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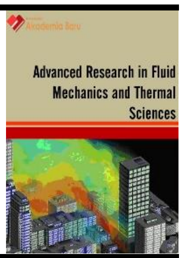

Application of Nanofluids for Photovoltaic Thermal (PVT) Collectors: A Review

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ABSTRACT

Nanofluids have received considerable attention in the past decades. Nanofluid is produced by dispersing nanoparticles into a base fluid with a typical size of less than 100 nm in a liquid. Nanofluids have been proposed as a replacement for conventional cooling fluid because of their enhanced thermal properties. This review presents descriptions and previous works conducted on the performance analysis of nanofluid-based photovoltaic thermal (PVT) collectors. Results on the performance analyses of nanofluid-based PVT collectors are summarised. The use of nanofluid as a heat transfer fluid in PVT collectors shows enhanced performance. The performance of nanofluids-based PVT collector will increase in terms of overall efficiency compared with conventional fluids. Thus, small and compact nanofluid-based PVT collectors can be manufactured, thereby reducing the weight, energy and cost of manufacturing.

1. Introduction

Energy is a useful and essential element people's daily activities. Energy can be renewable or non-renewable. Non-renewable energy sources, such as fossil energy comprising natural gas, coal, uranium (nuclear energy), and petroleum, cannot be added or enhanced within a short period of time. Meanwhile, renewable energy is collected from resources that are naturally added to human scale, such as wind, wave, sun, rain, and geothermal heat, and can be generated continuously. The development sector increases with the global population, which results in the increase in demand and energy consumption. Solar power is viable for a number of applications that use solar sources in most countries. Various technologies and applications based on solar energy have been developed as an alternative energy source. Among them is solar photovoltaic (PV) technology. This system works by directly converting the radiation obtained from sunlight into electricity. PV technology plays an important role in the field of renewable energy; this technology does not release any chemicals throughout its long and quiet life. To improve the efficiency of PV systems, thermal solar collectors

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are combined with and installed beneath PV panels. Water or air flowing through the thermal solar collectors can release heat from the PV panels. Therefore, the temperature on the bottom surface of the PV system can decrease while increasing the efficiency of the system [1–8].

Solar energy can be converted into electric energy via PV technology. The disadvantages in using PV cell include a decline in efficiency conversion when the temperature is raised and is responsive only to a portion of the solar spectrum. The solar cell conversion efficiency ranges from 6% to 18%, which is a value measured at the nominal operating cell temperature, whereas the rest of the solar radiation received are reflected and absorbed as heat energy. The low efficiency and high cost of PV cells has led to the idea of a hybrid PVT, which integrates the solar thermal collector and PV module. The advantages in using PVT collectors is that they enhance the electrical energy produced, remove waste heat from the PV module and minimise the usable space. Moreover, solar energy will convert into thermal energy as stored in air or water. The PVT collector can be classified into three categories, namely, water and air PVT collectors and the combination of both. PVT collectors accumulate from a glass cover, solar cell, or encapsulated material, with the collector attached at the back. In terms of physical structure, the module types can be classified as flat plate, concentrated and building integrated. The absorber functions to absorb heat and cool down the PV module simultaneously. The collected heat will be in the form of air or water [9-14].

Recently, various studies have been conducted on PVT collectors with water and air as heat carriers. Experimental and theoretical studies on air/water based PVT collectors are also available in the literature [15-21]. Most studies have focused on the size, arrangement and type of fluid used for cooling in PVT, whereas studies using nanofluids as coolants are still at an early stage. The emergence of advanced technology has produced nanoparticles, later dispersed in the fluid called as nanofluid enhanced heat transfer process substantially. The remarkable increase in thermal conductivity even when a low concentration of nanoparticles is added in fluid has been observed by many researchers [22]. Yousefi *et al.,* [23] investigated the efficiency of a flat plate solar water heater collector by varying the mass flow rate and volume concentration of alumina nanofluid. Results indicated that by increasing the mass flow rate from 1 L/min to 3 L/min, the efficiency of the solar collector increased at a constant volume concentration. However, the present review focused on nanofluid-based PVT collectors.

2. Nanofluids

One of the solutions is introducing foreign element of higher heat carrier capacity and thermal conductivity, known as nanoparticles which could improve the overall performance of heat transfer fluid. Nanoparticles are materials produced via nanotechnology method. Nanoparticle physical properties, with size of less than 100 nm, include various types of materials with particular substances [24-26]. In heat transfer applications, nanofluid has gained attention as new and efficient heat transfer fluid due to its superior thermophysical properties compared to conventional working fluid such as water, oil and ethylene glycol [27]. Experiments show a considerable increase for thermal conductivity by dispersion of less than 1% volume fraction of nanofluids. The ideal thermal properties of nanofluids with high thermal conductivity and heat transfer can be achieved, and a small and compact design of PVT collectors is possible without affecting the desired output. Heris *et al.,* [28] investigated the convective heat transfer of nanofluids in a laminar flow through a channel with a square cross-section, which resulted in an increase in heat transfer when the size of the nanoparticles was smaller and the volume fraction was increased. Faizal *et al.,* [29] calculated the efficiency, size reduction, cost and embodied thermal energy in solar collectors using various metal oxide nanofluids, such as TiO_2, SiO_2, CuO_2, and Al_2. The advantages of short period of time, less CO_2 emissions and size reduction can be achieved through the use of nanofluids more easily compared with the conventional solar collector. However, the stability of nanofluids and the aggregation of nanoparticles after a certain period hinder the maximum potential of nanofluids. Physical and chemical treatments must be conducted during the preparation of nanofluids. The stability of nanofluids has a good correlation with the enhancement of thermal conductivity, wherein a good dispersion indicates high thermal conductivity.

Thermal conductivity is the most preferable parameter evaluated by researchers in many experimental works, wherein the results from parameter observation have been recorded. It is measured using three methods, namely, transient hot wire, steady-state parallel-plate technique and temperature oscillation method. Thermal conductivity is the most important parameter responsible for enhanced heat transfer in many experimental works on this topic. Alumina and copper oxide are the most common nanoparticles used by researchers in their experimental investigations. The investigation on silica is limited compared with other nanoparticles. Temperature, particle size, dispersion and stability play important roles in determining the thermal conductivity of nanofluids [30]. Das *et al.,* [31] examined the effect of temperature on the thermal conductivity for nanofluids containing Al_2O_3 and CuO. They observed that a two- to four-fold increase in thermal conductivity over the temperature range of 21 °C–52 °C. The results suggest that nanofluids are suitable for a device with high energy density and operates at a temperature higher than room temperature. The remarks of enhancement in small nanofluids of thermal conductivity are explained by stochastic motion. Hwang *et al.,* [32] compared the thermal conductivity among four nanofluids (i.e., MWCNT/water, CuO/water, SiO_2/water and CuO/EG) and found that the multiwalled carbon nanotube (MWCNT)/water achieved the highest thermal conductivity of up to 11.3 % at 1 vol%.

Suspending a nanometre-scale solid particle into a base fluid, such as water, oil and ethylene glycol, produces nanofluids. The major problem in producing a nanofluid is the aggregation and inhomogeneity of the colloidal suspension. The techniques for nanofluid production are the single- and dual-step methods. The early single-step method proposed by Akoh *et al.,* [33] was called vacuum evaporation onto running oil substrate technique. The advantages of this technique are the minimisation of the agglomeration of nanoparticles and the acceptance of only low vapour pressure fluids. However, this method is costly and production of nanofluids in large scale is lacking. The dual-step method is more popular in nanofluid synthesis compared with the single-step method, wherein the purchase of nanoparticles from companies is possible. Nanoparticles are being produced as a powder and then mixed with a base fluid. Ultrasonication is the most economic method practiced in the industry and is used to disperse nanoparticles in the base fluid and reduce agglomeration. A surfactant or dispersant is added to the nanofluid to attain the stability of suspension, such as in the experiments conducted by Murshed *et al.,* [30] and Hwang *et al.,* [32]. Other methods, such as varying the pH value of the nanofluid or surface-active agent, will change the surface properties of the nanoparticles. Such methods are the most economic practice in industry.

3. Studies on Nanofluids-Based PVT Collectors

The use of nanofluid is not only a coolant, but also extends its function as an optical filter to the PV module. Taylor *et al.,* [34,35] evaluated the performance of nanofluid as an optical filter to replace the ordinary filter. Nano fluid filters achieve optimum conditions only by adding 0.00011 v/v% and thinner than normal fluids. Nanofluid thickness and concentration parameters as optical filters to PV modules are reviewed by Cui and Zhu [36] on the fluorescence of nanoscale and solar radiation. The nanofluid thickness at 2 mm, the concentration of 0.02 wt% is capable of producing energy of 4.5 W as compared to the concentration of 0.1 wt%. Radiation brightness decreases by 13% when the nanofluid is increased to 10 mm.

The advantages of the thermal properties of nanofluid evidenced from past studies attracted researchers in the field of solar energy to utilize the use of nanofluids in PVT collectors. One of the earliest investigators initiated studies on the efficiency of PVT collectors based on nanofluid were Sardarabadi *et al.,* [37]. They analyzed the comparison of nanofluid and water as well as the effects of nanofluid concentrations on PVT collector performance. The results of the study formulated the overall exergy of the PVT collector for nanosilica fluid 3 wt%, 1 wt% and water were 24.31%, 22.61% and 19.36% compared to PV modules. Different tube configurations and fluid concentrations are compared to evaluate cooling performance in PVT collectors. The helical tubing design in some parts accelerates heat transfer rather than straight tubes. PV surface temperature drops of 39.7% and 53.76% were recorded at boehmit concentration of 0.1 wt% for straight and helical tubes [38]. Xu and Kleinstreuer [39] showed that PVT using nanofluids is more suitable for silicon solar cells compared with multijunction solar cells, and the overall energy conversion efficiency of the CPVT collector is higher than that of the conventional system.

Nanofluid has been applied as a volumetric solar absorber and flowing-heat transfer medium in some studies. Chui and Zhu [36] investigated PVT collectors with MgO nanofluids applied to the top of a silicon PV panel and evaluated the transmittance of MgO–water nanofluids when concentrations are at 0.02, 0.06 and 0.1 %wt. The inferred result was a regular transmittance decrease with the increase in mass fraction. The electrical output of solar cells increased with the decrease in concentration of nanofluid and in using thin layers of nanofluid at the top of the PV cells. Jing *et al.,* [40] used the single-step method in preparing a highly dispersed SiO_2/H_2O with various particle sizes. They circulated the nanofluid above the PV panel to filter the IR part of the incident light and below the PV cell to remove the heat generated in the photoelectric conversion process. This design reduced the operation temperature of the PV cell and improved PVT efficiency. Using a liquid filter has the advantage of being dynamically controlled by pumps, magnetic/electric field and temperature changes. Ferrofluid has unique rheological and thermophysical properties under an external magnetic field. Ghadiri *et al.,* [41] evaluated the effect of ferrofluid as a coolant on the overall efficiency of PVT collectors. The results showed that a 50% increase in the overall efficiency was achieved when ferrofluid was placed under alternating magnetic fields with frequency of 50 Hz. An *et al.,* [42] conduct experiments for the enhancement of collectors and thermal energy at conditions of fluid temperature above 100 °C. The overall efficiency of PVT collector flowing with nanofluid filters increased by 17.9%. The resulting electricity and thermal energy levels can be adjusted according to the nanofluid concentration based on suitability.

The study of nanofluids as a filter continues with a combination of cooling systems for assessing the design of fluid tubes by Hassani *et al.,* [43]. The comparable designs based on simulation are separate pathways and multiple pathways where electrical efficiency is recorded higher when the nanofluid is streamed in a foreign pass tube. This design simulation was tested on GaAs and silicon PV cells, where PVT overall efficiency increased by about 5.8% and 4.6% at a concentration of 0.001-1.5% using foreign routes. Separate pathway designs using different nanofluid and thermal conductivity of nanofluid in path 2 may help cooling process faster. The study uses CFD analysis of nanofluid provided by a single step method conducted by Jing *et al.,* [40]. The heat generated by infrared (IR) and PV cells is absorbed by nanofluids in two parts. This allows PV modules to operate at optimum conditions and improve their efficiency. As a result, the efficiency of the exterior increased by 7% at a flow rate of 0.015m/s.

Table 1
Summary of the performance of nanofluid-based PVT collectors

Author	Year	Type of nanofluid	Remarks
Taylor *et al.,* [34]	2012	Au, SiO_2, Al and Ag	Volume fraction of 0.0011% was required to achieve optimum filters.
Chui and Zhu [36]		MgO/water	Transmittance of nanofluids decreased with the increase of mass fraction and film thickness. The overall efficiency of the PVT collector with a 2-mm-thick liquid layer was beyond 60%.
Sardarabadi *et al.,* [37],	2014	SiO_2/water	For 1 %wt and 3 %wt, energy efficiency increased up to 3.6% and 7.9%, respectively. Total exergy was 19.36%, 22.61% and 24.31% for water, 1 wt% and 3 wt% compared to PV module.
Jing *et al.,* [40]	2015	SiO_2/water	Transmittance of the nanofluid with particle size of 5 nm and 2 vol% could be as high as 97% and extremely close to pure water. Thermal conductivity of nanofluids with smaller nanoparticles is higher than those with larger nanoparticles.
Ghadiri *et al.,* [41]	2015	Fe_3O_4/water	For 3 %wt, the overall efficiency improved by 45% when alternating magnetic field (50 Hz) was applied; the overall efficiency increased up to 50%.
An *et al.,* [42]	2016	Cu_9S_5/ oleylamine	Overall efficiency increased by 17.9% compared to PVT without nanofluid.
Hassani *et al.,* [43]	2016	Ag/TherminolVP-1, Ag/water 0.001-1.5 v/v%	The D-1 tube system improves the efficiency of 5.8% for GaAs PV cells and 4.6% on silicon PV cells.
Sardarabadi *et al.,* [44]	2016	Al_2O_3, TiO_2, ZnO/air 0.2 wt%	ZnO/water and TiO_2/water have higher electrical efficiency compared to Al_2O_3/water and water, each with an increase of 6.54% and 6.46% compared to PV. Addition of nanofluid density increases the level of decreasing PV surface temperature.
Khanjari *et al.,* [45]	2016	Ag/water, Alumina/water	With nanofluids, PV, thermal and PVT energy efficiencies of 10%–13.7%, 55% and 90%, respectively, and PVT exergy efficiency of 15%.
Hjerrild *et al.,* [46]	2016	Ag-SiO_2 nanodisk/water	Shows the highest merit and its electric efficiency is 6.6%
Al-Shamani *et al.,* [47]	2016	Water-SiO_2/ TiO_2/ SiC	Results shows that with SiC nanofluid have the maximum thermal and electrical efficiencies of 81.73% and 13.52%.
Lari and Sahin [48]	2017	Water-silver	Shows that 13.2% PV energy efficiency was achieved for nanofluid-based PVT collector. Use of silver/water nanofluid resulted in a maximum of 18% more thermal output.
Al-Waeli *et al.,* [49]	2017	Water-paraffin wax mixed + nano-SiC	Results shows that with paraffin-nanofluid increased the electrical efficiency from 7.1% to 13.7%, the power from 61.1W to 120.7 W, and the open circuit voltage from 11–13 V to 20–21 V. The system made use of the thermal energy gained as its thermal efficiency reached 72%.
Al-Waeli *et al.,* [50]	2017	Water-Al_2O_3/ CuO/SiC	Results shows that thermal conductivity increased as nanoparticle were added to water. The improvement in thermal conductivity was 4.8, 3.42, and 1.96% for SiC, CuO, and Al_2O_3 nanofluids, respectively.
Al-Waeli *et al.,* [51]	2018	Water-SiC	Results shows that the superiority of the indoor test in thermal and electrical energies produced by about 5.46% makes it more efficient than the outdoor test.
Al-Waeli *et al.,* [52]	2018	Water-SiC, Water-paraffin wax/SiC	Results shows that nano-paraffin and SiC nanofluids are the best coolants out of the three methods, which yield the maximum efficiency as high as 13.32% compared with conventional PV value equal to 8.07%.
Al-Waeli *et al.,* [53]	2018	Water-SiC	Results shows that the with nanofluids as a coolant instead of water reduced the temperature of the PV module by 28.1% and increased the thermal energy by about 112.9 and the thermal efficiency up to 89.75% in comparison to water.

Nanofluid filters are more dynamically controlled and low operating costs due to the few required mixes. At higher concentrations, more and more solar radiation on low efficiency and ineffective strips to PV modules absorbed by nanofluid [42]. The saving time of PVT payback of nanofluids was shorter than normal fluid PVT and PV modules. In addition, the superior thermal properties of nanofluid help heat transfer efficiencies while reducing carbon emissions to the environment [43]. Studies on nanofluids-based PVT collectors have been recently conducted [44-53] as shown in Table 1.

Table 1 shows a summary of the studies of nanofluids-based PVT collectors. The study involved nanofluid in a flat plate PVT collector. Nanofluid acts as a coolant and is transmitted under the PV module to see the effects of fluid cooling on PVT efficiency. Flat plate designs are chosen based on easy installation and cost savings. Studies on CNT nanofluid cooling in PVT collectors have not been examined by experimental researchers. While the study of TiO_2 was carried out at lower concentrations than previous studies in comparison with the results of Sardarabadi *et al.,* [44]. Therefore, this study is very relevant to study the improvement of PVT performance when transmitted by CNT and TiO_2 nanofluid.

4. Conclusions

The following conclusions are drawn from this review.

- Researchers have attempted to use nanofluids as a replacement to existing fluids due to their limitations in terms of thermal conductivity, heat transfer coefficient and scattering stability involving micrometre-sized particles.
- Effective heat transfer can increase the efficiency of the PVT collector operation and power generation.
- The thermal conductivity of nanofluids is enhanced with the use of small-sized nanoparticles, high volume fraction and stable nanofluids.
- The preparation of nanofluids is an important parameter to optimize the use of superior thermal properties for practical applications.
- Nanofluid is predicted to be the next-generation heat transfer fluid because of its new and exciting properties compared with pure liquids.

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