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A review on Application of Hybrid Nanofluids for Thermal Management of Solar PV Modules

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Abstract

Renewable energy systems have received a special attention in the recent decades, mainly due to the environmental problems of using fossil fuels; fluctuation in the price of these fuels, limitations in their resources, and considerable demand for energy. Solar photovoltaic (PV) modules are among the most attractive options for power production using solar energy. A variety of factors including the material, operating conditions, and temperature influence the PV efficiency. Elevation in the cell temperature causes degradation in efficiency, and consequently, the production of electricity at a constant solar radiation intensity and operating conditions. In this regard, employment of thermal management systems is considered to avoid temperature increments. Hybrid nanofluids due to their significant thermophysical properties are attractive options for thermal management of the PV cells. This article reviews and presents studies on the thermal management of PV cells. We conclude that different factors such as the type of nanomaterial, cooling configuration, and operating conditions influence the effectiveness of hybrid nanofluids in thermal management of the PV cells. Furthermore, reports suggest that the use of hybrid nanofluids, depending on the nanomaterials, may be more effective than single nanofluids in reducing the temperature of the PV modules. Applying hybrid nanofluids instead of pure fluids would result in higher energy and exergy efficiencies. Aside from technical benefits, utilization of hybrid nanofluids in PV cooling could be beneficial in terms of economy. For instance, using hybrid nanofluids for module cooling can reduce the payback period of the systems.

Keywords: *Hybrid nanofluids, PV module, Thermal management, Exergy efficiency..*

1. Introduction

Environmental problems regarding the emissions of harmful greenhouse gases, increasing demand for the energy, and limitation in the fossil fuels resources in addition to their price instability are among the most important reasons for shifting towards development of renewable energy sources [1–3]. One of the most attractive types of renewable energies is solar due to its availability in different regions and applicability for a variety of purposes from power generation [4–8] to cooling [9–11], heating [12, 13], and desalination [14, 15]. In general, it is possible to use solar energy directly or indirectly for generation of power by means of different technologies and configurations [16–18]. In case of indirect configurations, thermal energy of solar radiation is used to drive a thermal cycle or turbine for power generation [19, 20]. Solar PV cells are widely used for electricity generation from solar radiation. The outputs of these devices are impacted by different items and elements including the material of the cell [21], operating condition, humidity, and temperature [22]. In different studies, it is pointed out that elevation in the Cell Temperature (CT) causes degradation in the efficiency and reduction of the output [23, 24]. In order to alleviate this problem, employment of a thermal management unit for cooling the cell and keeping their temperature low is recommended.

A variety of techniques are applicable for the PV cell thermal management [25–28]. The applied methods can be classified in two main groups including passive and active, although another class, namely hybrid, can be considered, which is the combination of the mentioned methods. In passive methods, there is no requirement for any energy consuming unit like pump or fan, while in the active approaches, an additional component consuming energy is considered [29, 30]. In general, use of active approaches leads to a better thermal management in comparison with the passive methods; however, there may be some disadvantages such as higher investment and maintenance cost. As one of the most conventional passive methods, use of Phase Change Material (PCM) can be referred. In this technique, PCM is applied to absorb heat from the cell and keep its temperature low. Ahmad et al. [31] proposed a new PCM/PV configuration in order to enhance the electrical efficiency of the cell by use of thermal management. They reported that by applying the proposed configuration, power generation, and efficiency could be enhanced by 14.6% and 17%, respectively, at peak times. In another study, Qasim et al. [32] investigated the effect of utilizing hybrid PCM on the PV panel thermal management. They assessed different numbers of fins from 2 to 11 in the system, and reported that using 11 fins leads to the maximum enhancement in electrical conversion efficiency by 12.2%. In another work [33], an experimental investigation was performed on the solar PV panel thermal management by use of PCM. The results obtained revealed that PCM decreased the surface temperature by 24.24%, and the maximum temperature of the panel was reduced by 17.57%. Furthermore, they reported that with the aid of PCM, hourly and daily efficiencies of the panel were enhanced by 4.43% and 6.34%, respectively. In addition to passive cooling, several studies have focused on the active thermal management of PV modules. One of the active approaches for PV thermal management is the employment of thermoelectric [34]. In addition to thermoelectric, cooling channels with fluid flow could be utilized for cooling the PV modules. Effectiveness of the active cooling methods with use of fluid flow is influenced by several factors, and can be enhanced by use of different techniques. For instance, Salman et al. [35] studied the PV performance enhancement by use of water flow via porous media. Their results revealed that adding porous media leads to the reduction of module mean temperature by 9-14 ℃. Moreover, great enhancement in heat transfer was reported in case of increment in the flow rate.

One of the approaches for improvement of cooling the PV modules by utilization of fluid flow is applying heat transfer fluid with improved properties. For this intention, the use of nanofluids has been evaluated by several scholars [36, 37]. In a study by Sharifpur et al. [38], Single-Walled Carbon Nanotube (SWCNT)/water nanofluid was applied for the thermal management of the PV module, and it was reported that the use of nanofluid instead of water could lead to a better cooling. The energy absorbed from the PV modules can be used for other purposes such as heating. These systems are known as PV/Thermal (PV/T), and have been investigated in several works. Suresh et al. [39] compared performance of the PV module in three conditions including without cooling, cooling with water, and cooling with CuO/water with a 0.6% concentration. The efficiencies of the systems mentioned were 10.23%, 11.39%, and 12.57%, respectively. Janardhana et al. [40] applied the SiO_2 nanofluid for cooling of a PV module to evaluate its effectiveness in cooling. They reported that employment of the nanofluid leads to 17.3% improvement in the mean electrical efficiency of the module. In a study [41], experimental investigation was done on the unglazed PV/thermal (PV/T) utilizing water and the CuO/water nanofluid. They reported that thermal efficiency of the system with nanofluid was higher than the water-cooled system owing to a better thermal energy absorption by use of a nanofluid. In a study by Elmir et al. [42], impact of concentration of a nanofluid, Al_2O_3/water, on the cooling of a PV panel was evaluated. They noted that at low Reynolds number, Re = 5, an increase in concentration from 0 to 10% resulted in 27% improvement in the rate of heat transfer. In another study [43], the effect of shape of nanoparticles, Al_2O_3 on the performance of a PV cell was investigated. In their work, different shapes of nanoparticles, namely, blade, spherical, platelet, cylinder, and brick were considered for the study. They reported that the use of the nanofluids with different shapes results in higher electrical efficiency compared with water. The best performance or the highest electrical efficiency was observed for the nanofluid with blade-shaped particles.

Hybrid nanofluids with significant thermophysical properties have a high potential to improve heat transfer. These kinds of nanofluids have been applied in different cooling systems, and have shown a significant performance [44, 45]. For instance, Chu et al. [46] investigated the use of AIN-Ti_2O_3/water in microchannel heat sink designed for cooling of electronic chips. They reported improvement in the coefficient of heat transfer by up to 43.77% compared with distilled water as the coolant. In another study [47], performance of Al_2O_3, and Cu-Al_2O_3/water nanofluids in thermal management of a battery. They pointed out that the use of the hybrid nanofluid leads to a 3.26% lower temperature of battery compared with the single nanofluid. In general, studies have shown that hybrid nanofluids have a high potential as coolant in thermal management systems [48, 49]. In this regard, these types of nanofluids could be used for an efficient heat removal from the PV modules. In this paper, studies on the usage of hybrid nanofluids in cooling of PV cells are reviewed, and their most significant results are represented and discussed. Moreover, recommendations are offered for future work in this field. The importance of this work and represented findings is provision of cooling by use of hybrid nanofluids to improve their efficiency and achieving a higher output power. The findings of the study would be applicable for the designers, engineers, and scholars to find the potential of hybrid nanofluids for a more efficient cooling of the PV cells and the factors influencing their effectiveness. The most important contributions and importances of the preset review article can be outlined as follows:

- Applications of hybrid nanofluids for thermal management of the PV modules by use of cooling channels and jet impingement systems.
- Effect of different factors on the PV cooling effectiveness by use of hybrid nanofluids.
- Providing suggestions for the future studies on using hybrid nanofluids for the PV modules thermal management.
- Challenges related to the use of hybrid nanofluids in cooling PV modules.

2. Applications of hybrid nanofluids in PV cooling

As mentioned, the performance of the PV cells would be degraded by an increase in their temperature, and applying cooling apparatus in these systems will improve their output. In this work, two main cooling methods including forced convection via the channels and tubes and jet impingement cooling are focused.

2.1. Forced convection via cooling channels and tubes

For thermal management of the PV modules by using liquid as coolant, cooling channels or tubes could be applied for fluid circulation inside them and heat removal form the cell. The coolant of these channels or tubes can be hybrid nanofluid to have a higher heat removal from the modules. In a study by Murtadha [50], cooling performance of Al_2O_3-TiO_2/water for the PV panel was evaluated and compared with the uncooled system. It was found that the use of cooling for the cell would result in a significant improvement in the output. Decrement in the surface temperature of the PV comparative to the PV panel without cooling for Al_2O_3/water, TiO_2/water, and the hybrid nanofluid with a 2% concentration was 19.8%, 14.9%, and 20.9%, respectively. Electrical efficiency of the panel for the mentioned cases were 15.6%, 14.9%, and 17.6%, respectively. Based on these findings, it was deduced that use of the hybrid nanofluid causes the best electrical output. In a study by Birjandi et al. [51], cooling effectiveness of water and a hybrid nanofluid, MWCNT-Fe_3O_4/water, in thermal management of a PV module was investigated and compared. As shown in figure 1, an increase in the mass flow rate causes elevation in the enhancement of efficiency; however, it should be taken into account that the pressure loss and required pumping power will be incremented. Moreover, it can be observed that the use of the nanofluid with a 0.3% concentration leads to a slight increase in the efficiency enhancement of the system. Moreover, it can be observed that cooling effectiveness on the improvement of the performance is more significant at a higher solar radiation.

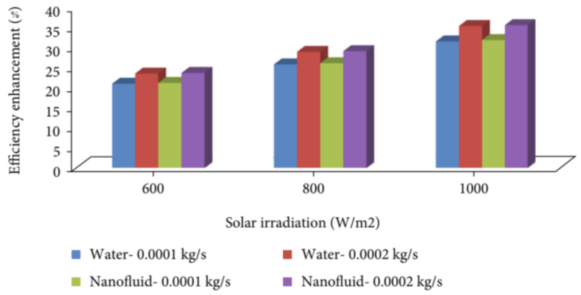

Figure 1. Effect of cooling with different coolants on the efficiency enhancement of the cell (reprinted from ref [51]).

As denoted, heat absorbed from the solar cell by the cooling systems could be applied for heating purposes. Hybrid nanofluids are applicable in these systems, PV/T, to achieve a higher output. In a study by Khan et al. [52], three nanofluids, namely Fe_3O_4/water, SiO_2/water, and Fe_3O_4-SiO_2/water in a PV/T system. The flow rate of the coolant was changed in the range of 20-40 LPM. They reported a higher electrical efficiency, by elevation in the flow rate of the coolant. Moreover, performance of the nanofluids were compared, and it was noted that utilization of the hybrid nanofluid leads to the best performance. At flow rate of 20 LPM, the highest PV temperature drop was 16 ℃, 24 ℃, and 25 ℃ for the system with Fe_3O_4/water, SiO_2/water, and Fe_3O_4-SiO_2/water nanofluids, respectively. In another study by Karaaslan and Menlik [53], performance of CuO/water and CuO-Fe/water nanofluids in a PV/T system was compared. The results obtained showed that employment of the hybrid nanofluid led to enhancement of thermal efficiency by 5.4% and 2% compared with water and single nanofluid, respectively. The system highest electrical efficiency for the hybrid nanofluid, single nanofluid, and water were 11.60%, 11.51%, and 11.36%, respectively. The pressure drops in conditions of using the mentioned working fluids were 214.78 Pa, 172.72 Pa, and 162.08 Pa.

Depending on the applied nanomaterial, the performance of single nanofluids could be better than hybrid nanofluids. For instance, Carbon Nanotubes (CNTs) have a high thermal conductivity, and significantly improve the thermal conductivity of nanofluids. Use of them as the solid phase in the nanofluids can lead to a higher thermal conductivity than the hybrid nanofluids with other types of nanomaterials. In a study by Moghaddam and Karami [54], use of hybrid, Ag-MgO/water, and single nanofluid, CNT/water in a PV/T system was investigated. They considered different concentrations of the nanofluids and channel heights. They found that increment in the concentration led to elevation in both the electrical and thermal efficiencies. Furthermore, they observed that the use of CNT/water nanofluid led to higher efficiencies than the hybrid nanofluid, as shown in figure 2. It should be noted that the friction factor in condition of applying CNT/water nanofluid was higher than the hybrid nanofluid. It is possible to utilize hybrid nanofluids with CNTs in the PV/T systems to benefit from their advantages. In an experimental study by Sathyamurthy et al. [55], the performance of a PV/T system by using water and CNT-Al_2O_3/water nanofluid was compared with the stand-alone PV. In comparison with the PV module without cooling, efficient heat removal from the collector improved the production of power by 21.4% and 11.7% by use of the hybrid nanofluid and water, respectively. Aside from the electrical efficiency, the use of the nanofluid resulted in higher thermal and overall efficiencies compared with water.

Hybrid nanofluids can contain more than two types of nanomaterials. Ternary hybrid nanofluids containing three types of nanomaterials are shown to remarkably increment the thermal conductivity and properties of heat transfer of base fluid [56]. These hybrid nanofluids are applicable in different thermal systems [57, 58]. These kinds of hybrid nanofluids have shown a significant performance for improvement in convective heat transfer [59]. Regarding their ability in heat transfer improvement, the use of these nanofluids could be advantageous in terms of heat removal improvement from the PV modules. In a study by Adun et al. [60], the application of ternary hybrid nanofluid in a PV/T system was evaluated, and compared with single nanofluids. As illustrated in figure 3, the use of the ternary hybrid nanofluid leads to a better improvement in both the thermal and electrical performance. A better performance of the ternary hybrid nanofluid in this system can be attributed to better thermophysical properties of this nanofluid, which means a higher heat removal from the cell, and consequently, a higher electrical and thermal efficiency, similar to the other hybrid nanofluids, mass flow rate of coolant influence heat removal, and overall performance of the system. Adun et al. [61] evaluated the use of a ternary nanofluid, Al_2O_3-ZnO-Fe_3O_4/water in a PV/T system. The numerical analysis on the optimal mixture ratio, 0.33, and the concentration of 0.005% reveals that with an increase in the mass flow rate of the coolant from 0.008 kg/s to 0.1 kg/s, leads to a 23.6% reduction in the temperature of cell.

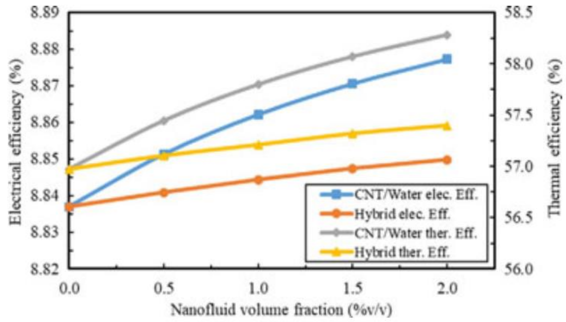

Figure 2. Effect of nanofluid concentrations on electrical and thermal efficiencies (reprinted from ref [54]).

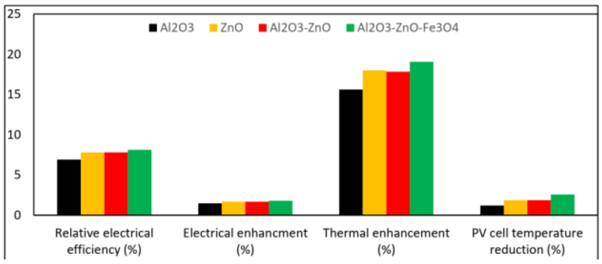

Figure 3. Comparison of PV/T system with ternary hybrid nanofluid and single nanofluids (reprinted (from ref [60]).

Characteristics of the nanofluids and the factors affecting their properties are influential in the performance of the PV/T systems with hybrid nanofluids. The mixture ratio of the hybrid nanofluids influence their properties, and consequently, their heat transfer performance in cooling systems. In a study by Osho et al. [62], impact of mixture ratio of a hybrid nanofluid, Al_2O_3-ZnO/water, on the performance of a PV/T system was investigated. The considered mixture ratios were 0.2, 0.4, 0.47, 0.6, and 0.8 (particle mixture ratio of Al_2O_3 in the hybrid nanofluid), and the concentration was in range of 0.0001-0.01. They found that there was an optimal value for the particle mixture ratio that was 0.47 for the considered cases in this work. In this condition and the concentration of 0.0001, the thermal, electrical, and exergy efficiencies of the system were 55.9%, 13.8%, and 15.13%, respectively. In a study by Kazemian et al. [63], different hybrid nanofluids were evaluated in a combined PV/T and solar collector system. They found that the use of MWCNT-SiC/water with mean overall efficiency of 70.40% had the maximum overall efficiency among the applied hybrid nanofluids. The overall exergy efficiencies of the system by use of Gr-SiC/water, Gr-Al_2O_3/water, MWCNT-SiC/water, and MWCNT-Al_2O_3/water were 15.89%, 15.76%, 15.85%, and 15.73%, respectively.

In addition to the technical benefits, the use of hybrid nanofluids can be advantageous in terms of economy and/or environment. In a study by Alktranee et al. [64], the application of TiO_2-CuO/water nanofluid in a PV/T system was investigated based on the technical and economic criteria. The overall efficiency and electrical power of the system at increased concentration of 0.3% in comparison with the uncooled system enhanced 58.2% and 77.5%, respectively. Moreover, overall exergy efficiency was elevated by 14.97%. Their economic analysis revealed that the payback period of the PV/T system with the hybrid nanofluid was 21 months lower than the conventional module with the payback period of 26 months. In another study by Alktranee et al. [65], applications of single and hybrid nanofluids, TiO_2/water, and TiO_2-Fe_2O_3/water in a PV/T system was investigated based on the technical and economic criteria. The PV/T electrical efficiency by use of the single and hybrid nanofluids in a 0.3% concentration instead of water was improved by 38.36% and 49.52%, respectively, while these values for the thermal efficiency were 35.15% and 38.83%, respectively. Compared with the reference module, utilization of the hybrid nanofluid, single nanofluid in 0.3% concentration and water for cooling led to reduction in exergy losses by 56.14%, 19.11% and 7.31%, respectively. According to the economic analysis, the use of hybrid nanofluid resulted in a better payback period compared with the reference module and the module cooled by the single nanofluid by 160 days and 54 days, respectively. The use of hybrid nanofluids instead of pure water can increase the payback period; however, there are some other advantages such as reduction in the emissions of CO_2. In a study by Adun et al. [61] on a PV/T system with Al_2O_3-ZnO-Fe_3O_4/water ternary hybrid nanofluid, it was reported that the payback period for the water-based and the hybrid-based nanofluids PV/T system was 0.85 years and 2.63 years, respectively; however, CO_2 reduction for the mentioned systems were 18719.88 kg and 19948.05 kg, respectively.

Some other configurations have been evaluated for cooling of PV modules by assistance of liquid flow. In these configurations, hybrid nanofluids can be applied to enhance the cooling performance. In a study by Jasim et al. [66], the performance of the PV/T system utilizing PCM and hybrid nanofluids in a spiral tube with three different geometries of cross-section was evaluated. Different hybrid nanofluids including Al_2O_3-CuO/water, TiO_2-Cu/water, and Fe_3O_4-MWCNT/water were tested in the system. They found that using Fe_3O_4-MWCNT/water led to the minimum temperature of the cell that was followed by TiO_2-Cu/water. In addition to the minimum temperature of the cell, the maximum outlet temperature belonged to the Fe_3O_4-MWCNT/water nanofluid. Moreover, they observed that the increase in the concentration of the nanofluid led to elevation in the electrical efficiency. Among the considered cross-sections, rectangular, circular, and triangular, use of rectangular cross-section resulted in the best performance owing to its larger area of heat transfer compared with the others.

2.2. Cooling by jet impingement

It is possible to use hybrid nanofluids with other cooling techniques in the PV systems [67, 68]. Jet impingement is one of the cooling techniques in which hybrid nanofluids can be applied. Jet impingement with pulsating flow could be applied for the cooling of PV cells. In a study by Maatoug et al. [69], different nanofluids including Al_2O_3/water with cylinder shape nanoparticles, Al_2O_3/water with spherical shape nanoparticles, and hybrid nanofluids, Ag-MgO/water were used in pulsating flow applied for cooling of PV cell, as shown in figure 4. They reported that the use of the hybrid nanofluid could lead to a higher average Nusselt number in comparison with the single nanofluid. Furthermore, it was found for the single nanofluid, shape of the nanoparticles influences cooling performance. The mean Nusselt number increases became 22.9%, 22.8%, and 3.5% for the hybrid nanofluid, nanofluids with cylinder shape particles, and spherical shape particles, respectively, when the minimum and maximum loading of nanomaterials were compared. Moreover, it was reported that the amplitude of pulsation was more influential on the improvement of cooling performance in comparison with its frequency.

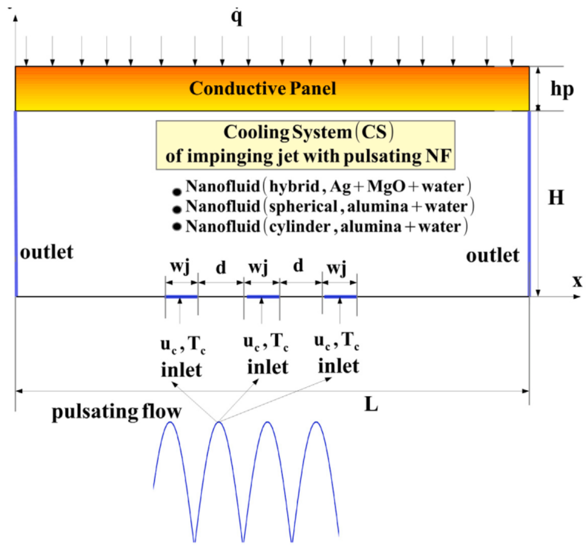

Figure 4. Schematic representation of using pulsating flow for cooling of PV cell [69].

In table 1, the results of the studies reviewed in the current article are provided.

3. Future studies

In section 2 of this article, applications of hybrid nanofluids for the PV modules cooling were reviewed. Consideration of some ideas for the upcoming research works related to the cooling of PV modules by employment of hybrid nanofluids could be worthwhile. For instance, thermophysical properties of nanofluids are influenced by several factors like sonication time and surfactant [70, 71]. Variation in the thermophysical properties would affect their heat transfer characteristics. In regard to this fact, it is recommended to consider hybrid nanofluids with different sonication times or surfactants to evaluate its influence on the cooling performance. Furthermore, there are few research projects on the applications of ternary hybrid nanofluids in cooling of the PV modules, while these hybrid nanofluids can be focused more due to their high potential in heat transfer. Moreover, there are some techniques for enhancement of heat transfer like use of vortex generator in the fluid flow [72]. In the future studies, it would be a good idea to apply vortex generator in the cooling channels of the PV modules in addition to hybrid nanofluids to further increase heat removal. Intelligent methods like Support Vector Machines (SVMs) and Artificial Neural Networks (ANNs) are interesting and practical tools for modeling, and prediction of electrical and thermal systems outputs [4, 73, 74]. These methods could be developed for the PV modules cooled with hybrid nanofluids to facilitate their modeling and time saving for their performance and output prediction. Consideration of sensitivity analysis is another suggestion for the new studies. By implementation of sensitivity analysis, better insight can be obtained on the level of effect of each factor on the output of the system. Aside from the suggestions mentioned, it is useful to perform more types of analyses such as exergoeconomic and exergoenvironmental on the PV modules cooled by hybrid nanofluids.

Table 1. Summary of the reviewed studies.

References	Nanofluid	Key findings
Murtadha [50]	Al_2O_3/water, TiO_2/water, and Al_2O_3-TiO_2/water	Employment of the hybrid nanofluid led to the highest electrical efficiency.
Birjandi et al. [51]	MWCNT-Fe_3O_4/water	Use of the hybrid nanofluid in a 0.3% concentration instead of water leads to a slight improvement in the efficiency.
Khan et al. [52]	Fe_3O_4/water, SiO_2/water, and Fe_3O_4-SiO_2/water	The highest reduction in the temperature was observed for the system with hybrid nanofluid.
Karaaslan and Menlik [53]	CuO/water and CuO-Fe/water	Despite a higher efficiency of the system by use of the hybrid nanofluid, the pressure drop increased compared with the single nanofluid.
Moghaddam and Karami [54]	Ag-MgO/water and CNT/water	Using the CNT/water nanofluid resulted in higher electrical and thermal efficiencies.
Sathyamurthy et al. [55]	CNT-Al_2O_3/water	Use of the hybrid nanofluid provided higher thermal and electrical efficiencies than water.
Osho et al. [62]	Al_2O_3-ZnO/water	Mixture ratio of the hybrid nanofluid influences the performance of the system.
Adun et al. [60]	Al_2O_3 /water, Fe_3O_4 /water, ZnO/water, and Al_2O_3-ZnO-Fe_3O_4/water	The ternary hybrid nanofluid provided higher electrical and thermal efficiencies than the single nanofluids.
Adun et al. [61]	Al_2O_3-ZnO-Fe_3O_4/water	Use of the hybrid nanofluid instead of water leads to an increase in the payback period and CO_2 emission reduction amount.
Kazemian et al. [63]	Gr-SiC/water, Gr-Al_2O_3/water, MWCNT-SiC/water, and MWCNT-Al_2O_3/water	Type of the hybrid nanofluids influence both the energy and exergy efficiencies.
Alktranee et al. [64]	TiO_2-CuO/water	Use of the hybrid nanofluid in the PV/T system leads to an increase in

		the exergy efficiency and decrease in the payback period compared with the conventional PV.
Alktranee et al. [65]	TiO_2/water and TiO_2-Fe_2O_3/water	Compared with the single nanofluid, use of the hybrid nanofluid was preferred in term of the payback period.
Jasim et al. [66]	Al_2O3-CuO/water, TiO_2-Cu/water, and Fe_3O_4-MWCNT/water	Use of Fe_3O_4-MWCNT/water provided the minimum temperature of the cell.
Maatoug et al. [69]	Al_2O_3/water and Ag-MgO/water	Use of hybrid nanofluids lead to a higher average Nusselt number than the single nanofluid.

4. Challenges of using hybrid nanofluids in PV cooling

Although the use of hybrid nanofluids in the PV cooling systems instead of conventional coolants could be advantageous in terms of heat removal, economy, and environment, there are some challenges for development of these systems that must be taken into account. As one of the most important challenges, preparation of a stable hybrid nanofluid can be referred. In the preparation of hybrid nanofluids, nanomaterials tend to agglomerate due to a substantial van-der-Waals interaction effect. Mostly, the long-term stability of dispersion of nanomaterials is one of the key needs of hybrid nanofluid usage [75]. Unstable hybrid nanofluids can disturb cooling of the PV modules. When there exist clusters of particles, settlement of particle clusters at the foundation of cooling system starts that causes increment in the thermal resistance and elevation in the pumping power of fluid by narrowing down the passages of the flow [76]. High preparation cost is another challenge for development of the applications of some hybrid nanofluids [76]. High manufacturing cost of nanofluids is one of the reasons behind delay in their utilization into industry. Both one- or two-step processes for nanofluid process require specialized and sophisticated facilities and equipment [77, 78]. In solar applications, changes in the viscosity will need the system of circulation to change its pumping power. As a consequent, variations in the pumping power and flow rate would disserve the system entirely [79]. Another challenge in the use of hybrid nanofluids is the complexity of the proposed models for the properties of hybrid nanofluids [76]. This can cause some problems for an accurate modeling and simulation of the PV systems cooled by hybrid nanofluids.

5. Conclusion

Hybrid nanofluids as the heat transfer fluids with modified heat transfer properties are attractive options for thermal management of the PV modules to enhance their performance. This article reviewed research works on the usage of hybrid nanofluids in cooling the PV cells. The important results of the research work can be outlined as follows:

- In comparison with the single nanofluids, hybridization of the same nanomaterials can be more effective in temperature reduction of the PV modules.
- Aside from the thermal efficiency, the use of hybrid nanofluids would lead to the improvement of the electrical and overall efficiency of the PV/T systems.
- Performance elevation of PV modules cooled by hybrid nanofluids is impacted by different factors such as the system configuration, solar radiation, mass flow rate, and concentration.
- Aside from the technical benefits, it is possible to have economic advantages by using hybrid nanofluids for the PV modules thermal management.
- Mixture ratio of the hybrid nanofluids would influence the thermophysical features, and consequently, their cooling performance.
- The nanomaterials in the hybrid nanofluids influence the thermal features and cooling effectiveness.
- The use of hybrid nanofluids instead of pure fluids for cooling of PV modules could lead to increase in reduction of CO_2 emission.

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