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REVIEW ARTICLE

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Application of metal oxides-based nanofluids in PV/T systems: a review

Abstract Having the wide application of metal oxides in energy technologies, in recent years, many researchers tried to increase the performance of the PV/T system by using metal oxide-based nanofluids (NFs) as coolants or optical filters or both at the same time. This paper summarizes recent research activities on various metal oxides (Al_2O_3, TiO_2, SiO_2, Fe_3O_4, CuO, ZnO, MgO)-based NFs performance in the PV/T system regarding different significant parameters, e.g., thermal conductivity, volume fraction, mass flowrate, electrical, thermal and overall efficiency, etc. By conducting a comparative study among the metal oxide-based NFs, Al_2O_3/SiO_2-water NFs are mostly used to achieve maximum performance. The Al_2O_3-water NF has a prominent heat transfer feature with a maximum electrical efficiency of 17%, and a maximum temperature reduction of PV module of up to 36.9°C can be achieved by using the Al_2O_3-water NF as a coolant. Additionally, studies suggest that the PV cell's efficiency of up to 30% can be enhanced by using a solar tracking system. Besides, TiO_2-water NFs have been proved to have the highest thermal efficiency of 86% in the PV/T system, but TiO_2 nanoparticles could be hazardous for human health. As a spectral filter, SiO_2-water NF at a size of 5 nm and a volume fraction of 2% seems to be very favorable for PV/T systems. Studies show that the combined use of NFs as coolants and spectral filters in the PV/T system could provide a higher overall efficiency at a cheaper rate. Finally, the opportunities and challenges of using NFs in PV/T systems are also discussed.

Keywords metal oxide, nanofluids (NFs), nanoparticles (NPs), optical filter, PV/T systems, solar energy

1 Introduction

Solar energy is clean, free, boundless, eco-friendly, sustainable, and everlasting, which is the paramount source of renewable energy [1–6]. The earth receives a power of about 1.8×10^{11} MW from the sun which is 1000 times bigger than the power consumption from all sources [2,7,8]. This incoming solar energy can be directly transformed into electrical energy via a PV module [9–13]. But PV modules can convert only up to 20% of solar energy into electrical energy, and the remaining solar energy is either reflected to the atmosphere or transformed into heat, which increases the PV cell temperature [2,14–18]. The PV module electrical conversion efficiency highly depends on the working temperature. With the increase of cell temperature, the PV module electrical conversion efficiency is decreased [19–30]. Therefore, it is necessary to cool down the PV panel to maximize its efficiency. Different cooling techniques, such as the active and passive cooling technique, are implemented by different researchers for cooling the PV panel. In the active cooling technique, nanofluids (NFs), H_2O, etc. used for cooling on the other hand PCM (phase change materials) like organic materials, paraffin wax, cotton wick, etc. are used for cooling purposes in the passive cooling technique [14,31–33]. Photovoltaic thermal (PV/T) systems are introduced to provide both electrical and thermal energy at the same time, with high efficiencies. Installing PV/T systems have the benefit of supplying effective solar technology, space reduction, single warranty, and cost-saving associated with installing a solar thermal and solar PV separately. In PV/T systems the extracted heat by coolant from the PV panel is further used for thermal energy generation [34–40]. As is known, effective cooling of PV panels is one of the challenges for PV/T systems; therefore, in recent years researchers are fascinated to use NFs as cooling media

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because of their greater heat transfer characteristics compared to conventional fluids [2,41–51]. In PV/T systems NFs can be used as coolants or spectral filters or both at the same time. In spectral filter cooling, NFs are used to selectively absorb/separate the incoming solar radiation incident on the PV cell surface which can be converted into electricity, while it can capture the rest of the solar radiation for thermal applications and the using of NFs as optical filters can increase the PV/T system efficiencies [52–61].

Many researchers studied the performance of NFs in PV/T systems but in previous reviews, to the best of the author's knowledge, no study combined the performance of metal oxide-based NFs in PV/T systems. Metal oxides are widely used in the energy production and conversion technology. Consequently, many researchers [41,62–100] used metal oxides-based NFs in PV/T systems as coolants or spectral filters or both at the same time for improving the performance of PV/T systems. Therefore, this paper investigated the performance of metal oxide-based NFs in PV/T systems regarding various important parameters such as thermal conductivity, nanoparticle concentration, temperature reduction of PV panel, mass flowrate, solar radiance, electrical efficiency, and thermal and overall efficiency. Additionally, it also compared the performances of metal oxide-based NFs in PV/T systems by including almost all recent studies which center on metal oxide-based NFs on PV/T systems. The first segment of this paper presents important parameters related to a very brief detailed study of metal oxides, NFs, PV/T systems, and the optical filter. The second segment compiles the recent experimental and numerical studies of metal oxide-based NFs in PV/T systems. The last segment discusses the opportunities and challenges of using NFs/metal oxide in PV/T systems.

2 Metal oxides, NFs, PV/T systems, and optical filter

2.1 Metal oxides

A metal-oxides is defined as a crystalline solid that holds a metal cation and oxide anion [101]. As shown in Fig. 1, metal oxides have a wide variety of applications. In energy storage technologies, metal oxides are commonly applied because they are typically capable of producing charge carriers when energy is applied. Via the development of renewable energy and the decay of environmental organic pollutants, metal oxide catalysts and electrode materials have become critically important in eliminating energy and environmental crises. Solar panels, fuel cells, and other new energy transformation technologies are increasingly becoming suitable regarding efficiency, price, and long-term stability. Metal oxides have captivated researchers over the past four decades with their extensive uses from power production, transformation and storing to the hydrogen economy, energy-saving smart windows, the atmosphere, and transmission and conversion of AC power [102].

2.2 PV/T systems

PV modules that convert sunlight directly into electrical energy are semiconductor devices. Hybrid PV/T systems replaced the PV modules to establish both thermal and electrical output with high efficiencies [2,62,103–108]. The main purpose of this kind of design is to afford cooling for the PV panel by fascinating its temperature [62]. Due to system features, the losses of efficiency ascending from the PV modules overheating are prohibited and the unused heat can be recovered by the working fluid which can be further used for thermal applications [103,109]. PV/T

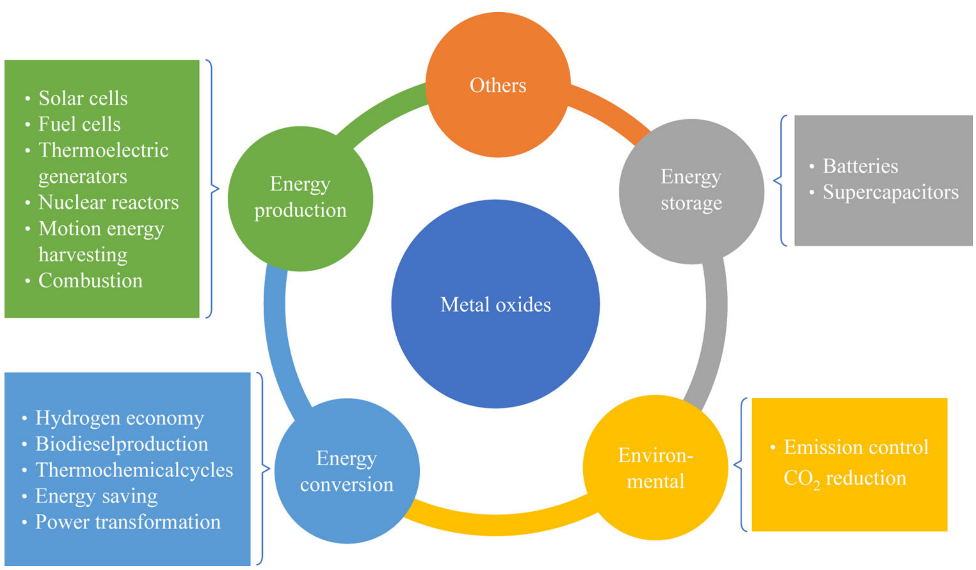

Fig. 1 Metal oxide applications in energy technologies (adapted with permission from Ref. [102]).

system technologies are mainly classified into three types, i.e., collector type, coolant type, and material type, as demonstrated in Fig. 2 [110].

2.3 NFs

In 1995 Choi and Eastman first proposed the term “nanofluid.” NF is a combination of nanoparticles (NPs) having a 1–100 nm diameter, suspended in base fluids (BF) like water, ethanol, EG, oil, refrigerants, and glycerin, etc [62,111–120]. By utilizing NFs, the heat transfer through the fluid can be improved along with the thermal performance of the entire system [46,113,121,122]. In general, NPs are classified into three groups, metal-based, carbon-based, and nanocomposites, as illustrated in Fig. 3 [113].

In the review methodology, the papers were focused on where researchers used metal oxide-based NFs as coolants or optical filters or both at the same time in the PV/T systems for improving their performance in recent years, i.e., mostly in the range of 2015–2020 from Scopus database searched by the selected keywords. In addition, in paper evaluation, the thermal and electrical efficiencies of the PV/T system were mainly focused on. Moreover, in paper selection, the hybrid NF, carbon-based NFs, and nanocomposites were excluded in.

The heat transfer capability of NFs entirely depends on their thermophysical properties [46]. Table 1 summarizes the thermo-physical properties of different metal oxide NPs.

2.3.1 Preparation of NFs

In general, two types of methods, i.e., the one/single step and the two-step methods, are utilized for the preparation of NFs, respectively [112,127,128]. Figure 4 briefly classified the two preparation methods of NFs.

In the single-step method, NPs preparation and a mixture of NFs are completed in a single step. The dispersion and making of NPs happen in the very same phase in this process. It is possible to perform this process either by physical or chemical means. For the synthetization of NPs, the ultra-sonic aided submerged arc scheme is utilized in the physical method. To melt the NPs and vaporize the deionized water (DIW), the electrical energy produced from titanium electrodes that are sinker into the dielectric liquid is utilized. After this, the NF is produced in the vacuum chamber, which is the mixture of the melted NPs and DIW. The chemical process, on the other hand, relies on applying a reduction agent to the mix of NPs and BF, accompanied by stirring and heating [112,113]. In the two-step method, at first, the NPs are purchased or produced in the dry powder form and then dispersed in the BFs. Ultrasonic bath, magnetic stirrers, high-shear blenders, homogenizers, and bead mills are usually used for dispersing NPs in the BFs [112,130]. In general, the two-step method is usually practiced for NFs preparation because of its low preparation cost, and large availability of commercially provided NPs from many companies [112]. The preparation of NFs, either employing one-step or two-step method is not easy. It faces some difficulties such as long-term stability due to agglomeration is the main drawbacks of the two-step method. Again the one-step method has residual reactants in the NFs because of imperfect reaction or stabilization [131]. Furthermore, production process of NFs requires advanced equipment which excludes the uses of NFs [132].

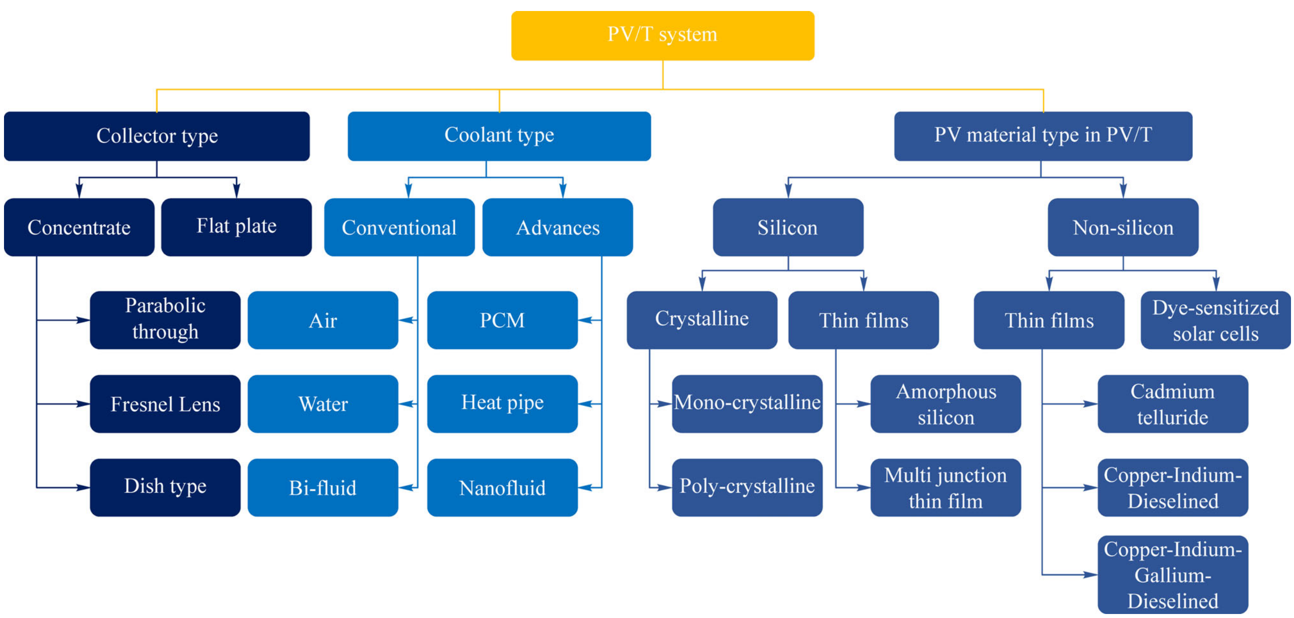

Fig. 2 Categorization of PV/T technologies (adapted with permission from Ref. [110]).

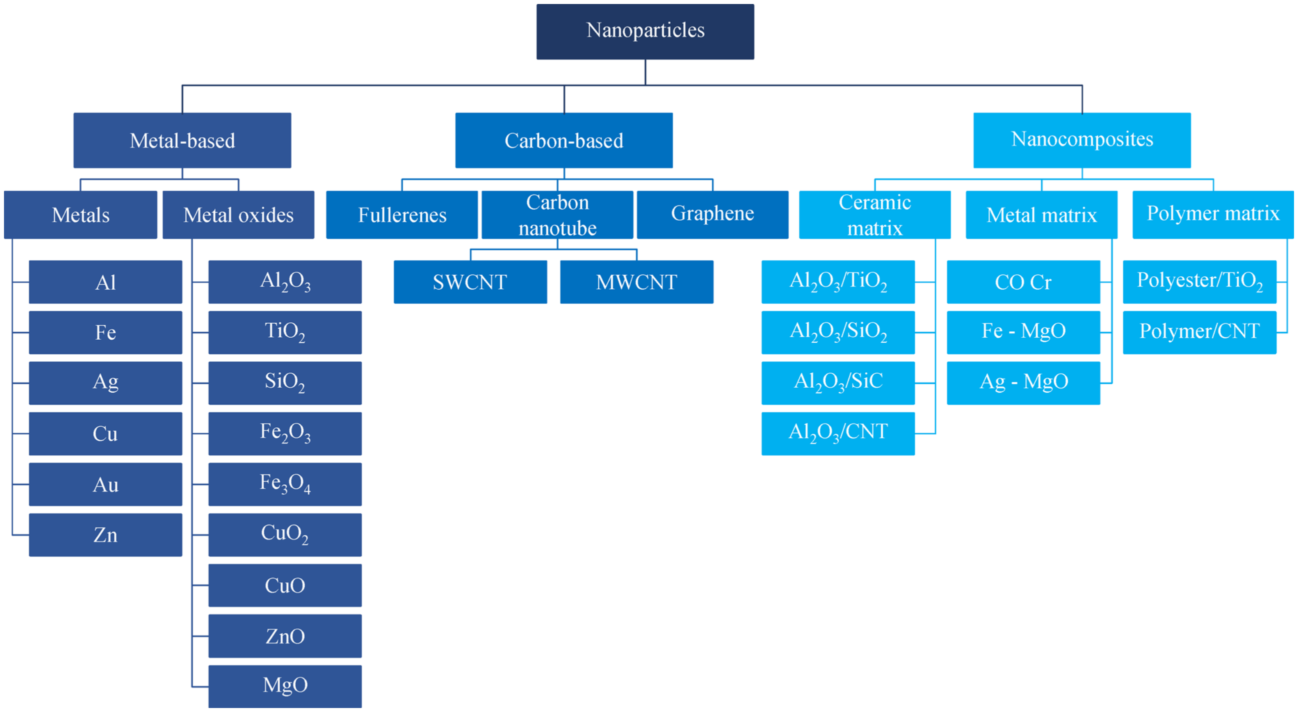

Fig. 3 Nanoparticle classification and types (adapted from Ref. [113] under the Creative Commons Attribution License).

Table 1 Thermophysical properties of metal oxide NPs

Ref.	Metal oxide	Thermal conductivity, $k/(\mathrm{W\cdot(m\cdot K)^{-1}})$	Specific heat, $C_P/(\mathrm{J\cdot(kg\cdot K)^{-1}})$	Density, $\rho/(\mathrm{kg\cdot m^{-3}})$
[123]	Al_2O_3	40	773	3960
[123]	TiO_2	8.4	692	4230
[124]	SiO_2	1.4	745	2220
[125]	Fe_3O_4	9.7	670	5180
[123]	CuO	33	551	6000
[64]	ZnO	13	495	5600
[126]	MgO	8.15 (at 699.8 K temp)	925.92 (at 300 K temp)	3650 (at 298 K temp)

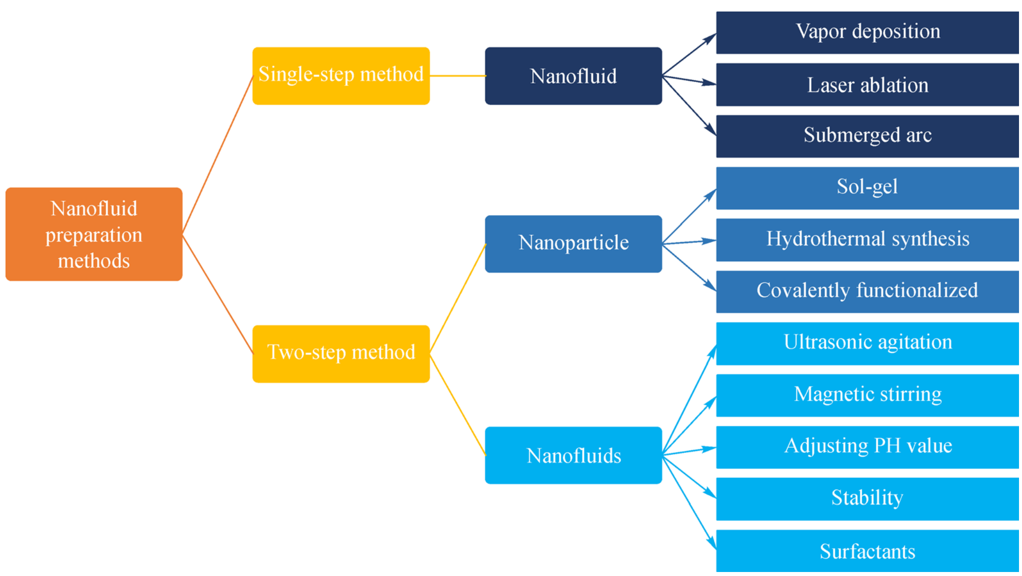

Fig. 4 Classification of NF preparation method (adapted from Ref. [129] under the Creative Commons Attribution License).

2.3.2 NFs uses in PV/T energy system

As is known, PV system performance is extremely affected by its high operating temperature. With the increase of temperature, the electrical efficiency of the PV module is decreased. NFs help to enhance the heat removal and heat transfer of the PV system as a working fluid [9,65,133]. The application of NFs in PV/T systems enhances the electrical and thermal efficiency because the thermal conductivity of conventional fluids is significantly lower than that of the NFs [103]. NFs are dually utilized in the PV/T systems as coolants and as optical filters. Again, these two types can be classified into four types as depicted in Fig. 5. Among these four types, in the PV/T system, many studies are focused on the use of NFs as coolants [47,134].

2.4 Optical filters

An optical filter is a device that is used to selectively transmits or reject the optical spectrum. PV cells are not able to utilize a complete solar spectrum that falls into it. They are capable of converting only a portion of the solar spectrum into electricity. Incoming light greater than a wavelength of 700–1100 nm is converted into heat, increasing the cell temperature, and consequently, decreases in efficiency [49]. NFs are a decent applicant for spectral splitting. NFs work as good optical filters by the spectral splitting system. In the PV/T system, a NF based optical filter can be utilized as a heat transfer as well as thermal storing medium [135]. A NF-based spectral splitting CPV/T system is exhibited in Fig. 6, where the cooled NF enters the glass tube and exits as heated fluid by absorbing the light between a wavelength of 1100–2500 nm, which can be further used for thermal energy [136]. A 2-D PV/T system model was designed by Jing et al. [98] based on the experimental measurements. In that model, NFs were flowing first below and then above the PV panel. The NFs flowing above the PV panel work as optical filters of the solar spectrum, and by flowing through below the PV panel, the NFs take away the extra heat of the PV panel, in such kind of model optical NF and thermal NF work together to improve the overall efficiency of the PV/T systems, which could provide electricity and thermal energy at an economical price [2,49].

3 Literature of the previous work

Al-Waeli et al. [62] numerically studied the effect of operating different NPs (Al_2O_3, CuO, and SiC) and BF types of (water, EG, and glycerin) in PV/T systems on the

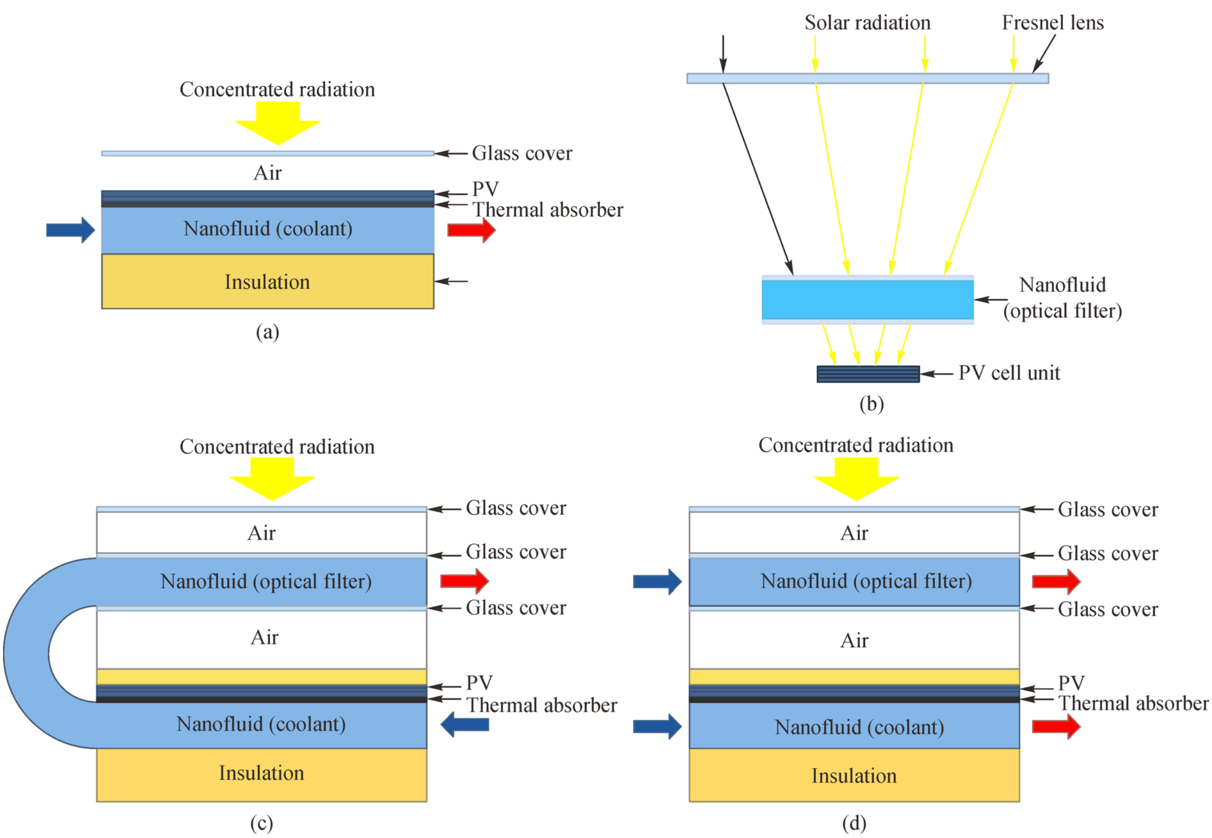

Fig. 5 Schematic of PV/T system with NF (adapted with permission from Ref. [47]).
(a) Coolant; (b) spectral filter; (c) coolant and spectral filter with a double-pass channel; (d) coolant and spectral filter with separate channels.

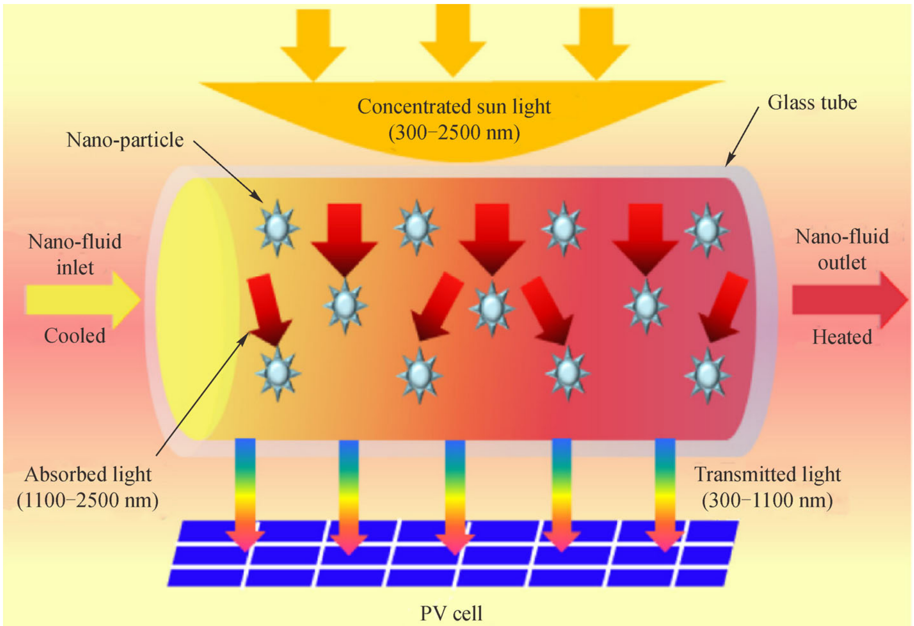

Fig. 6 NF-based spectral splitting CPV/T system (adapted with permission from Ref. [136]).

convective heat transfer. They found that the BF and the added NPs thermophysical properties had a strong impact on the pressure drop and convective heat transfer of PV/T systems. With the increase of flowrate, the heat transfer coefficient and pressure drop were increased. As a BF, the water presented the minimum pressure drop while glycerin showed the maximum value.

Rejeb et al. [66] directed a combined numerical and experimental study to assess the performance of NF-based PV/T collector using Al_2O_3 and Cu NPs at a mass fraction of 0.4%, 0.2%, and 0.1% and BF as pure H_2O and EG. Figure 7 displays the experimental setup and schematic diagram of this study. The result indicates that with the enhancement of NPs addition, the electrical and thermal performance of the system is increased. Besides, as a BF, pure water has a better performance compared to EG.

Ghadiri et al. [67] experimentally studied the performance of the PV/T system utilizing Fe_3O_4-water NF as a coolant at two different mass fractions (1% and 3%). Figure 8 shows the experimental setup and schematic diagram of the study. The result shows that at at a mass fractions of 3% Fe_3O_4-water NF, the overall efficiency is improved by about 76% compared with DW. Using Fe_3O_4-water NF at a mass fraction of 3% and an alternating magnetic field of 50 Hz, the thermal efficiency of the system reaches about 74.96%. On the other hand, using Fe_3O_4-water NF at a mass fraction of 3% and an alternating magnetic field of 50 Hz, the electrical efficiency reaches about 7.7%.

Al-Shamani et al. [68] directed an experimental study to assess the performance of different NPs (SiO_2, TiO_2, and SiC) at different flowrates and solar irradiance on PV/T systems, whose experimental setup is plotted in Fig. 9. The result shows that the efficiency of the PV/T system is improved with the increase of flowrate and solar irradiance. The electrical and thermal efficiency is about 10%, 11%, and 73%, 76% when utilizing SiO_2-water and TiO_2-water NFs, respectively.

Hussien et al. [69] utilized Al_2O_3-water NF as a coolant to improve the performance of PV/T systems. The result suggests that utilizing Al_2O_3-water NF at a mass fraction of 0.3% and a mass flowrate of 0.2 L/s, the temperature of the PV module decreases significantly from 79.1°C to 42.2°C which directs to an electrical and thermal efficiency increase of solar panel of about 12.1% and 34.4%, respectively.

Hosseinzadeh et al. [64] validated a 3D numerical model and compared with the experimental result, using ZnO-water NF as coolant. Figure 10 displays the schematic diagram of the study. The result indicats that the thermal efficiency of the PV/T system is increased with the increase of solar irradiance absorbance, the mass fraction of NF, the mass flowrate of coolant, and ambient temperature. The PV/T system thermal performance is increased by about 16.21% as the inlet temperature of the coolant reduces from 40°C to 20°C.

Sardarabadi et al. [70] experimentally studied the effects of using Al_2O_3-H_2O, TiO_2-H_2O, and ZnO-H_2O NFs as a coolant in PV/T systems at a mass fraction of 0.2% at FUM, Mashhad, Iran on particular days in August and September. The result demonstrates that the electrical and thermal efficiency is about (13.44%, 13.63%, and 13.59%) and (36.66%, 44.34%, and 46.05%) for Al_2O_3-H_2O, TiO_2-H_2O, and ZnO-H_2O, respectively. Besides, the overall

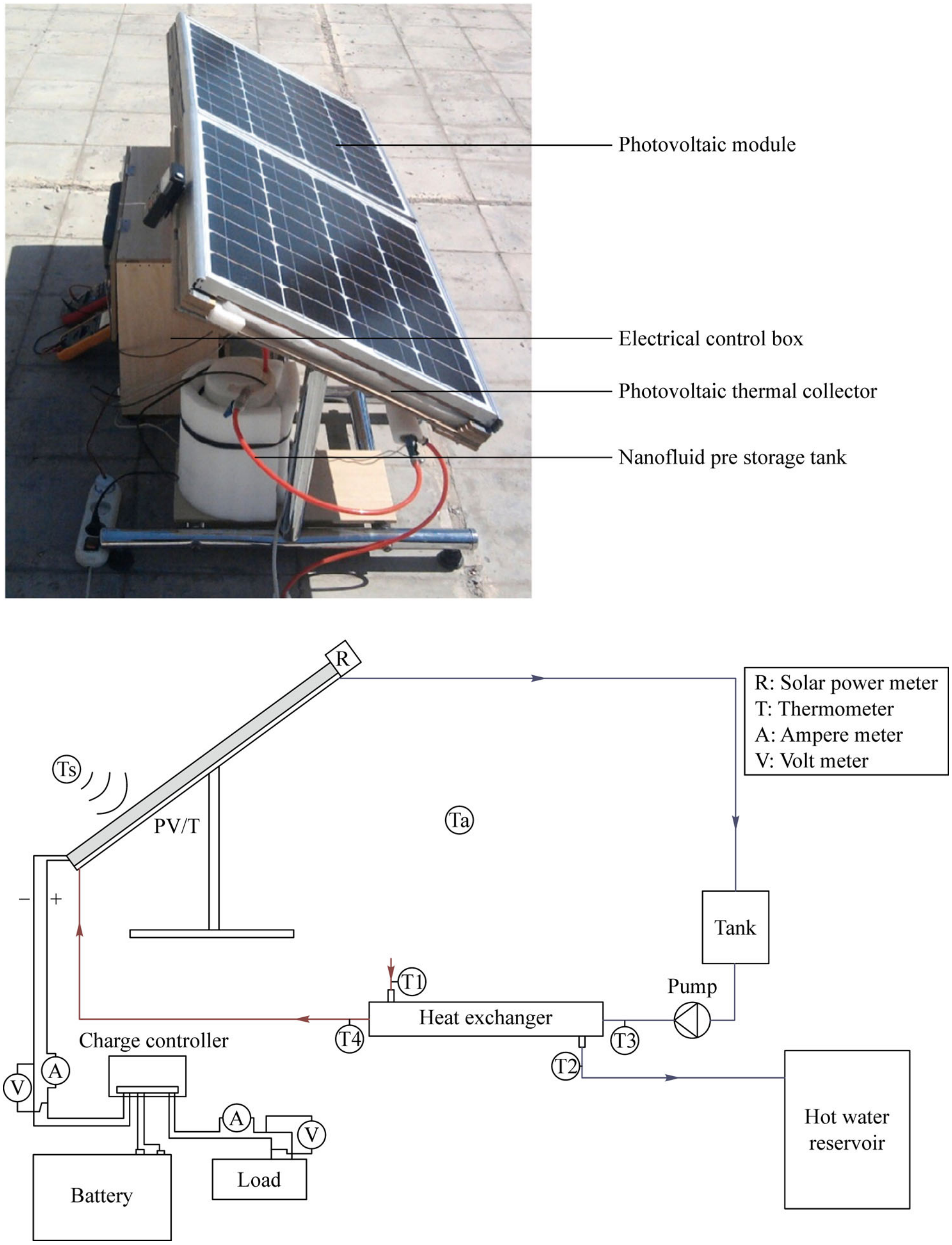

Fig. 7 Experimental setup and schematic diagram of PV/T system (adapted with permission from Ref. [66]).

exergy efficiency is about 18.27%, 15.93%, and 15.45% for Al_2O_3-H_2O, TiO_2-H_2O, and ZnO-H_2O, respectively, compared with the PV unit having no collector.

Hussain and Kim [71] used a trapezoidal-shaped receiver to collect solar radiance using Al_2O_3-H_2O and CuO-H_2O NFs as coolant. The temperature reduces from 69.9°C (reference PV cell temperature) to 53.7°C and 50.6°C for Al_2O_3-H_2O and CuO-H_2O NFs, respectively. The thermal efficiency of the reference PV is about 35.53% but by using Al_2O_3-H_2O and CuO-H_2O NFs as coolant, the thermal efficiency increases up to 78.83% and 80.94% for Al_2O_3-H_2O and CuO-H_2O NFs, respectively.

Al-Shamani et al. [65] mathematically and experimentally assessed the thermal and electrical performance of PV/T collectors using CuO, SiO_2, and ZnO-water NFs at a mass flowrate of 0–0.04 kg/s. Figure 11 shows the schematic diagram of the study. The result suggests that a mass flowrate of 0.03 kg/s is optimal for achieving the maximum temperature reduction and overall efficiency of the system. When SiO_2-H_2O NF is used as a coolant, the PV module temperature is reduced from 65°C to 45°C. Besides, the thermal, electrical, and overall efficiency increased for SiO_2-water NF is about 64.40%, 12.70%, and 77.10%, respectively. With the increase of the solar irradiance ranging from 400 to 1000 W/m^2, the highest power of the PV/T system with SiO_2-water NF improves remarkably from 43.77 W to 75.62 W.

Al-Waeli et al. [72] conducted an indoor experimental

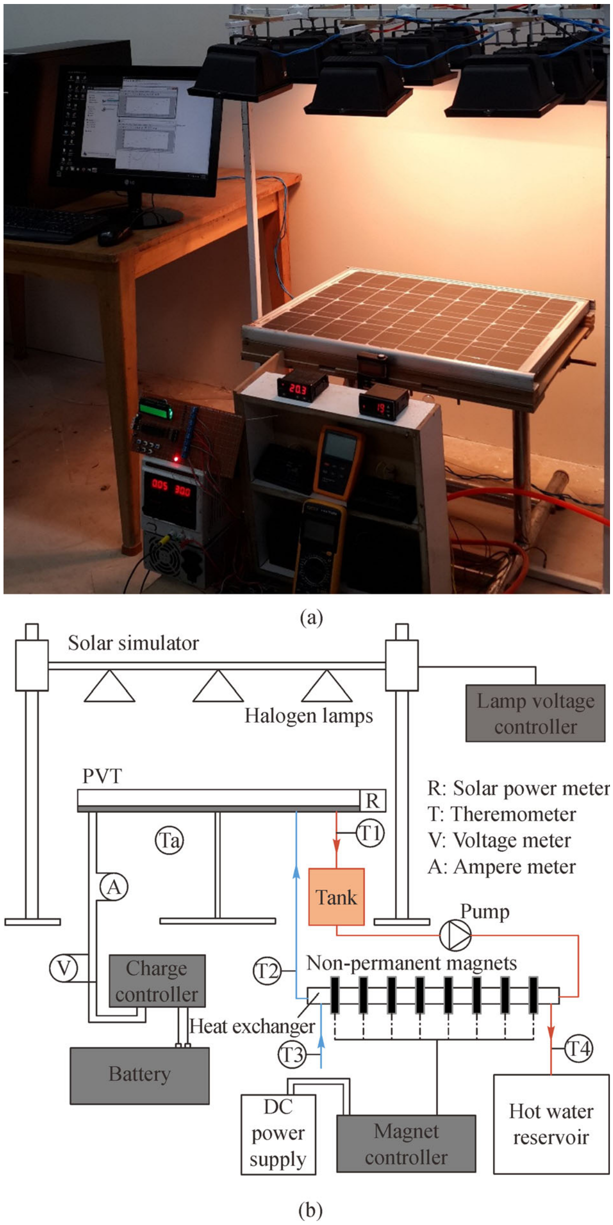

Fig. 8 Experimental setup and schematic diagram for studying performance of PV/T system utilizing Fe_3O_4-water NF as a coolant (adapted with permission from Ref. [67]).
(a) Experimental setup; (b) schematic diagram.

study to assess the thermophysical properties of different NPs (Al_2O_3, CuO, and SiC) and BF as water in PV/T systems. The results indicate that by adding NPs to water, the thermal conductivity is increased. The thermal conductivity is improved by about 1.96% and 3.42%, for Al_2O_3-water and CuO-water NFs at a volume fraction of 4%, respectively.

Chamkha and Selimefendigil [73] analyzed the effects of different particle shapes, water inlet temperature, solar irradiations, and wind speed on PV/T systems using SiO_2-water NF. The greatest performance in the case of efficiency improvements is found for cylindrical shape particles. By cylindrical shapes particles, about 7.39% of total efficiency improves at the maximum volume fraction (%). Efficiencies are increased with the increase of volume fraction (%) where the maximum volume fraction was 0.05%. At the maximum volume fraction (%) for NP, the thermal efficiency increase by about 9.82% for NF. Even though the SiO_2 NP has a low thermal conductivity associated with other particles, its low-price, chemical properties, and advantages in physical properties make it favorable for practice with water.

Kolahanet [74] conducted an experimental and numerical combined study to evaluate the effect of addition of NPs in PV/T systems on entropy generation using Al_2O_3-water, TiO_2-water, and ZnO-water NFs. It is found that SiO_2-water NF shows the maximum entropy generation which is not promising. On the other hand, Al_2O_3-water NF has the best performance in the case of thermal and total entropy production. Moreover, ZnO-water NF generates the lowest frictional entropy.

Binti Rukman et al. [75] experimentally evaluated the performances of using MWCNT and TiO_2 NPs-based PV/T systems. The result shows that PV/T systems functioning with NFs offer better temperature changes. The minimum temperature of PV modules is found when TiO_2-water NF at a mass fraction of 1.0% is used in the collector. With the increase of the mass flowrate at the PV surface, the temperature reduction is increased.

Hussain et al. [76] conducted a numerical study using Al_2O_3, TiO_2, and CuO NPs in dual-fluid PV/T systems, and studied the effect of using metal oxides NPs in various concentrations on BF. The study indicates that with the increase in mass flowrate, the performance of PV/T systems is increased. The result shows that the heat transfer performance is extremely reliant on NP concentration and a CuO NP concentration of 0.75% has a more promising output compared with the colloidal solutions. In the studied range of concentrations and flowrates, TiO_2 NP shows the maximum performance compared with without cooling and water cooling.

Lee et al. [77] experimentally studied the improvement of the efficiency of PV/T systems using CuO-water and Al_2O_3-water NFs at a mass fraction of 0.05% and a flowrate of 3 L/min. The study confirms that adding NPs to the BF can increase the heat transfer characteristics, which suggests that using NP can increase the efficiency of PV/T systems. From the result, the thermal and electrical efficiency of CuO-water NF in PV/T systems is found to be 48.88% and 13.20%, respectively. The thermal efficiency and electrical efficiency of the water-based PV/T system are 27.58% and 13.13%, respectively. On the other hand, the thermal efficiency and electrical efficiency of Al_2O_3-water NF in PV/T systems are 46.95% and 12.22%, respectively. Besides, the thermal efficiency and electrical efficiency of the water-based PV/T system is 31.81% and 12.21%, respectively. The study indicates that using NFs in PV/T systems can slightly increase the electrical efficiency but can greatly increase the thermal

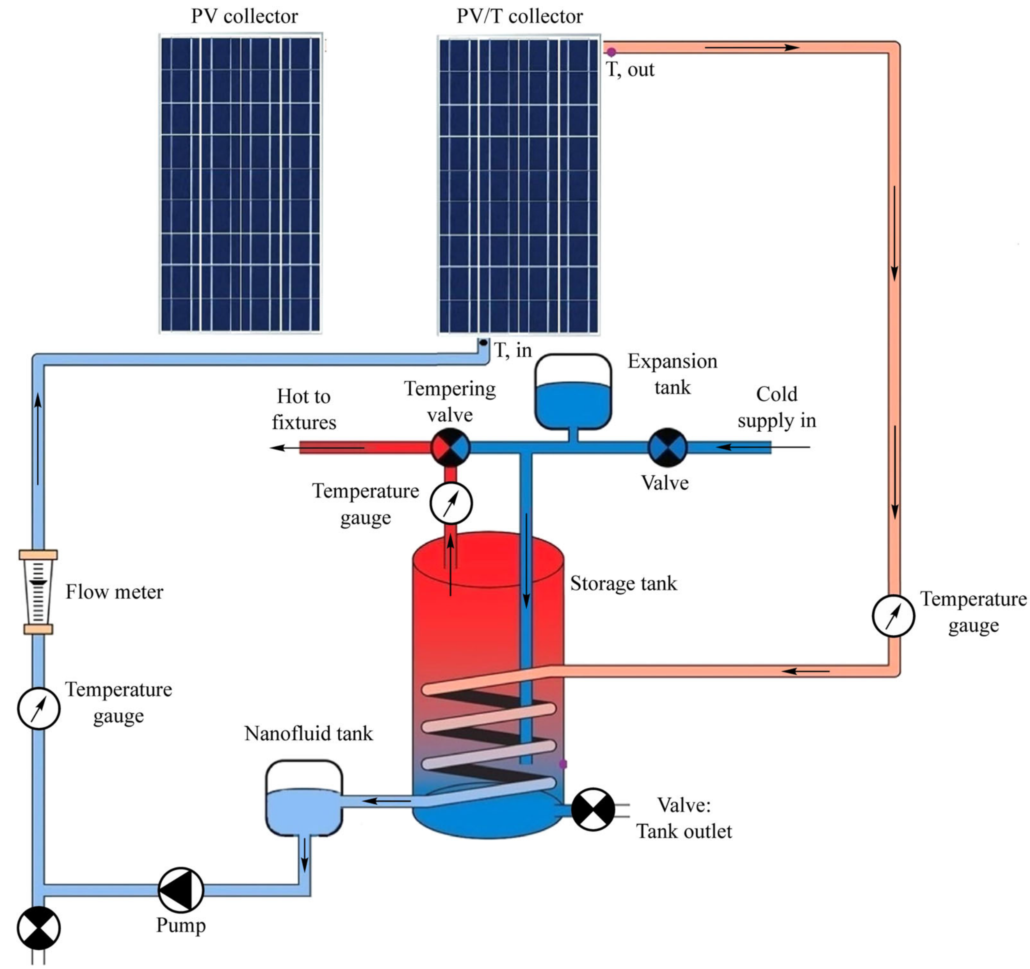

Fig. 9 Schematic diagram of experimental setup (adapted with permission from Ref. [68]).

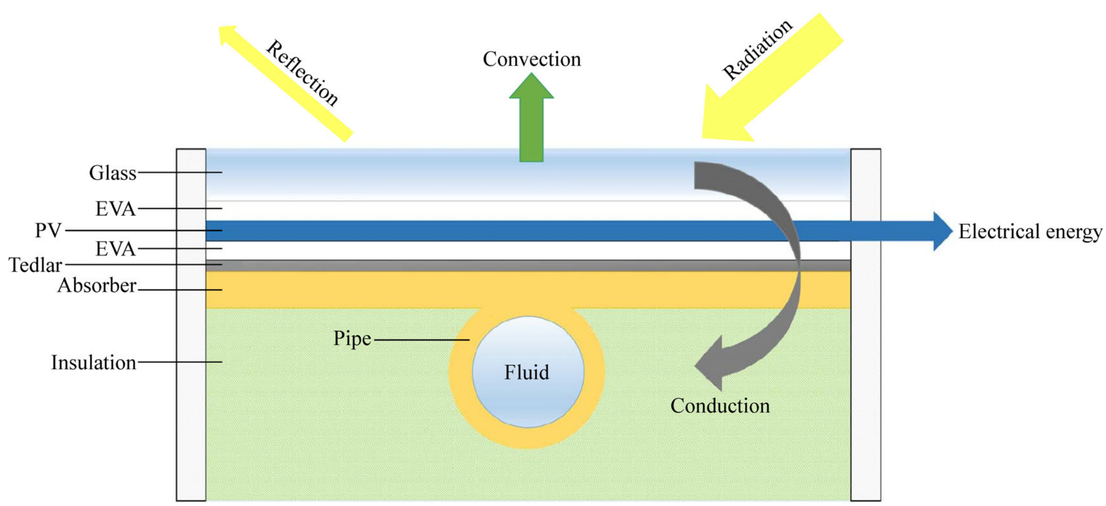

Fig. 10 Schematic diagram of study (adapted with permission from Ref. [64]).

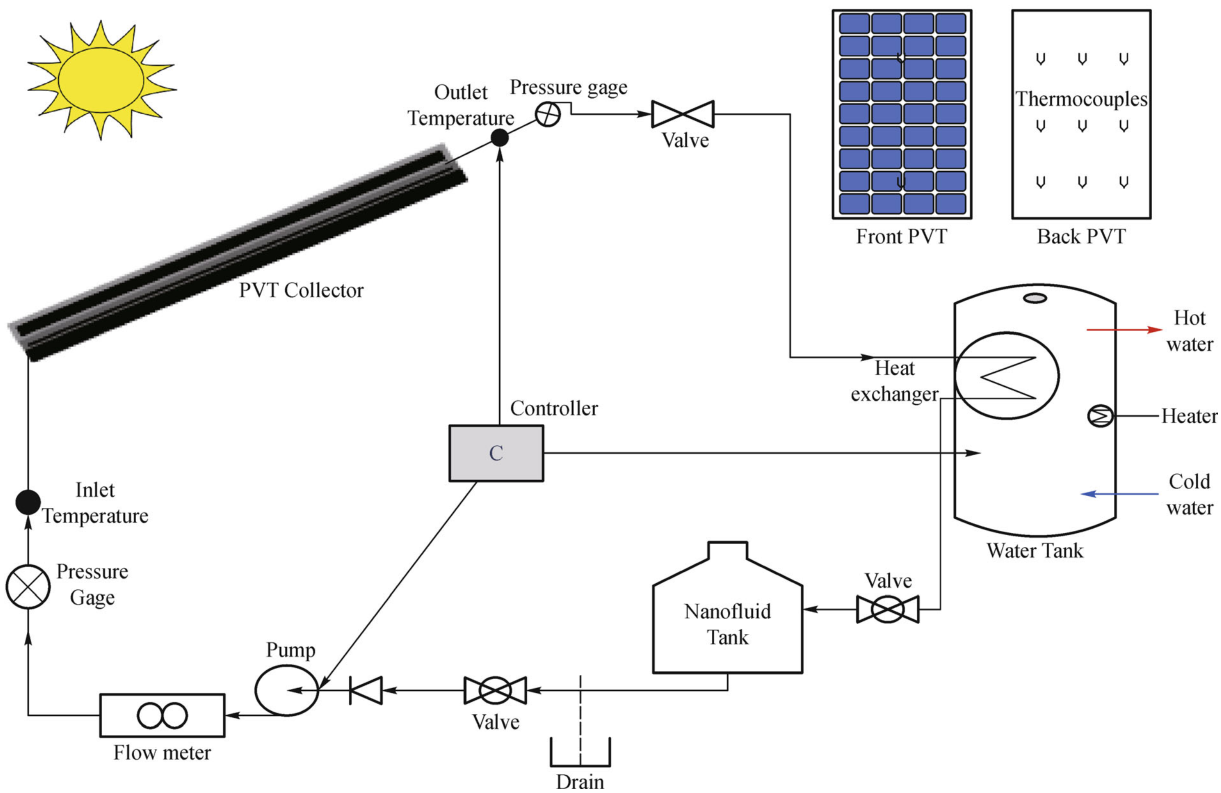

Fig. 11 Schematic diagram of experimental setup of PV/T system (adapted with permission from Ref. [65]).

efficiency. The flowrate of 3 L/min is found to be the best according to the efficiency analysis.

The experimental study of Gangadevi et al. [41] shows that using NFs as a working fluid can increase the thermal and electrical performance of PV/T systems.

Maadi et al. [78] both experimentally and numerically assessed the performance of PV/T systems by adding different NPs, in the view of entropy generation. The study indicates that frictional entropy decreases with the increase of metallic NFs mass fraction, but the opposite effect is gained for metalloid NF. The lowest and the highest frictional entropy is generated by ZnO-water and SiO_2-water NFs, respectively, and Al_2O_3-water NF has the minimum thermal energy generation at a mass fraction of 10%. Moreover, the thermal exergy efficiency of the system is increased by adding NPs. The SiO_2-water and ZnO-water NFs has the minimum and maximum thermal exergy efficiency, respectively. The electrical exergy efficiency is slightly increased with the increase of mass fraction compared with pure water. Compared with other NFs, ZnO-water has the maximum total exergy efficiency. The numerical result show that the thermal efficiency of Al_2O_3, TiO_2, ZnO, and SiO_2-water NFs at a mass fraction of 10% increases by about 6.23%, 6.02%, 6.88%, and 5.77%, respectively, compared to pure water.

Michael and Iniyan [79] experimentally studied the performance of a novel PV/T system with CuO-water NF at a volume fraction of 0.05%. The maximum electrical efficiency of using CuO-water NF in PV/T systems is about 7.62% without glazing whereas the maximum electrical efficiency of the reference PV panel is about 8.98%. However, the maximum thermal efficiency is about 30.43% using CuO-water NF with glazing. There is a decrease in electrical efficiency using CuO-water NF in PV/T collector compared with water, which suggests that the electrical efficiency can be increased if the heat exchanger is redesigned for the new NF.

Sardarabadi et al. [80] experimentally investigated the effect of using SiO_2-H_2O NF on the PV/T system. In general, irrespective of the financial features of NF preparation, for both exegetically and energetically silica/water NF suspension significantly improves the performance of a PV/T system. The result indicats that maximum electrical efficiency is about 13.31% of silica-water NF at a mass fraction of 3%. The average equivalent thermal efficiency is about 69.2% and 72.1% for the silica-water NF at a mass fraction of 1% and 3%, respectively, while the equivalent thermal efficiency of the reference or conventional system (PV without collector) is about 28.9%. The average overall efficiencies for the system are 49.8% and 52.4% in the case of silica-water NF at a mass fraction of 1% and 3%, respectively, whereas the reference system average overall efficiency is about 11% only.

Sardarabadi and Passandideh-Fard [81] performed a combined numerical and experimental study to evaluate the PV/T system cooling approach by using Al_2O_3-H_2O,

TiO_2-H_2O, and ZnO-H_2O NFs at a mass fraction of 0.2%. Figure 12 shows the schematic diagram of the study. Both numerical and experimental results expose that metal-oxides/H_2O NFs mostly affect the thermal performance of PV/T systems. ZnO-H_2O NF has the highest thermal performance compared with other NFs. The result indicates that the thermal performance of the PV/T system is extremely reliant on the NPs mass fraction, and with the changing of mass fraction, the electrical efficiency of the system varies very slightly. The numerical study shows that the thermal performance of the system is increased approximately four times when the NPs mass fraction is increased from 0.05% to 10%. In the experimental and numerical study, the maximum electrical efficiency is obtained by around 15%, 15.1%, and 14.8% and 14.8%, 14.85%, and 14.9% by using TiO_2-H_2O, ZnO-H_2O, and Al_2O_3-H_2O NFs, respectively.

Hasan et al. [82] experimentally investigated jet array NFs impingement in PV/T collector, whose schematic diagram is presented in Fig. 13, using (SiC, TiO_2, and SiO_2)-H_2O NFs as working fluids at different mass flowrates in the range of 0.05–0.1666 kg/s and different solar radiances at 500–1000 W/m^2 (step is 100). The result shows that the electrical efficiency of the PV/T system is increased with mass flowrates and solar radiance, and after the first increase of thermal efficiency with mass flowrate, the electrical efficiency remains constant. The maximum thermal efficiency of 86% and 80% is achieved by using TiO_2-water and SiO_2-water NFs, respectively. The solar irradiance at 1000 W/m^2 and the maximum electrical efficiency of TiO_2-water and SiO_2-water NFs are around 12.25% and 11.6%, respectively, at a solar irradiance of 1000 W/m^2. For both, the cases SiC-water NF has the highest performance followed by (TiO_2 and SiO_2)-H_2O NFs, and the lowest electrical efficiency is shown by the PV module deprived of cooling.

A new NF-based cooling method was proposed by Soltani et al. [83] for a hybrid PV/TE system, and compared to the conventional methods of cooling experimentally using SiO_2-water and Fe_3O_4-water NFs at a mass fraction of 0.5%. The result shows that the cooling performance of SiO_2-water NF is better than that of Fe_3O_4-water NF. In addition, SiO_2-water NF cooling generates an enhancement of about 54.29% and 3.35% in maximum power and efficiency while Fe_3O_4-water NF cooling presents an enhancement of 52.40% and 3.13%, compared to the method of natural cooling.

An innovative design of the PV/T system was proposed by Hader and Al-Kouz [84], integrated with fins and Al_2O_3-water NF as a working fluid for increasing the heat transfer. The numerical result indicates that with the increase of the volume fraction of NPs and the length of the fin, the overall efficiency is increased for both cases with a drawback of increasing friction coefficient.

Radwan and Ahmed [85] proposed a cooling technique for the concentrator PV system using a wide MCHS with NFs of various fractions. The result shows that the net electrical power improves as the *Re* number of coolant flow improves up to a definite value. With additional improvements of the *Re* number, it is observed that the cell net increased power is reduced, because of the enhancement of the friction effect. The Al_2O_3-water NF shows a maximum cell temperature reduction of about 3.1°C and an electrical efficiency increase of up to 13.7% at a volume fracton of 4% and a *Re* of 12.5.

Elayarani [86] compared the thermal performance of the PV/T system of various volume fractions of Al_2O_3-water NF, i.e., 0.5%, 0.3%, and 0.1% using a spiral flow thermal collector which is attached below the PV panel. The investigation result shows that the nano loop gives a higher performance than the water loop. NF at a valume fraction of 0.5% shows a better electrical and thermal efficiency on the PV/T system. The PV/T thermal and electrical efficiency of the system is increased by 84%, 82%, and

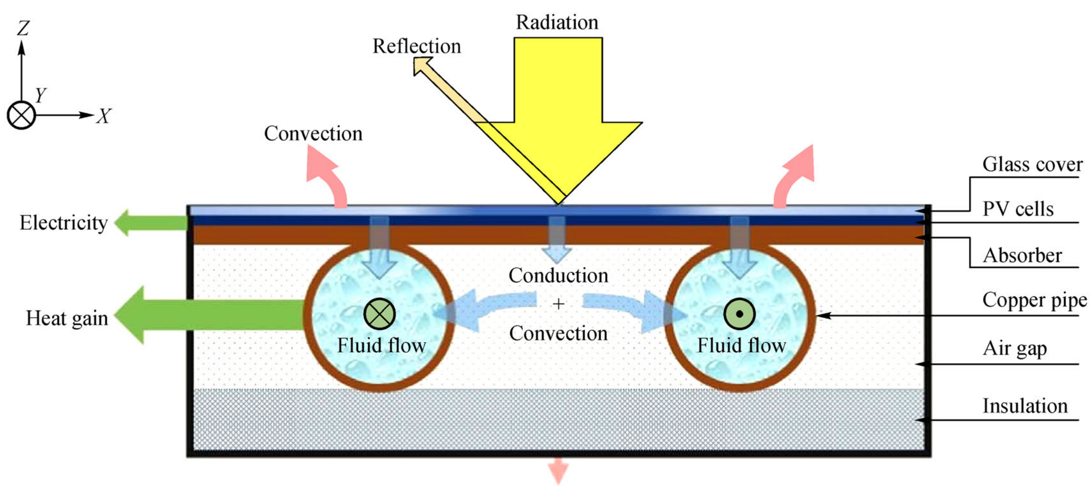

Fig. 12 Schematic diagram of heat transfer mechanisms in across-section of a selected control volume (adapted with permission from Ref. [81]).

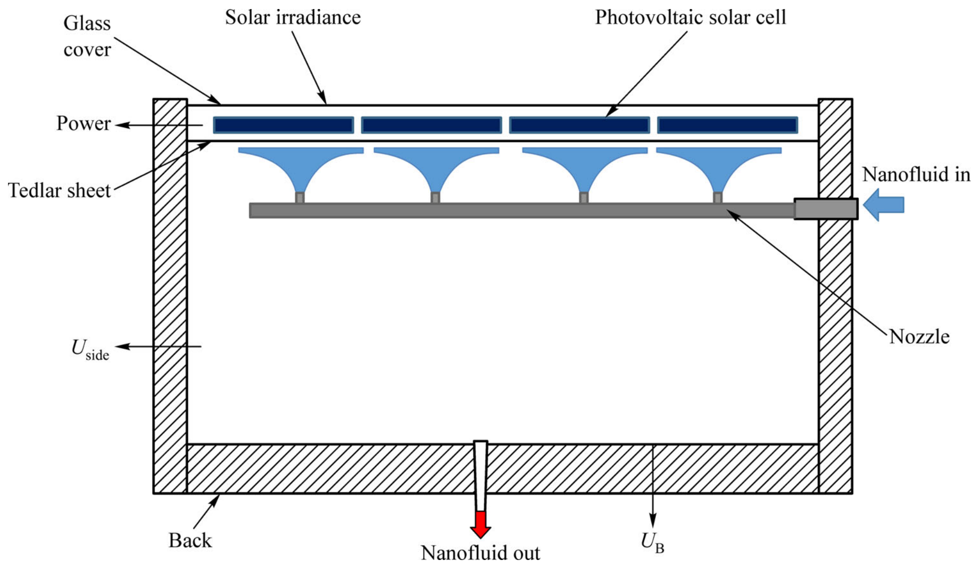

Fig. 13 PV/thermal collector with jet NFs impingement (adapted with permission from Ref. [82]).

79% and 17%, 14%, and 12% at a volume fraction of 0.5%, 0.3% and 0.1%, respectively. It is very clear that with the increase of the volume fraction of the NF PV/T system, the thermal and electrical efficiency are increased.

Cieslinski and Dawidowicz [87] experimentally studied the performance of the PV/T solar collector using Al_2O_3-water NF at a mass fraction of 1% and 3%. The result shows that using Al_2O_3-water NF as a coolant on the PV/T collector, no noticeable effect of the NPs fraction on the overall efficiency is recorded. For Al_2O_3-water NF, a mass fraction of 1% causes a lower thermal efficiency than water while a mass fraction of 3% does not have any change in thermal efficiency, compared with water.

Hussain and Kim [88] conducted a study based on environmental and techno-economic analysis using CuO-H_2O and Al_2O_3-H_2O NFs as coolants to improve the overall performance of the PV/T system. The result indicates that CuO-H_2O NF-based PV/T system gives the maximum electrical and thermal output compared with Al_2O_3-H_2O NF-based PV/T system. It is worth referring to the fact that the overall performance of the CuO-H_2O NF-based PV/T system is suitable even at a high working temperature. For the 30 years lifetime of the PV/T system, with CuO-H_2O and Al_2O_3-H_2O NF, the net CO_2 mitigation and net CO_2 credit are 7.4 t and US $181.6, 6.9 t and US $171.2, respectively.

Mustafa et al. [89] numerically investigated the performance of TiO_2-water NF on PV/T systems at a volume fraction of 0.5% to 1.5% and different mass flowrates under solar irradiances of 650, 850, and 1000 W/m^2. The result suggests that the thermal and electrical efficiencies increase with the increase of mass flowrate, but decrease with the increase of solar irradiance. The thermal efficiency decreases with the increase of the volume fraction of NPs, due to the buildup pressure inside the tube because of the increase of the NFs density. The highest thermal efficiency is found at about 71.7% at a volume fraction of 0.5%, a mass flowrate of 0.174 kg/s, and a solar irradiance of 650 W/m^2.

Maadi [90] conducted a combined numerical and experimental study to evaluate the effects of NFs thermophysical properties on the First Law of Thermodynamic and heat transfer in a serpentine PV/T system using Al_2O_3-H_2O, SiO_2-H_2O, ZnO-H_2O, and TiO_2-H_2O NFs. The result indicates that, in general, based on the First Law of Thermodynamic, irrespective of the economic feature of NFs preparation, utilizing NFs can increase the performance of a PV/T system. At a fixed mass flowrate, NP adding improves the thermal conductivity (minimum for SiO_2-H_2O and maximum for Al_2O_3-H_2O NFs), density (maximum for ZnO-H_2O and minimum for SiO_2-H_2O NFs), and viscosity (minimum for ZnO-water and maximum for SiO_2-water NFs) and reduced the *Re* number (minimum for SiO_2-H_2O and maximum for ZnO-H_2O NF) and specific heat capacity (nearly equal for all investigated NFs). The numerical results demonstrate that the thermal efficiency increases by 6.23%, 5.77%, 6.88%, and 6.02% at a mass fraction of 10% for Al_2O_3-H_2O, SiO_2-H_2O, ZnO-H_2O, and TiO_2-H_2O NFs, respectively, compared to pure water.

Sardarabadi et al. [91] experimentally conducted a combined study of the use of PCM and ZnO-water NF in the PV/T system as a coolant. The result indicates that using ZnO-H_2O NF at a mass fraction of 0.2%, the average thermal and electrical power output is about 183 W/m^2 and 99.63 W/m^2, respectively, and it can decrease the cell surface temperature by an average of around 10°C.

Tang and Zhu [92] experimentally studied the PV/T system performance using Al_2O_3-water NF at a mass fraction of 0.02%. The result shows that the electrical, thermal, and overall efficiency is about 14.43%, 73.56%, and 111.53%, respectively using a flowing-over PV/T system with Al_2O_3-H_2O NF.

Yazdanifard and Ebrahimnia-Bajestan [93] numerically studied the effect of NPs shape on NF-based parabolic trough PV/T collector utilizing Al_2O_3-EG: H_2O NF at a volume fraction of 1% to 4%. The result shows that with the increase of NPs, in the laminar flow PV temperature decreases and increases in the turbulent flow. Nevertheless, in both flow conditions, the outlet temperature increases. The minimum PV temperature in the turbulent and laminar flow condition is allied with the brick and cylindrical shaped NP, respectively. In the laminar flow, the overall energy efficiency increases, but in the turbulent flow, it decreases. The use of cylindrical shape NPs in the laminar flow regime and brick-shaped NPs in a turbulent flow regime led to maximum overall exergy and energy efficiencies. In the laminar flow condition, with the increase of the volume fraction, the thermal and electrical energy efficiency increasing cause an increase in overall energy efficiency.

Yazdanifard et al. [94] numerically studied the performance of concentrating parabolic trough PV/T (CPV/T) system utilizing TiO_2-H_2O NF as a working fluid from an energy and exergy point of view in both turbulent and laminar flow condition. Figure 14 shows the linear parabolic trough CPV/T. The result indicates that with the increase of the volume fraction of NF, the overall exergy and energy efficiencies increase in the laminar flow condition but decrease in the turbulent flow condition. Hence, it appears that applying the NFs in PV/T and CPV/T systems is not appropriable in the turbulent flow regime but appropriable in the laminar flow condition.

Xu and Kleinstreuer [95] numerically studied the thermal act of compactly packed PV cells utilizing Al_2O_3-water NF as coolant at a high volume fraction, and for the better use of incoming solar energy, they proposed a combined CPV/T system as well as electricity generation. In this system, incoming solar radiation is partly converted directly into electricity by the solar cell, and the most of the remaining solar energy is transformed into heat and collected by the flowing NF. Formerly, the thermal energy is shifted toward the bodies of air or water, in a heat exchanger. The hot water can be utilized for space heating or desalination, and the hot air can be utilized for air ventilation needs and building heating.

Hussein et al. [96] conducted an experimental investigation using 2-axes solar tracking systems to increase the efficiency of the PV/T system with Al_2O_3-water NF as working fluid at a mass flowrate of 0.1, 0.2, and 0.3 L/s. It is found that using solar tracking systems is very significant since it can enhance the efficiency of PV cell by about 30%. Besides, using Al_2O_3-water NF as a coolant increases the performance of the PV/T. This work approves that the flowrate of coolant mass affects the electrical efficiency. At a mass flowrate of 0.2 L/s, the maximum electrical and thermal efficiency is found for Al_2O_3-water NF at a concentration ratio of 0.3% and 0.5%, respectively.

Radwan et al. [97] developed a novel comprehensive model of cooling for LCPV/T (low concentrated photovoltaic thermal) system using an MCHS with Al_2O_3-water and SiC-water NFs, at various volume fractions and an assumed constant sun radiation of 1000 W/m^2. A dual-axis tracking system, a microchannel heat sink, solar cell layers, a refractive solar concentrator are included in the CPV/T

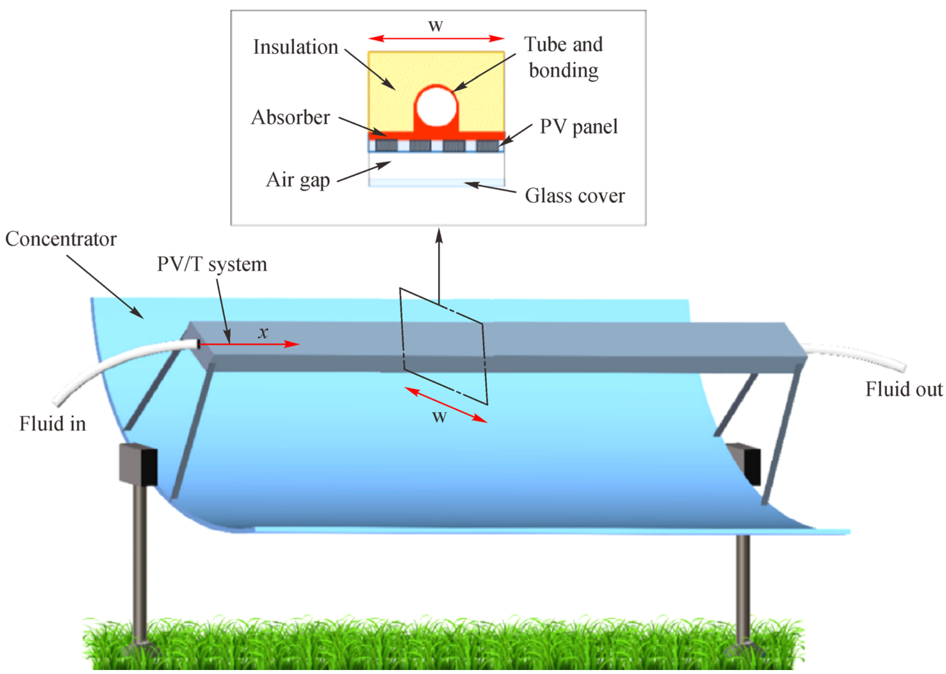

Fig. 14 Linear parabolic trough CPV/T (adapted with permission from Ref. [94]).

system, as is seen in Fig. 15. The result shows that the solar cell temperature is significantly reduced by using NFs at a high concentration ratio, compared to water. SiC-water NF reduces cell temperature more than Al_2O_3-water NF. By increasing the volume fraction of NPs, the cell temperature is greatly reduced. With the increase of the concentration ratio, the thermal efficiency is increased, whereas the electrical efficiency is decreased.

PV cells are not capable of using the complete solar spectrum. It can be operated in a certain range of wavelengths (300–1100 nm). Additionally, the remaining wavelengths (1100–2500 nm) can be filtered for producing heat by the thermal receiver [137].

Cui and Zhu [63] used MgO-water NF on the PV/T system as a coolant and an optical filter both at the same time and under different conditions to study the performance of the PV/T system. The study indicates that the transmittance of NFs decreases with the film thickness and mass fraction. With the increase of mass fraction PV/T systems output power is decreased because with the mass fraction the visible light transmittance through NFs is reduced. The result indicates that the thermal and electrical efficiency of the PV/T system with a liquid film of 2 mm thick is about 47.2% and 14.7%, respectively while thermal and electrical efficiency of the PV/T system with a liquid film of 4 mm thick is about 32.0% and 14.0%, respectively.

Utilizing a one-step sol-gel method, Jing et al. [98] successfully prepared a highly dispersed SiO_2-H_2O NFs of various particle sizes. They designed a 2-D PV/T system model developed on the experimental calculation. In the model, the NFs were flowing first below and then above the PV panel. The NFs flowing above the PV panel work as an optical filter of the solar spectrum, and by flowing through below the PV panel, the NFs take away the extra heat of the PV panel. Figure 16 shows the designed model. The operating temperature of the PV panel is greatly reduced by this model which is probable to enhance its photoelectric efficiency. The result suggests that transmittance of SiO_2-water NFs is always less than the DIW (deionized water) and with the increase of particle sizes, the transmittance of SiO_2-water NFs is decreased. At a NF size of 5 nm and a volume fraction of 2%, the transmittance of NF can be as much as 97%. The thermal conductivity of SiO_2-water NF with smaller particles is more than that of the SiO_2-H_2O NFs with bigger particle sizes. Considering both the thermal conductivity and the optical properties of the NFs, the SiO_2-water NF with a size of 5 nm and a

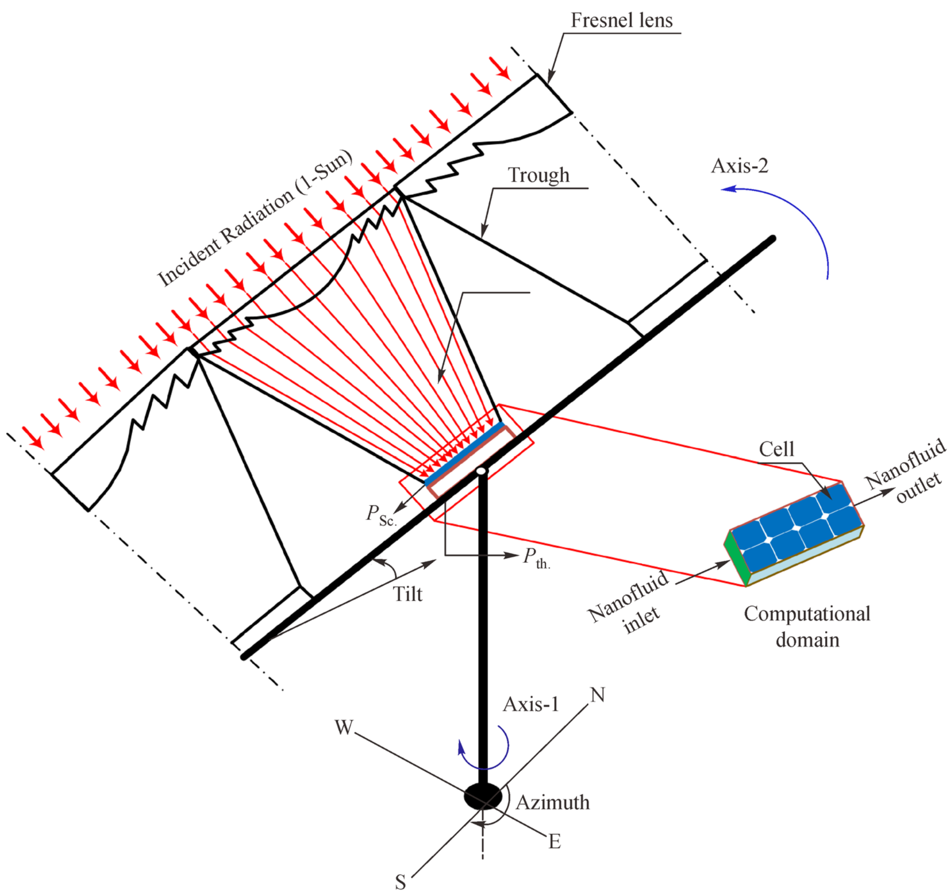

Fig. 15 Proposed physical model and coordinate system (adapted with permission from Ref. [97]).

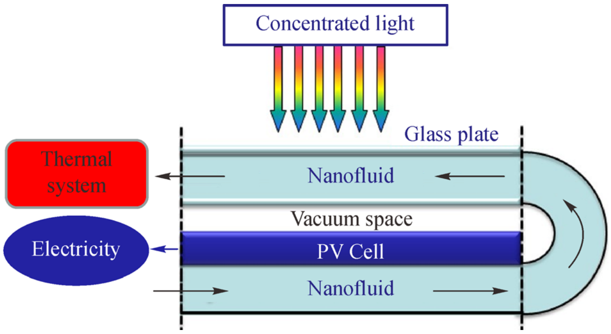

Fig. 16 2D sketch of de-coupled PV/T system concept (adapted with permission from Ref. [98]).

volume fraction of 2% seems to be very favorable for the PV/T system.

Abadeh et al. [99] experimentally studied the environmental and economic aspects of using Al_2O_3-H_2O, TiO_2-H_2O, and ZnO-H_2O NFs as a coolant on the PV/T system, compared to conventional PV unit. The results demonstrate that the NF based PV/T system can improve the electrical efficiency by 7% compared to the conventional PV unit. From the economic point of view, using Al_2O_3-water, TiO_2-H_2O, ZnO-H_2O, and pure water, the size of the PV/T system is reduced by 24%, 32%, 33%, and 21%, respectively. From the energy point of view, the emission production of Al_2O_3-H_2O, TiO_2-H_2O, ZnO-H_2O, and pure water PV/T system is decreased by 12%, 16%, 17%, 10% compared with the conventional PV unit, respectively. From the environmental point of view, the investigated data show that emission production can be reduced by the NF based PV/T system by 17% more than a conventional PV unit. From the result, the shortest payback period is about 2.5 years with a government subsidy of 75%, while the longest payback period is about 8 years without any government subsidies.

Khanjari et al. [100] directed a numerical study to evaluate the effect of environmental parameters on the performance of the PV/T system utilizing Al_2O_3-H_2O NF as a working fluid at a volume fraction of 1% and 2% and different solar radiations from 200 to 800 W/m^2. The result indicates that with the increase of solar radiation, the electrical efficiency is decreased. However, after an initial rise, the thermal efficiency turns into constant. Using Al_2O_3-H_2O NF at a volume fraction of 2%, the thermal and electrical efficiencies are always higher than those of pure water. Moreover, with the increase of inlet fluid temperature, the electrical efficiency is decreased but the thermal efficiency leftovers are constant. Under the same condition, the heat transfer coefficient of Al_2O_3-H_2O NF is better than that of pure water.

Table 2 is a summary of the metal oxide-based NFs used in PV/T systems and Table 3 shows the parameters studied in the previous literature.

4 Discussion

From the existing literature, it is found that these seven (Al_2O_3, TiO_2, SiO_2, Fe_3O_4, CuO, ZnO, MgO) metal oxides-based NFs are frequently used by many researchers in their study to improve the performance of PV/T systems. Of all the metal oxides, Al_2O_3 is mostly used due to its higher thermal conductivity compared with other metal oxides. The second most frequently used metal oxides are SiO_2 and TiO_2 where SiO_2 has the lowest thermal conductivity of all. Even though the SiO_2 NP has a low thermal conductivity compared to other particles, its low-price, chemical properties, and advantages in physical properties make it favorable for usage with water [73].

From the above literature review, it can be concluded that most of the researcher found that using metal oxides-based NFs in PV/T systems increases the thermal and electrical efficiency. However, Michael and Iniyan [79], Cieslinski and Dawidowicz [87]) used CuO-water NF at a volume fraction 0.05% and a mass flowrate of 0.01 kg/s and detected a decrease in electrical efficiency compared with water. Besides, using Al_2O_3-water NF at a mass fraction of 1% and 3%, Cieslinski and Dawidowicz [87] did not observe any noticeable data. Figure 17 shows that the maximum electrical efficiency of about 17% is achieved by Elayarani [86] by using Al_2O_3-water NF at a mass fraction of 0.5% and a spiral flow thermal collector which is attached below the PV panel and a maximum thermal efficiency of about 86% is attained by Hasan et al. [82] by utilizing TiO_2-water NF of at a mass fraction of 1% and a mass flowrate of 0.05 to 0.1666 kg/s.

The maximum temperature of the PV module is reduced to about 36.9°C by Hussien et al. [69] who used AL_2O_3-water NF at a mass fraction of 0.3% and a mass flowrate of 0.2 L/s.

In the existing literature, few researchers study the effect of coolant flowrates on the performance of PV/T systems, which confirms that coolant flowrate is an important parameter for PV/T systems. According to Al-Shamani et al. [68], Hosseinzadeh et al. [64], Hasan et al. [82], Radwan and Ahmed [85], Mustafa et al. [89], Hussain et al. [76], Binti Rukman et al. [75], Al-Waeli et al. [62], Al-Shamani et al. [65], Lee et al. [77], and Hussein et al. [96], with the increase of flowrate up to a certain limit, the performance of the PV/T system is increased. But the effect of this parameter or optimal flowrate on PV/T systems is not clear yet.

Yazdanifard et al. [93,94] found that applying the NFs in PV/T is appropriable in the laminar flow condition but not appropriable in the turbulent flow condition while Yazdanifard et al. [93] found that the use of cylindrical shape NPs in the laminar flow condition leads to maximum overall exergy and energy efficiencies.

Cui and Zhu [63] and Jing et al. [98] used NFs as an optical filter and coolant in their study. Cui and Zhu found

Table 2 A summary of metal oxide-based NFs used in PV/T systems

Ref.	Study type	NP, size and concentration	Base fluid	PM	Flowrate	PV panel specification	Collector type	Key findings
[62]	Num	AL_2O_3, 30–60 nm, 3% mass fraction; CuO, 35–45 nm, 3% mass fraction	H_2O, gly and EG	2-S	0.025–0.225 kg/s	Solar module type APM-P 110–12	PV/T	As a BF, the water presents the minimum pressure drop while glycerin shows the maximum value
[66]	Exp and num	AL_2O_3, –, 0.1%, 0.2% and 0.4% mass fraction	H_2O, EG	2-S	Constant flowrate	Conventional monocrystalline Si PV module	Sheet and tube	Electrical and thermal efficiency is increased with the increase of NPs addition
[67]	Exp	Fe_3O_4, 45 nm, 1% and 3% mass fraction	H_2O	2-S	30 L/h	40 W monocrystalline Si PV module	PV/T	Overall efficiency is improved by about 76% at the concentration of 3% mass fraction Fe_3O_4-water NF
[68]	Exp	SiO_2, –, 0.5%, 1% and 2% mass fraction; TiO_2, –, 0.5%, 1% and 2% mass fraction	H_2O	2-S	0.068 to 0.170 kg/s	PV-M model STF–120P6	PV/T	With the increase of mass flowrate and solar radiance, the PV/T system efficiency is increased
[69]	Exp	AL_2O_3, 30 nm, 0.1% to 0.5% mass fraction	H_2O	–	0.2 L/s	Monocrystalline solar panel	PV/T	The electrical and thermal efficiency increase by about 12.1% and 34.4%, respectively
[64]	Num and exp	ZnO, 35–45 nm, 0%– 12% mass fraction	H_2O	2-S	30 to 70 kg/h	Two 40 W monocrystalline Si PV modules	Sheet and tube	With the increase of solar irradiance, the mass flowrate of coolant, NP mass fraction %, and ambient temperature PV/T systems efficiency was increased
[70]	Exp	AL_2O_3, 10–30 nm, 0.2% mass fraction; TiO_2, 20–60 nm, 0.2% mass fraction; ZnO, 35–45 nm, 0.2% mass fraction	H_2O	2-S	30 kg/h	Two 40 W monocrystalline Si PV modules	Sheet and tube	Maximum electrical and thermal efficiency is shown by TiO_2-water and ZnO-water NFs 13.63% and 46.05%, respectively
[71]	Num	CuO, –, 0.7% mass fraction; AL_2O_3, –, 0.7% mass fraction	H_2O	–	–	A monocrystalline Si cell	Sheet and tube	Thermal efficiency increases by up to 78.83% and 80.94% for Al_2O_3-water, and CuO-water NFs, respectively
[65]	Exp and num	CuO, –, 1% mass fraction; SiO_2, –, 1% mass fraction; ZnO, –, 1% mass fraction	H_2O	2-S	0.01 to 0.04 kg/s	120 W PV polycrystalline	Sheet and tube	Thermal, electrical, and overall efficiency increases for SiO_2-water NF is about 64.40%, 12.70%, and 77.10%, respectively

(*Continued*)

Ref.	Study type	NP, size and concentration	Base fluid	PM	Flowrate	PV panel specification	Collector type	Key findings
[72]	Exp	CuO, 35–45 nm, 0.5%–4% volume fraction; AL_2O_3, 30–60 nm, 0.5%–4% volume fraction	H_2O	2-S	–	Solar module type-APM-P 110-12	PV/T	The enhancement in thermal conductivity is 1.96% and 3.42%, for Al_2O_3 and CuO NFs with 4% volume fraction, respectively
[73]	Num	SiO_2, –, 0%–0.05% volume fraction	H_2O	–	–	PV/T module	PV/T	Cylindrical shape particles show the greatest performance compared to others
[74]	Exp and num	AL_2O_3, –, 3% and 0.2% mass fraction; TiO_2, –, 3% and 0.2% mass fraction; ZnO, –, 3% and 0.2% mass fraction; SiO_2, –, 1% mass fraction	H_2O	2-S	30 kg/h	40 W monocrystalline Si PV module	Sheet and tube	SiO_2-water NF generates the maximum entropy and ZnO-water NF generates the lowest frictional entropy
[75]	Exp	TiO2, –, 0.5% and 1% mass fraction	H_2O	2-S	0.012 to 0.0255 kg/s	A standard polycrystalline 80 W PV module	PV/T	TiO_2-water fluid with 1% mass fraction causes the maximum temperature change
[76]	Num	CuO, –, 0%–0.75%; AL_2O_3, –, 0%–0.75%; SiO_2, –, 0%–0.75%	H_2O	–	0 to 0.03 kg/s	A standard monocrystalline Si PV panel	Dual-fluid PV/T	Heat transfer performance is tremendously dependent on NPs concentrations
[77]	Exp	CuO, 50–100 nm, 0.05% mass fraction; AL_2O_3, 50 nm, 0.05% mass fraction	H_2O	2-S	3 L/min	10 monocrystalline Si	Flat plate	Thermal and electrical efficiency is about (48.88% and 46.95%) and (13.20% and 12.22%) for CuO-water and Al_2O_3-water NFs in PV/T systems, respectively
[41]	Exp	AL_2O_3, <50 nm, 0.5% volume fraction	H_2O	2-S	–	PV panel	Flat plate	NFs increase the thermal and electrical efficiency of PV/T systems as it is used as a working fluid
[78]	Exp and num	AL_2O_3, –, 3% and 0.2% mass fraction; TiO_2, –, 3% and 0.2% mass fraction; ZnO, –, 3% and 0.2% mass fraction; SiO_2, –, 1% mass fraction and for num. study up to 10% mass fraction	H_2O	2-S	30 kg/h	A 40 W monocrystalline Si PV module	PV/T	The increase of thermal exergy efficiency, with the addition of NPs is promising, but in the case of increased electrical exergy efficiency, it is very negligible

(*Continued*)

Ref.	Study type	NP, size and concentration	Base fluid	PM	Flowrate	PV panel specification	Collector type	Key findings
[79]	Exp	CuO, 75 nm, 0.05% volume fraction	H_2O	2-S	0.01 kg/s	PV module	PV/T	The maximum thermal and electrical efficiency is about 30.43% and 7.62%, respectively
[80]	Exp	SiO_2, 11–14 nm, 1% and 3% mass fraction	H_2O	2-S	20, 30 and 40 L/h	Two 40 W monocrystalline Si PV modules	Sheet and tube	Maximum electrical efficiency is about 13.31% for silica-water NF with 3% mass fraction
[81]	Exp and num	AL_2O_3, 20 nm, 0.2% mass fraction (exp); TiO_2, 10–30 nm, 0.2% mass fraction (exp); ZnO, 10–25 nm, 0.2% mass fraction (exp)	H_2O	2-S	30 kg/h	A 40 W, monocrystalline Si, PV modules	Sheet and tube	In the case of the exp study, maximum electrical efficiency is about 15.1% for ZnO-water NF and maximum electrical efficiency of num study is about 14.9% for Al_2O_3-water NF
[82]	Exp	TiO_2, –, 1% mass fraction; SiO_2, –, 1% mass fraction	H_2O	2-S	0.05 to 0.167 kg/s	Polycrystalline Si PV module	PV/T	The maximum thermal and electrical efficiency is about 86% and 80%, 12.25% and 11.6%, for TiO_2-water and SiO_2-water NFs, respectively
[83]	Exp	SiO_2, 22 nm, 0.5% mass fraction; Fe_3O_4, 50 nm, 0.5% mass fraction	H_2O	2-S	–	Crystalline Si PV-cell	PV cell	SiO_2-water NF shows a better performance compared with the Fe_3O_4-water NF
[84]	Num	AL_2O_3, –, 0%–0.2% volume fraction	H_2O	–	0.00982–0.00996 kg/s	PV module	PV/T	Overall efficiency is increased with an increase of NPs volume fraction fraction and fin length.
[85]	Num	AL_2O_3, 20 nm, 0%–4% volume fraction	H_2O	–	–	Polycrystalline Si solar module	LFL	The cell electrical efficiency increases by up to 13.7% for Al_2O_3-water NF with 4% volume fraction at *Re* of 12.5
[86]	Exp	AL_2O_3, <50 nm, 0.1%, 0.3% and 0.5% volume fraction	H_2O	2-S	–	Polycrystalline solar module	PV/T	PV/T system thermal and electrical efficiency is increased by (84%, 82%, and 79%) and (17%, 14% and 12%) for 0.5%, 0.3% and 0.1% volume fraction of NF, respectively

(*Continued*)

Ref.	Study type	NP, size and concentration	Base fluid	PM	Flowrate	PV panel specification	Collector type	Key findings
[87]	Exp	AL_2O_3, 47 nm, 1% and 3% mass fraction	H_2O	2-S	–	Polycrystalline solar cell	Flat plate	Al_2O_3-water NF as a coolant on the PV/T collector no noticeable effect of the NPs fraction on the overall efficiency is recorded
[88]	Num	CuO, –, 0%–0.8% mass fraction; AL_2O_3, –, 0%–0.8% mass fraction	H_2O	–	–	Monocrystalline PV module	Fin and tube	Using CuO-water and Al_2O_3-water NF, the net CO_2 mitigation and net CO_2 credit is 7.4 t and US $181.6 and 6.9 t and US $ 171.2, respectively
[89]	Num	TiO_2, –, 0.5%–1.5% volume fraction	H_2O	–	0.125, 0.134, 0.142, 0.151, 0.164 and 0.174 kg/s	Monocrystalline PV module	PV/T	The maximum thermal efficiency is found at about 71.7% with 0.5% volume fraction, mass flowrates of 0.174 kg/s, and solar irradiance of 650 W/m^2
[90]	Exp and num	AL_2O_3, –, 0.2% mass fraction; SiO_2, –, 1% and 3% mass fraction; ZnO, –, 0.2% mass fraction; TiO_2, –, 0.2% mass fraction	H_2O	2-S	30 kg/h	A 40 W monocrystalline Si PV module	Sheet and tube	Compared to pure water maximum thermal efficiency is shown by ZnO-water NF to be about 6.88%.
[91]	Exp	ZnO, 35–45 nm, 0.2% mass fraction	H_2O	2-S	40 kg/h	40 W monocrystalline Si	Sheet and tube	The average thermal and electrical power output is about 183 W/m^2 and 99.63 W/m^2, respectively
[92]	Exp	AL_2O_3, –, 0.02% mass	H_2O	–	15 L/h	PV cells	PV/T	The electrical and thermal efficiency is about 14.43% and 73.56%, respectively
[93]	Num	AL_2O_3, –, 1%–4% volume fraction	EG and H_2O mix. 50:50	–	–	PV module	PTC	In the laminar flow condition with the increase of volume fraction, the thermal and electrical energy efficiency increasing steer to an improvement in overall energy efficiency
[94]	Exp	TiO_2, 21 nm, 0%–4% volume fraction	H_2O	–	0.02 and 0.18 kg/s	PV panel	L-PTC	Applying the NFs in PV/T and CPV/T systems is not appropriable in the turbulent flow condition but appropriable in the laminar flow condition

(*Continued*)

Ref.	Study type	NP, size and concentration	Base fluid	PM	Flowrate	PV panel specification	Collector type	Key findings
[95]	Num	AL_2O_3, 38.4 nm, 0% and 4% volume fraction	H_2O	–	–	Silicon (Si) solar cell	CPV/T	For the better use of incoming solar energy, the study proposes a combined CPV/T system
[96]	Exp	AL_2O_3, 30 nm, 0.1%–0.5%	H_2O	–	0.1, 0.2, 0.3 L/s	Monocrystalline solar cell	PV/T	At a mass flowrate of 0.2 L/s, the maximum electrical and thermal efficiency is found for Al_2O_3-water NF at a concentration ratio of 0.3% and 0.5%, respectively
[97]	Num	AL_2O_3, 20 nm, 0%–4% volume fraction	H_2O	–	*Re*	Polycrystalline Si solar cell	LFL	With the increase of CR value, the thermal efficiency is increased, whereas the electrical efficiency is found in a decreasing trend.
[63]	Exp	MgO, 10 nm, 0.02%, 0.06%, and 0.1% mass fraction	H_2O	2-S	8 L/h	25 W PV module	PV/T	The thermal and electrical efficiency for the PV/T system with a 2 mm thick liquid film is about 47.2% and 14.7%, respectively
[98]	Num and exp	SiO_2, (5, 10, 25, 50) nm, 0.5%, 1%, and 2% volume fraction	H_2O	1-S	0.015 m/s (flow velocity)	Monocrystalline Si solar cell	De-coupled PV/T	SiO_2-water NF with a size of 5 nm and volume fraction of 2%, seemed to very favorable for the PV/T system.
[99]	Exp	ZnO, –, 0.2% mass fraction; AL_2O_3, –, 0.2% mass fraction; TiO_2, –, 0.2% mass fraction	H_2O	2-S	30 and 40 L/h	Two 40 W monocrystalline Si PV module	Sheet and tube	Using ZnO-H_2O in PV/T systems, there is a size reduction of about 33% and in the energy point of ZnO-H_2O PV/T systems, emission production is decreased by 17% compared with conventional PV unit.
[100]	Num	AL_2O_3, 50 nm, 1% and 2% volume fraction	H_2O	–	0.00136 kg/s	PV panel	Sheet and tube	Using Al_2O_3-water NF with a 2% volume fraction, the thermal and electrical efficiencies are always higher than those of pure water.

Notes: PM = Preparation method, 2-S = Two-step, 1-S = Single-step, PTC = Parabolic trough collector, LFL = Linear fresnel lens.

Table 3 Parameter studied in the previous literature

Metal oxide	Ref.	Use of NF	Studied parameter					
			Thermal conductivity	Mass flowrate	Solar radiance	Electrical efficiency/output	Thermal efficiency/output	Overall efficiency
Al_2O_3	[62]	Coolant	–	√	–	–	–	–
	[66]	Coolant	√	–	√	√	√	–
	[69]	Coolant	–	–	–	√	√	–
	[70]	Coolant	–	–	–	√	√	√
	[71]	Coolant	√	–	–	√	√	–
	[72]	Coolant	√	–	–	√	√	–
	[74]	Coolant	–	–	–	–	–	–
	[76]	Coolant	√	√	–	√	√	–
	[77]	Coolant	√	√	–	√	√	√
	[41]	Coolant	–	–	–	√	√	–
	[78]	Coolant	√	–	–	√	√	–
	[81]	Coolant	–	–	–	√	√	–
	[84]	Coolant	–	–	–	–	–	√
	[85]	Coolant	–	–	–	√	√	–
	[86]	Coolant	–	–	–	√	√	–
	[87]	Coolant	–	–	–	√	√	√
	[88]	Coolant	√	–	–	√	√	–
	[93]	Coolant	√	–	–	√	√	√
	[90]	Coolant	√	–	–	√	√	–
	[92]	Coolant	–	–	–	√	√	√
	[95]	Coolant	–	–	–	–	–	–
	[96]	Coolant	–	√	–	√	√	–
	[97]	Coolant	–	√	–	√	√	–
	[99]	Coolant	–	–	–	√	√	–
	[100]	Coolant	–	–	√	√	√	–

(*Continued*)

Metal oxide	Ref.	Use of NF	Studied parameter					
			Thermal conductivity	Mass flowrate	Solar radiance	Electrical efficiency/output	Thermal efficiency/output	Overall efficiency
TiO_2	[68]	Coolant	√	√	√	√	√	√
	[70]	Coolant	–	–	–	√	√	√
	[74]	Coolant	–	–	–	–	–	–
	[75]	Coolant	–	√	–	–	–	–
	[78]	Coolant	√	–	–	√	√	–
	[81]	Coolant	–	–	–	√	√	–
	[82]	Coolant	–	√	√	√	√	–
	[89]	Coolant	√	√	√	√	√	–
	[99]	Coolant	–	–	–	√	√	–
	[94]	Coolant	√	–	–	√	√	√
	[90]	Coolant	√	–	–	√	√	–
SiO_2	[68]	Coolant	√	√	√	√	√	√
	[65]	Coolant	√	√	√	√	√	√
	[73]	Coolant	√	–	√	–	√	–
	[74]	Coolant	–	–	–	–	–	–
	[76]	Coolant	√	√	–	√	√	–
	[78]	Coolant	√	–	–	√	√	–
	[80]	Coolant	–	√	–	√	√	√
	[82]	Coolant	–	√	√	√	√	–
	[83]	Coolant	–	–	–	√	–	√
	[90]	Coolant	√	–	–	√	√	–
	[98]	Optical filter and Coolant	√	–	–	–	–	√
Fe_3O_4	[67]	Coolant	–	–	–	√	√	√
	[83]	Coolant	–	–	–	√	–	√

(*Continued*)

Metal oxide	Ref.	Use of NF	Studied parameter					
			Thermal conductivity	Mass flowrate	Solar radiance	Electrical efficiency/output	Thermal efficiency/output	Overall efficiency
CuO	[62]	Coolant	–	√	–	–	–	–
	[71]	Coolant	√	–	–	√	√	–
	[65]	Coolant	√	√	√	√	–	–
	[72]	Coolant	√	–	–	√	√	–
	[76]	Coolant	√	√	–	√	√	–
	[77]	Coolant	√	√	–	√	√	√
	[79]	Coolant	√	–	–	√	√	√
	[88]	Coolant	√	–	–	√	√	–
ZnO	[64]	Coolant	–	√	√	√	√	√
	[70]	Coolant	–	–	–	√	√	√
	[65]	Coolant	√	√	√	√	–	–
	[74]	Coolant	–	–	–	–	–	–
	[78]	Coolant	√	–	–	√	√	–
	[81]	Coolant	–	–	–	√	√	–
	[90]	Coolant	√	–	–	√	√	–
	[91]	Coolant	–	–	–	√	√	√
	[99]	Coolant	–	–	–	√	√	–
MgO	[63]	Optical filter and Coolant	–	–	–	√	√	√

Table 4 Discussions about previous literature

Metal oxide	Authors, years and references	Discussion	Maximum electrical efficiency	Maximum thermal efficiency
Al_2O_3	Al-Waeli et al., 2018 [62] Rejeb et al., 2016 [66] Hussien et al., 2015 [69] Sardarabadi et al., 2017 [70] Hussain and Kim, 2018 [71] Al-Waeli et al., 2017 [72] Kolahan, 2017 [74] Hussain et al., 2019 [76] Lee et al., 2019 [77] Gangadevi et al., 2013 [41] Maadi et al., 2017 [78] Sardarabadi and Passandideh-Fard, 2016 [81] Hader and Al-Kouz, 2018 [84] Radwan and Ahmed, 2018 [85] Elayarani, 2017 [86] Cieslinski and Dawidowicz, 2016 [87] Hussain and Kim, 2018 [88] Yazdanifard and Ebrahimnia-Bajestan, 2018 [93] Maadi, 2017 [90] Tang and Zhu, 2014 [92] Xu and Kleinstreuer, 2014 [95] Hussein et al., 2017 [96] Radwan et al., 2016 [97] Abadeh et al., 2018 [99] Khanjari et al., 2017 [100]	Using Al_2O_3-based NF, a maximum electrical and thermal efficiency of about 17% and 84% is attained by Elayarani [86] who used Al_2O_3-water NF at a volume fraction 0.5% and a spiral flow thermal collector which is attached below the PV panel	17% [86]	84% [86]
TiO_2	Al-Shamani et al., 2016 [68] Sardarabadi et al., 2017 [70] Kolahan, 2017 [74] Binti Rukman et al., 2019 [75] Maadi et al., 2017 [78] Sardarabadi and Passandideh-Fard, 2016 [81] Hasan et al., 2017 [82] Mustafa et al., 2017 [89] Abadeh et al., 2018 [99] Yazdanifard et al., 2017 [94] Maadi, 2017 [90]	Using TiO_2-based NF, a maximum electrical efficiency of about 15% is achieved by Sardarabadi and Passandideh-Fard [81] who use TiO_2-water NF at a mass fraction of 0.2% and a mass flowrate of 30 kg/h and a maximum thermal efficiency of about 86% is attained by Hasan et al. [82] by using TiO_2-water NF at a mass fraction of 1% and a mass flowrate of 0.05 to 0.1666 kg/s.	15% [81]	86% [82]
SiO_2	Al-Shamani et al., 2016 [68] Al-Shamani et al., 2018 [65] Chamkha and Selimefendigil, 2018 [73] Kolahan, 2017 [74] Hussain et al., 2019 [76] Maadi et al., 2017 [78] Sardarabadi et al., 2014 [80] Hasan et al., 2017 [82] Soltani et al., 2017 [83] Maadi, 2017 [90] Jing et al., 2015 [98]	Using SiO_2-based NF, the maximum electrical efficiency of around 13.31% is achieved by Sardarabadi et al. [80] who use silica-water NF at a mass fraction of 3% while a maximum thermal efficiency of around 80% is attained by Hasan et al. [82] using SiO_2-water NF at a mass fraction of 1% and a mass flowrate of 0.05 to 0.1666 kg/s	13.31% [80]	80% [82]
Fe_3O_4	Ghadiri et al., 2015 [67] Soltani et al., 2017 [83]	Using Fe_3O_4-based NF, a maximum electrical and thermal efficiency of about 7.7% and 74.96% is attained by Ghadiri et al. [67] by using Fe_3O_4-water NF at a mass fraction of 3% and a mass flowrate of 30 L/h	7.7% [67]	74.96% [67]
CuO	Al-Waeli et al., 2018 [62] Hussain and Kim, 2018 [71] Al-Shamani et al., 2018 [65] Al-Waeli et al., 2017 [72] Hussain et al., 2019 [76] Lee et al., 2019 [77] Michael and Iniyan, 2015 [79] Hussain and Kim, 2018 [88]	Using CuO-based NF, a maximum thermal efficiency of about 80.94% is achieved by Hussain and Kim [71] by using CuO-water NF at mass fraction of 0.7% while a maximum electrical efficiency of about 13.20% is attained by Lee et al. [77] using CuO-water NF at a mass fraction of 0.05% and a mass flowrate of 3 L/min	13.20% [77]	80.94% [71]

(*Continued*)

Metal oxide	Authors, years and references	Discussion	Maximum electrical efficiency	Maximum thermal efficiency
ZnO	Hosseinzadeh et al., 2018 [64] Sardarabadi et al., 2017 [70] Al-Shamani et al., 2018 [65] Kolahan, 2017 [74] Maadi et al., 2017 [78] Sardarabadi and Passandideh-Fard, 2016 [81] Maadi et al., 2017 [90] Sardarabadi et al., 2017 [91] Abadeh et al., 2018 [99]	Using ZnO-based NF, Sardarabadi and Passandideh-Fard [81] achieve a maximum electrical efficiency of about 15.1% by using ZnO-water NF at a mass fraction of 0.2% and a mass flowrate of 30 kg/h while a maximum thermal efficiency of 46.05% is attained by Sardarabadi et al. [70] who use ZnO-water NF at a mass fraction 0.2% and a mass flowrate of 30 kg/h	15.1% [81]	46.05% [70]
MgO	Cui and Zhu, 2012 [63]	By using MgO-water NF at mass fraction of 0.02% and a mass flowrate of 8 L/h, Cui and Zhu [63] achieve a maximum electrical and thermal efficiency of about 14.7% and 47.2%	14.7% [63]	47.2% [63]

that the transmittance of NFs declined with the film thickness and mass fraction. Jing et al. found that with the increase of particle sizes, the transmittance of SiO_2-water NFs was decreased and SiO_2-water NF with a size of 5 nm and a volume fraction of 2%, seemed to be very promising for PV/T system. In addition, the thermal conductivity of SiO_2-H_2O NF with smaller particles is more than that of bigger particle sizes. Hence, it seems that smaller particle sizes of NPs are better than bigger particle sizes.

An NF-based solar collector reduces the collector size significantly than a conventional solar collector. A maximum size reduction of about 33% of a solar collector was achieved by Abadeh et al. [99] who used ZnO-H_2O NF at a mass fraction of 0.2% in a PV/T system and greatly reduced the CO_2 and greenhouse gases emission. For a 30-years lifetime of the PV/T system, using CuO-H_2O and Al_2O_3-H_2O NF, the net CO_2 reduction and net CO_2 credit are 7.4 t and US $181.6, 6.9 t and US $ 171.2, respectively (see Hussain and Kim [88]).

Kolahanet [74] and Maadi et al. [78] used AL_2O_3, TiO_2, ZnO, SiO_2 metal oxides in their study from an entropy point of view. In the case of entropy generation, both researchers found that the maximum and minimum entropy is generated by SiO_2-water and ZnO-water NFs, respectively.

Many researchers used metal oxides-based NF in PV/T systems both experimentally and numerically. Most

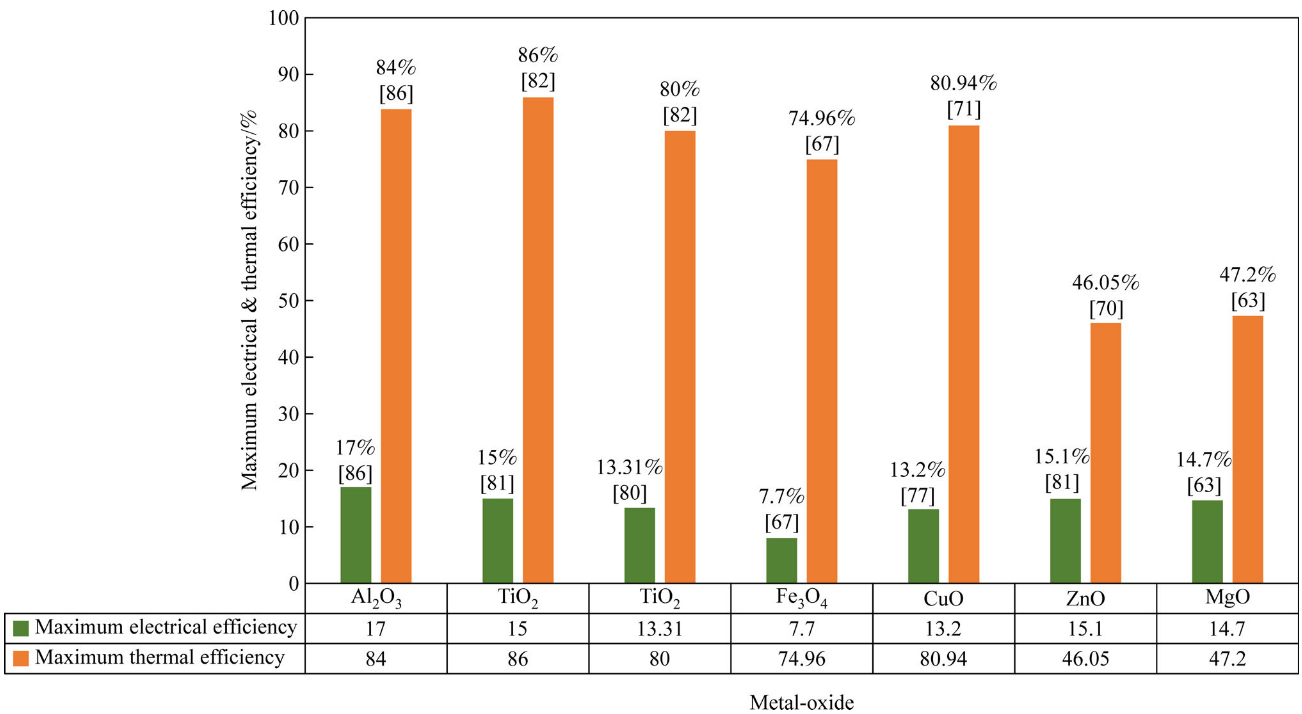

Fig. 17 Maximum electrical and thermal efficiency achieved by different researchers by using metal-oxide based NF.

researchers found that the performance of PV/T systems is increased by using metal oxides-based NF. From the above discussion, it can be concluded that a lot of research should be conducted before using metal oxide/NFs in PV/T systems practically. It has to be checked precisely and accurately from an environmental and economic point of view.

5 Opportunities and challenges

There are some opportunities and challenges regarding the uses of NFs/metal oxide in the PV/T system.

Opportunities:

- The heat transfer coefficient of working fluid can be increased by increasing its thermal conductivity [111,113].
- Increased specific heat capacity and density product can lead to the convey of higher quantities of thermal energy [111,113].
- Both the thermal and electrical efficiencies of the PV system can be increased [113].
- NF-based solar collectors can greatly reduce the size of the collector which can save a large amount of material without sacrificing the desired output [53].
- The material of the PV/T system can be protected by reducing the temperature of the absorber [113].
- Using metal oxide-based/NFs in PV/T systems can greatly reduce the emissions of greenhouse gases and CO_2. In this present energy crisis, PV/T systems is excessive importance for electricity generation. It can reduce the dependence on fossil fuels [2].

Challenges:

- First, the higher production expense of NFs can be estimated as the main obstacle. In this regard, it is agreed that excessive production expenses exclude the use of NFs in solar systems [56,103,138].
- Additionally, another severe problem is related to human health and the environment. Human health is highly endangered by NPs relative to bulk materials [103,113]. Especially, TiO_2 NPs with no doubt can be extremely dangerous for human health and the environment. TiO_2 NPs may be mounted in lung tissues of human bodies. Then, these particles will interact with DNA, organelles, and proteins. Mechanistic toxicological studies show that TiO_2 NPs primarily induce adverse effects of inflammation, genotoxicity, cell injury, and immune response, etc., by inducing oxidative stress. The International Organization for Research on Cancer listed TiO_2 NPs as "possible carcinogenic to humans" based on the preliminary data from inhalation experiments in animals, and National Institute for Occupational Safety and Health as an occupational carcinogen [113,139].
- The use of NFs may result in high operating expenses because of an increase in pump work [56,113].
- The long-term stability of NFs for practical uses is still a great challenge [45,56,138].

6 Recommendation

Based on this present comparative study of these metal oxides, i.e., Al_2O_3, TiO_2, SiO_2, Fe_3O_4, CuO, ZnO, MgO-based NFs, it is recommended that Al_2O_3/SiO_2-water NFs be used in PV/T systems, which seem to be very favorable for achieving a better performance. Besides, combined use of NFs in the PV/T system as a coolant and a spectral filter could have a better overall efficiency at a cheaper price.

7 Conclusions

This paper provides a review of recent applications of metal oxide-based NFs in the PV/T system. From this review, the following major conclusions can be reached:

It is found that many researchers in their studies frequently use these seven metal oxide-based NFs (Al_2O_3, TiO_2, SiO_2, Fe_3O_4, CuO, ZnO, MgO) to improve the performance PV/T systems. In the existing literature, most researchers use Al_2O_3 NPs due to its higher thermal conductivity compared with other NPs. A maximum electrical efficiency of about 17% and a maximum temperature reduction of about 36.9°C of the PV module are achieved by using Al_2O_3-water NF as a coolant. Besides, the efficiency PV cells can be enhanced by about 30% by using Al_2O_3-water NF with solar tracking systems. The second most frequently used metal oxides are SiO_2 and TiO_2, where SiO_2 has the lowest thermal conductivity of all the mentioned NPs, but its low-priced, chemical properties, and advantages in physical properties make it favorable for use with water. The highest thermal efficiency of about 86% is achieved by using TiO_2-water NF, but TiO_2 NPs can be extremely dangerous for human health. Therefore, the study suggests using Al_2O_3/SiO_2 based NFs in PV/T systems, which seems to be very favorable for achieving a better performance.

The flowrate of coolant is an essential parameter on the performance of the PV/T system, but the effect of this parameter or optimal flowrate is not clear yet.

Applying the NFs in the PV/T system is appropriable in the laminar flow condition but it is not appropriable in the turbulent flow regime and the use of cylindrical shape NPs in the laminar flow condition can lead to maximum overall exergy and energy efficiencies.

Metal oxide-based NFs can be used as a good alternative to spectral filters. The transmittance of NFs declines with the film thickness and concentration. With increasing particle sizes, the transmittance of SiO_2-water NF is decreased. SiO_2-water NF with a size of 5 nm and a volume fraction of 2%, seems to be very favorable for the PV/T system.

Based on the performance of NFs in PV/T systems, it seems that the combined use of NF as a coolant and an optical filter gives a better overall efficiency. In PV/T systems, NFs work as a good coolant as well as a good optical filter by spectral splitting. In such kind of model, the optical NF and thermal NF work combinedly to increase the overall efficiency of PV/T systems, which could provide electricity and thermal energy at a cheaper price.

The NF-based solar collector reduces the collector size significantly than a conventional solar collector. Using metal-oxide-based NF, the maximum size reduction of a solar collector is about 33% by ZnO-H_2O NF. For 30-years lifetime of the PV/T system, utilizing CuO-H_2O and Al_2O_3-H_2O NFs, the net CO_2 reduction and net CO_2 credit are 7.4 t and US $181.6, 6.9 t and US $171.2, respectively.

Of the four metal oxides-based NFs, i.e., AL_2O_3, TiO_2, ZnO, SiO_2, the maximum and minimum entropy is generated by SiO_2 -H_2O and ZnO-H_2O NF, respectively.

Studies confirm that with the increase of nanoparticle concentration up to an optimum value, the efficiency of the PV/T system is increased. Moreover, smaller sized NPs show a higher thermal conductivity than bigger sized NPs.

Although using NFs/metal oxide in PV/T systems is very effective, they are facing some serious challenges like higher production costs. In addition, a serious challenge is associated with human health and environment. Stability issues because of agglomeration in the near future require serious attention.

Notations

C_p	Specific heat/$(J\cdot(kg\cdot K)^{-1})$
k	Thermal conductivity/$(W\cdot(m\cdot K)^{-1})$
Re	Reynolds number
T	Temperature/K
G	Incident radiation/$(W\cdot m^{-2})$
m	Mass flowrate/$(kg\cdot s^{-1})$
ρ	Density/$(kg\cdot m^{-3})$
η	Efficiency
PV	Photovoltaic
PV/T	Photovoltaic thermal
CPV/T	Concentrated photovoltaic thermal
LCPV/T	Low concentrated photovoltaic thermal
PVM	PV module
LFL	Linear Fresnel lens
CSP	Concentrated solar power
PTC	Parabolic trough collector
PM	Preparation method
PCM	Phase change materials
MCHS	Microchannel heat sink
CR	Concentration ratio
DIW	Deionized water
DW	Distilled water
2-S	Two-step
1-S	Single-step
Th	Thermal
El	Electrical
NF	Nanofluid
NP	Nanoparticle
Ref	Reference
BF	Base fluid
Num	Numerical
Avg	Average
Exp	Experimental
Cond	Conductivity

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