes the most reduction in PV module temperature, which in turn will affect its electrical efficiency, as it is shown in Fig. 16. In general, the curves are similar with exception

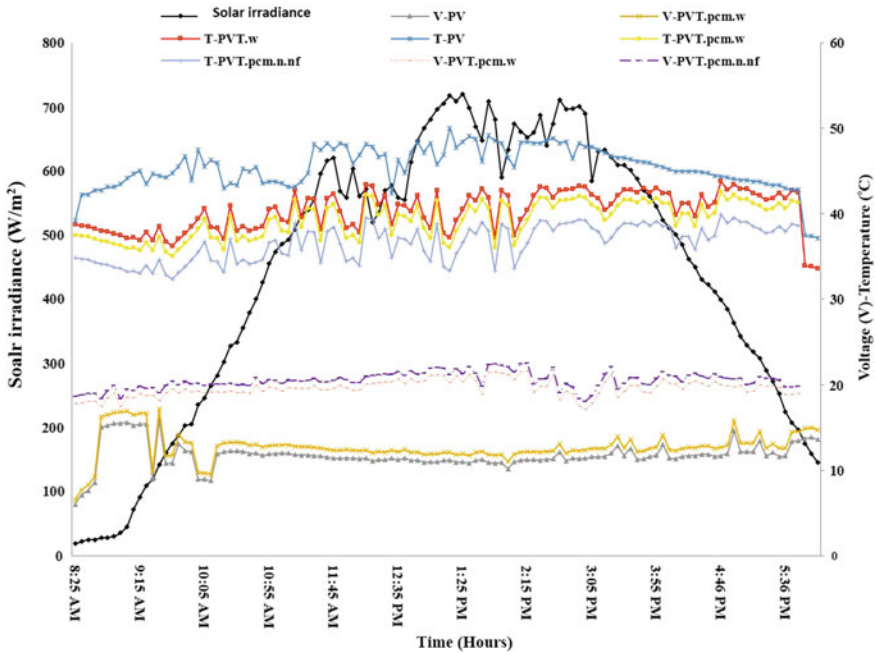


Fig. 13 Electrical voltage of PV/T collector

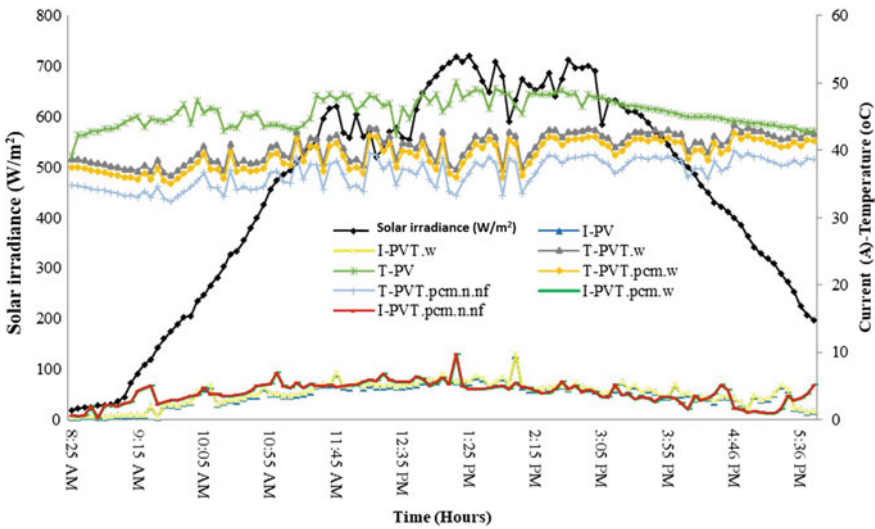


Fig. 14 Electrical current of PV/T collector

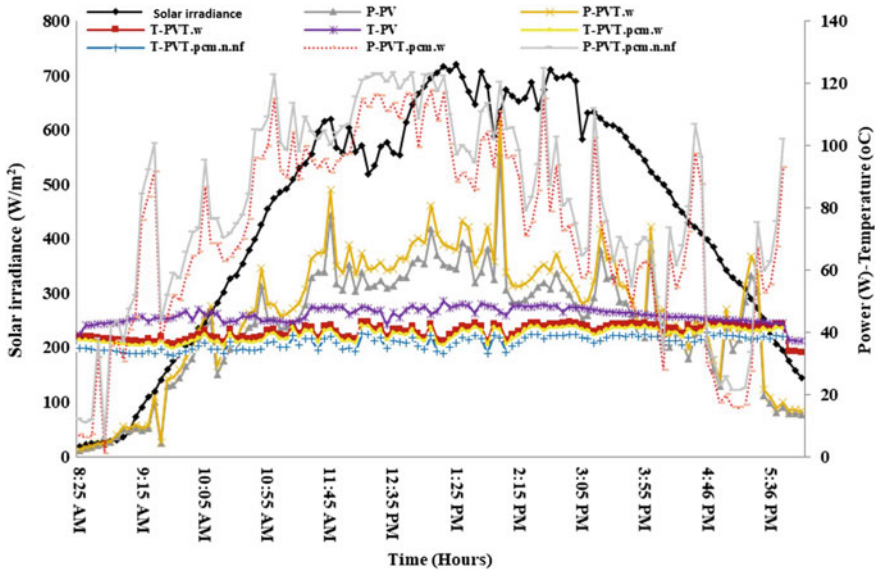


Fig. 15 Electrical power of PV/T collector

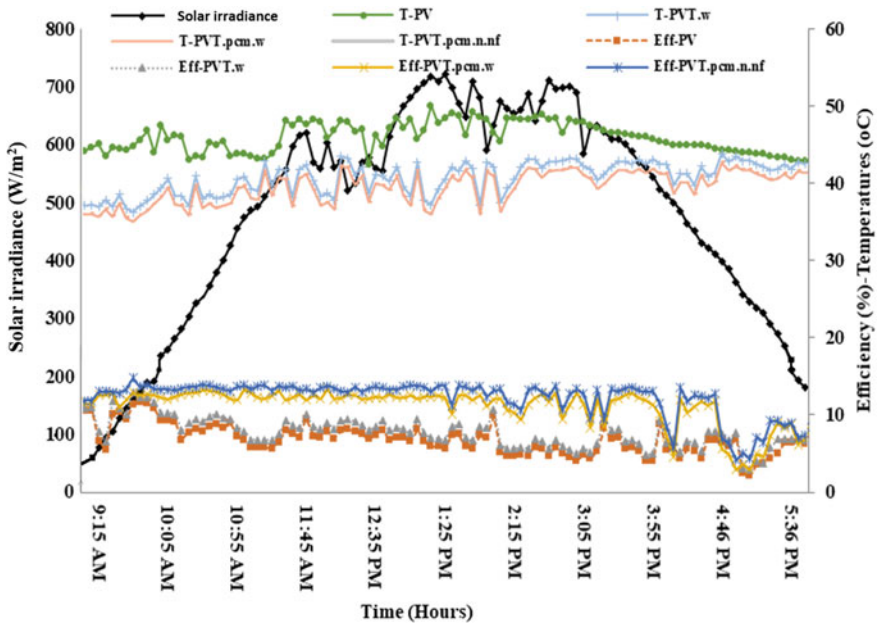


Fig. 16 Electrical efficiency of PV/T collector

to that of the proposed system which shifts due to its ability to store heat better. This heat could be utilized in many applications ranging from residential water cooling to industrial pre-heating for steam generation [65]. This system although has significant thermal efficiency, and there are multiple risks that need to be studied and considered for large-scale.

Firstly, it is the type of nanofluid and the preparation process. The performance of the system itself may vary according to the nanofluid and nano-PCM employed. Good mixing and preparation of the nanofluid and nano-PCM would lead to better thermal conductivity, while bad mixing would change that result.

Secondly, it is also important to ensure accurate pouring of nano-PCM into the nano-PCM container, or tank, to avoid gaps in the tank. Moreover, the stability analysis of the employed nanofluid over long period of times must be considered as well. Good welding of the design material must be ensured, and leaks of both liquid and heat must be avoided. Complete covering of the PV module is important to cover more area of the collector for heat transfer.

To assess the electrical performance of the collector, it is preferable to state the general properties of the PV module. The PV power, open-circuit voltage, short-circuit current, and efficiency at standard testing conditions (STC) are $120 \pm 3\%$ W_p , 21.5 V_{OC} , 7.63 I_{SC} , and 14%, respectively. The elements affecting the system are solar irradiance, ambient temperature, and mass flow rate. Remaining elements such as atmospheric pressure, wind speed, and age of the PV were neglected. A source meter was used to measure the output of the module. Figures 13 and 14 show the electrical voltage and current of the different collectors, respectively.

Both figures, of voltage and current, are with respect to solar irradiance and temperature. The voltage waveform of the PV is more affected by variations in solar irradiation, given that it would affect the potential barrier of the cell itself and cell temperature. However, current waveform is consistent with solar irradiance. Given continuous changes in instantaneous solar irradiance, fluctuations, and spikes appear for both the voltage and current, as shown in Figs. 13 and 14. The highest voltages for the systems were around 18–20 V and 20–21 V for the PVT.pcm.w and PVT.pcm.n.nf, respectively. Moreover, the average voltages are around 19.7 V and 20.6 V, respectively. The current curve is highly affected by solar irradiance curve. The current increased with the increase of cell temperature, which is consistent with the theory; however, for all PV modules the current fluctuated throughout the experiments but the change is insignificant. The electric power and efficiency of the systems are presented in Figs. 15 and 16, respectively.

From Fig. 15, the highest production of electric power during the experimental period is achieved by the nano-PCM and nanofluid-based PV/T. The instantaneous peak power generation of the systems is 61.1 W, 85.7 W, 116.1 W, and 119.5 W for the PV, PVT.w, PVT.pcm.w, and PVT.pcm.n.nf, respectively. These values are subject to uncertainty of 3%.

Moreover, the electrical efficiency follows, as Fig. 16 shows the electrical efficiency, which is also a success domain for the PVT.pcm.n.nf which achieved peak instantaneous efficiency at around 13.7% that is very close to that of standard testing conditions. However, instantaneous efficiency should not be a representation of the

PV performance throughout the day, nor overtime. The second-highest efficiency is achieved by PVT.pcm.w with around 11.3%, followed by 8.6% for PVT.w, respectively. The lowest electrical efficiency is found for the typical PV module that may seem shocking; however, it is very reasonable under tropical climates. It is noteworthy to mention that one pyranometer is used in-between all four-system collector; meaning slight variation of incident solar irradiance occurs from the one shown in graph. Moreover, changing pyranometer tilt angle can affect the measurement as well. The modules are installed at a tilt angle, and the hence difference between recorded solar irradiance and actual irradiance received by PV can differ slightly.

The thermal and electrical efficiencies of the proposed system effectively showcase the importance of nano-material for solar energy development. Nano-PCMs have a massive potential for these systems. It is important to note that the water-based PV/T with a water tank is not very common, as most research only employed direct pipes with water or flat-plate designs. PV module can decrease in efficiency up to a substantial margin due to environmental elements such as heat, humidity, dust, and inner device losses [66]. Irregularities, spikes, and discontinuity are major issues associated with PV modules and need to be addressed. Establishing PV/T for cooling and heat extraction is a cost-effective method and has great potential for success in the field.

Voltage and current of the PV are majorly affected by the cell temperature as established by Figs. 13 and 14. Hence, cell temperature is the main link between PV and solar thermal to forming PV/T. Figure 13 shows an inversely proportional relationship between voltage and cell temperature. In Fig. 16, the electrical efficiency, partially as a product of PV cell temperature, is shown to be high for the proposed system in comparison with other designs. The results displayed in this section are summarized in Table 2.

It is important to differentiate between the results displayed in Table 2, maximum values, and average operational values. For comparison with other systems, the type of PV at STC must be unified for far comparison. However, in terms of thermal collector it is not necessary to compare it to a similar type, for thermal comparison. The claim is to compare the proposed type to other types of thermal collectors, of PV/T to see which holds the highest efficiency. The main challenges of this

Table 2 Summary of electric/thermal behavior of different PV/T systems

System	Peak PV temperature (°C)	Peak output cooling fluid (°C)	Max. thermal energy (kW)	Maximum electric efficiency (Wp)	Max. total PV/T efficiency (%)
PV	68.3	–	–	77.6	7.11 (no thermal)
PVT.W	45.22	49.72	9.51	85.1	45.32
PVT.PCM.W	42.22	52.52	10.5	107.4	62.82
PVT.PCM.N.NF	39.52	58.62	13.8	119.5	85.7

configuration are mainly in preserving the stability of produced material for repeated cycles and establishing cheaper and simpler methods for preparing the end-product nanofluids and nano-PCM for the end-consumer. Discharging process after sunset is also considered an issue given that more power is spent to ensure no temperature revert to the PV module. Finally, the use of PCM will lead to increased weight and hence further construction costs.

5 Summary and Conclusions

This chapter presented advances of nano-material utilized in photovoltaic thermal (PV/T) collectors. The chapter introduces solar energy, PV and solar thermal, and PV/T collectors. The concepts and classifications of PV/T are explained, and the literature work is reviewed as well. Nano-material and nanofluids were introduced and explained as working fluids for PV/T systems. PCM and nano-PCM were also introduced as thermal regulation mediums for PV and PV/T systems. The evolution of nano-material use in PV/T collectors is further summarized in Fig. 17 [61, 67, 68].

With regard to nano-material, the following conclusions summarize the information presented in this chapter:

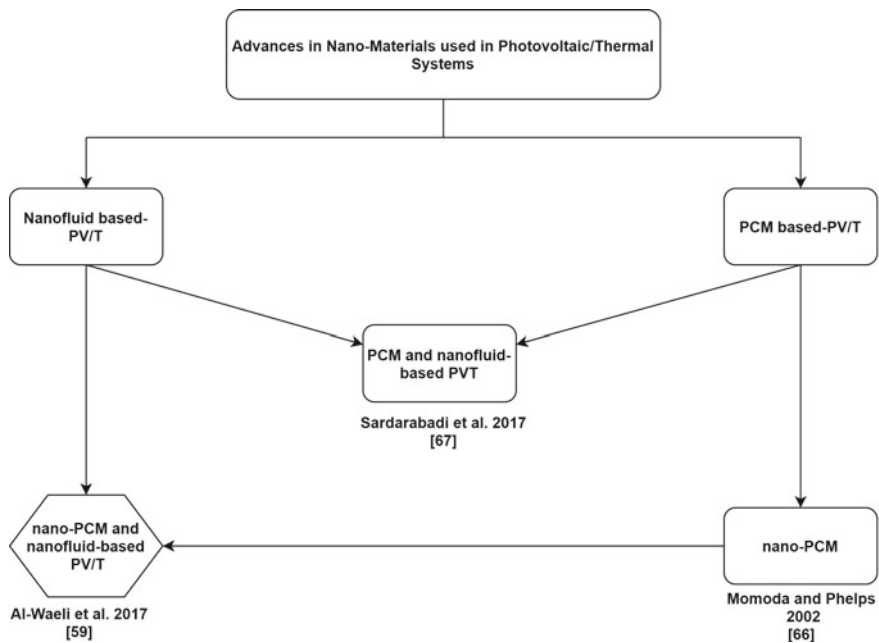


Fig. 17 Summary of PV/T classifications with nano-material innovative solutions

1. Nano-materials are special materials produced at nano-scale which have favorable properties for various industrial applications (e.g. electronics).
2. Nano-materials have a high surface area-to-volume ratio which makes them more chemical reactive than normal-sized material.
3. Nano-material synthesis is extremely important to produce them for the desired application and is classified into physical and chemical methods.
4. Nanofluids are nano-materials mixed with a base fluid. They exhibit better thermo-physical properties than water, or ethylene glycol. Hence, they are used for heat transfer applications.
5. Nanofluid preparation is a critical stage to obtain stable nanofluids. Mixing/shaking process and nano-material mass fraction have significant effect on the fluid's thermal conductivity, viscosity, and density.
6. Higher mass fraction of nano-material leads to higher thermal conductivity and lower density. However, an offset would be the cost associated with adding more nano-material.
7. The biggest issue associated with nanofluids is agglomerations and sedimentations which are bound to occur but could be minimized.
8. Stability, particle structure, and morphological properties are among characterizing factors which can be examined using various scanning methods such as FESEM, EDS, and XRD.
9. Nanofluids are considered Newtonian fluids and are affected by gravity and Brownian motion.
10. Nanofluids are used for different types of PV/T collectors, spectral splitting filters, jet impingement, and flat-plate designs.

Phase change materials (PCM) are effective tools for maintaining and thermal regulating the temperature of the PV modules. However, they lack thermal conductivity. Hence, employing nano-materials will affect this process, yielding 'nano-PCM.'

The implementation of nanofluids has massive effects on thermal and electrical behavior of PV/T systems. Highlighted below are important factors associated with nanofluid-based PV/T:

1. Nanofluid-based PV/T has higher thermal and electrical efficiency than water-based PV/T.
2. PCM-based PV and PV/T have higher thermal efficiency than conventional PV modules.
3. Nano-PCM has higher thermal conductivity than PCM and is more suitable for heat transfer applications.
4. Increase of nanofluid mass flow rate leads to better cooling and heat extraction, up to a certain point.
5. Thermal isolation and elimination of air-gaps are crucial to the successful design of PV/T.
6. Higher solar irradiance leads to higher electrical efficiency when cooling the PV modules.

Currently, the main challenges facing this technology are the high costs for producing nanofluids and nano-PCM. Other challenges extend to stability of nano-material and accurate methods of measuring latent heat change.

The design described in the results and discussion sections can be improved for future research with consideration of the following points:

1. Using the photovoltaic module frames as the nano-PCM tank buy simply placing a sheet at their back to cover it. Also, this will eliminate the need for silicon oil in the design.
2. Varying the design of the pipes to examine different configurations for improved performance.
3. Employing concentrated CPC PV/T with the nano-PCM and nanofluids to test the effect of concentration on thermal and electrical power generation.

Further, research investigations must be conducted to examine various environmental conditions and PV/T system configurations using nano-material for efficiency enhancement and offering cost-effective solutions for consumers.

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