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Application of Nanofluids for Thermal Management of Photovoltaic Modules: A Review

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Abstract

Mounting temperature impedes the conversion efficiency of photovoltaic systems. Studies have shown drastic efficiency escalation of PV modules, if cooled by nanofluids. Ability of nanofluids to supplement the efficiency improvement of PV cells has sought attention of researchers. This chapter presents the magnitude of improved efficiency found by different researchers due to the cooling via nanofluids. The effect of factors (such as, nanoparticle size, nanofluid concentration, flowrate of nanofluid and geometry of channel containing nanofluid) influencing the efficiency of PV systems has been discussed. Collective results of different researchers indicate that the efficiency of the PV/T systems (using nanofluids as coolant) increases with increasing flowrate. Efficiency of these systems increases with increasing concentration of nanofluid up to a certain amount, but as the concentration gets above this certain value, the efficiency tends to decline due to agglomeration/clustering of nanoparticles. Pertaining to the most recent studies, stability of nanoparticles is still the major unresolved issue, hindering the commercial scale application of nanofluids for the cooling of PV panels. Eventually, the environmental and economic advantages of these systems are presented.

Keywords: PV systems, Nanofluids, efficiency, concentration, Flowrate, stability

1. Introduction

Exceeding energy demands and swiftly eliminating conventional energy resources have compelled the researchers to find the alternative means of power generation. To date, only 14% of the world's power demands are being met via renewable energy means. Sun is the most

vital source of energy, almost 1.8×10^{11} MW energy from the sun intercepts the earth's surface [1]. According to the estimate of International Energy Agency (IEA), quarter of world's power demands could be fulfilled by solar energy by 2050 [2]. Silicon-based photovoltaic cells are used to convert the solar radiations into electricity. But the issue with these PV solar cells is that almost 85% of the solar energy reaching the surface of the PV unit is either reflected or absorbed as heat energy [3]. Al-shamani et al. [4] reviewed that only 5–20% of the solar radiation reaching to the PV cell surface is converted into electrical energy. Whereas, rest of the radiations are either reflected back or absorbed by the cell in the form of heat. Absorbed heat can increase its temperature up to 70°C . Oruc et al. [5] found that the electrical efficiency of PV module drops by 0.5% with every unit degree increment in the temperature of the module above 25°C due to the contraction of the band gap and increased number of carriers. Increased number of carriers cause the saturation current to increase whereas the open circuit voltage to decrease thus lowering the electrical power output. Cooling of PV units depicts electrical efficiency enhancement as per the experimental results obtained by the researchers. Underdeveloped countries like Pakistan, with hot and sunny days throughout the year, are well suitable for power production via solar energy. According to research, during summer, temperature of the module can elevate in a devastating way (about 20°C higher), in turns destructing the conversion efficiency of PV modules [6, 7]. Bashir et al. [8] reported that cooling of PV modules via water minimized heat losses and module's temperature elevation, thus, improving the efficiency by 13% and 6.2% for monocrystalline and polycrystalline PV modules respectively. Ali et al. [9] experimentally showed that cooling of PV modules by using micro-channels increased the efficiency of PV modules by 3%.

There are several methods of PV cooling such as, air cooling (natural air circulation and forced air circulation), water cooling, heat pipe cooling, cooling with Phase Change Materials (PCMs) and cooling via nanofluids [10, 11]. A PV/T system consists of PV module coupled with a heat absorbing unit in which a liquid (water or nanofluid) is circulated to absorb the heat of PV unit to improve the efficiency. The researches show that a PV/T system performs way better than conventional PV systems [12, 13]. Lelea et al. [14] investigated the effect of cooling via Al_2O_3 on the performance of concentrated PV/T system. The results showed a decrement in the temperature of module, when cooled by nanofluid and water.

Mixture of solid particles (metallic oxides, metals or carbon nanotubes) of less than 100 nm size at least in one dimension (nanoparticles) disseminated in the liquid fluids like water and polyethylene glycol etcetera (base fluid), is known as nanofluid. Nanofluids can be employed as a coolant as well as optical filters within PV/T systems [15]. PV/T system using nanofluid as coolant can produce far better results than the water cooled system. Al-Waeli et al. [16] conducted an experimental study and they found that cooling of PV module via SiC increased the electrical efficiency by 24.1%, thermal efficiency by 100.19% and overall efficiency by 88.9% as compared to the water-cooled PV/T system. Xu and Kleinstreuer [17] suggested nanofluid based silicon PV/T systems as a useful option for domestic applications as its overall efficiency reached up to 70% (11% electrical efficiency and 59% thermal efficiency).

This chapter reviews the efficiency of PV systems being cooled by various nanofluids. The common ways of cooling PV system via nanofluids are stated in detail along with the parameters influencing the efficiency of the PV/T systems such as irradiance, concentration and

flow rate of nanofluid, size of nanoparticles and geometry of micro-channels. Impact of other factors such as the type of nanoparticles and base fluid on the system efficiency are discussed. Eventually, economic and environmental advantages are described.

2. Methods of cooling of PV systems via nanofluids

There are several methods of extracting heat from the PV units via nanofluids. The most common ways are, employing heat collector at the rear end of the panel and using nanofluid as a liquid in spectral splitting filter joined on the front surface of PV module. Sometimes, both methods are used simultaneously in order to increase the efficiency.

2.1. Rear end cooling

In rear-end cooling a thermal collector is coupled at the back end of the PV module to extract the heat. Nanofluid is set to flow through the collector thus taking up the heat of the cells and increasing its own temperature. Nanofluid gets warmed and its heat is further employed for useful purposes. Nanofluid is able to extract major part of the heat energy because of its improved thermophysical properties. The most important thermophysical property is the thermal conductivity. A schematic display of such an arrangement is depicted in the **Figure 1**.

Energy balance of such PV/T systems is evaluated by the following equation by [19].

$$\dot{E}_{in} = \dot{E}_{el} + \dot{E}_{th} + \dot{E}_{loss} \quad (1)$$

Here, " \dot{E}_{in} " is the incident irradiation, " \dot{E}_{el} " is output electrical power, " \dot{E}_{th} " is useful thermal energy obtained by the collector and " \dot{E}_{loss} " presents the energy losses from the control volume. Overall efficiency of the system is found by the following formula.

$$\eta_{pvt} \cong \frac{\dot{E}_{el} + \dot{E}_{th}}{\dot{E}_{in}} \Rightarrow \eta_{pvt} = \eta_{pvt} = \eta_{th} + r \times \eta_{el} \quad (2)$$

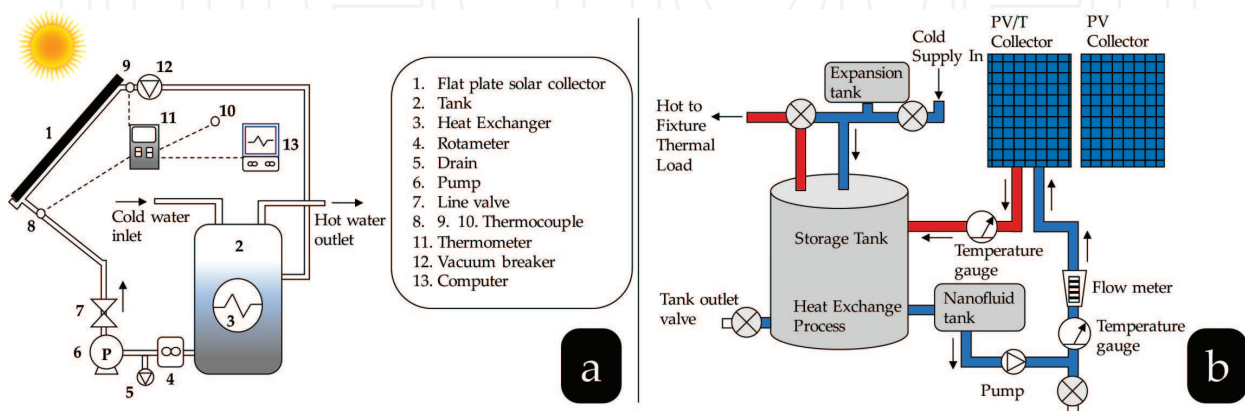


Figure 1. Schematic setup of rear end cooling of PV panel via Nanofluid. (a) [18], (b) [16].

Here, " r " is the packing factor.

$$r = \frac{A_{pv}}{A_c} \quad (3)$$

Here, " A_c " is the collector area and " A_{pv} " is area of PV cells.

Area of PV to produce a certain amount of electrical power is calculated by the following formula.

$$A_p = \frac{R E_{out,max}}{E_{out,1m^2}} \quad (4)$$

Here, " $E_{out,1m^2}$ " is output electrical power per unit area and " $R E_{out,max}$ " is the required output power.

Thermal output energy is found by the following equation.

$$\dot{E}_{th} = m_f \times C_{pf} \times (T_{fo} - T_{in}) \quad (5)$$

Here, " m_f " is the mass flowrate of the fluid through the collector, " C_{pf} " is the fluid's specific heat and " T_{in} " and " T_{fo} " depicts the fluid's inlet and outlet temperature respectively. The formulas to determine " C_{pf} " are given in Ref [20].

Electrical efficiency is found by the following formula.

$$\eta_{el} = \frac{\dot{E}_{el}}{\dot{E}_{in}} = \frac{V_{oc} \times I_{sc} \times FF}{G_{eff}} \quad (6)$$

Here, " V_{oc} " is the open circuit voltage, " I_{sc} " is the short circuit current, and " G_{eff} " is the effective absorbed solar irradiation by the PV module. "FF" represents the fill factor and it is defined as the maximum power conversion efficiency.

$$FF = f \times \left(\frac{V_{oc}}{T} \right) \quad (7)$$

Using the aforementioned formulas, the efficiency of a PV/T system is determined.

Radwan et al. [20] examined the cooling effect of Al_2O_3 , SiC nanoparticles and water on the performance of concentrated PV system. Pertaining to the results, SiC-water nanofluid produced better impact as compared to Al_2O_3 and water. It was observed that at higher concentration ratio (area of aperture/area of cell) and smaller Re, higher electrical efficiency was found. Using the pure water at CR = 40, the cell temperature reached a maximum of 68°C. Were as, for 4vol% SiC, the maximum temperature of the cell was found to be 60°C.

2.2. Optical filter cooling

Extensive work has been carried out on efficiency improvement by using nanofluid flowing through optical filters [21, 22]. Silicon-based Photovoltaic cells can generate electricity by absorbing the part of solar radiation with 400 nm to 1200 nm wavelength. Rest of the solar radiation's part is either reflected back or absorbed by the PV cells as heat. In optical filter cooling, an optical filter containing nanofluid is held above the front surface of cells to split

the spectrum of radiation. Nanofluid-based optical filters separate the part of solar radiation for the PV cells from the radiation part that is more useful for heat generation. There are two kinds of proposed configurations of these systems.

1. Single Pipe System

2. Two Pipe System

In single pipe system, there are two sections of pipe; primary section and secondary section. Primary section is set underneath the rear surface of the Photovoltaic module having aluminum sheet in between. Primary section further elongates above the upper surface of PV module. Nanofluid enters from the inlet of primary section, thus, absorbing heat of the module. Heated nanofluid further passes over the PV's upper surface, in turns filtering the solar radiation. Part of radiation having wavelength equal to silicon bandgap is filtered and rest of the section is absorbed by the nanofluid flowing in the secondary channel which gets out of the secondary pipe at secondary outlet. Air exists between upper surface of PV module and secondary channel section. As the air gets hot, it flows in upward direction and the cool air still remains in contact with PV surface. It is assumed that no convection current is produced in the air. The results indicated, 83% and 80% overall and 76.5% and 74% thermal efficiency for Ag/water and Cu/water nanofluid respectively for above configuration [23]. Schematic diagram of such system is shown in the following **Figure 2**.

Wei An et al. [24] designed a spectral splitting Polypyrrole nanofluid based PV/T system in order to impede thermal losses and escalate the system's efficiency. Nanofluid used in spectral splitting filter is capable to absorb the part of solar radiations that cannot be utilized by PV cell and converts it into medium temperature thermal energy. The efficiency of PV/T system was found to be 25.2% for nanofluid based spectral splitting filter whereas, its value was 13.3% when there was no filter employed. Hjerrild et al. [25] worked on the cooling of PV system by the help of optical filters, they used Silver as nanoparticle (50 nm diameter) with coating of Silica. The results showed that, base fluid absorbed the ultraviolet part of solar radiation thus decreasing the heat losses whereas, nanoparticles absorbed visible portion of radiation, in turns increasing the overall efficiency of the system. Water showed highest electrical efficiency (85% higher than unfiltered PV) whereas highly diluted nanofluid ($Ag-SiO_2$) showed highest

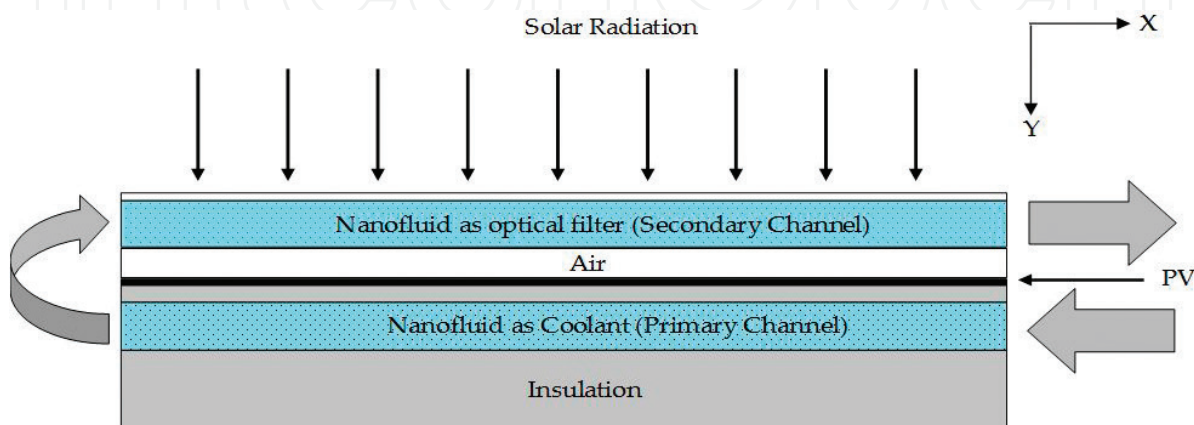


Figure 2. Schematic diagram of Nanofluid based spectral splitting filter PV/T system (reproduced) [23].

overall efficiency as well as greatest merit function. Hassani et al. [26] numerically investigated the effect of cooling on PV performance. The results revealed that PV system with optical filter (containing Ag-Water nanofluid) held above the PV surface along with thermal receiver (containing CNTs) at the rear end of PV, performed best in terms of high-grade energy as compared to conventional PV, PV being cooled by water only, PV being cooled by CNTs and PV being cooled by CNTs at rear end and optical filter containing water held at upper surface of the panel. Optical filter containing nanofluid was able to absorb both UV and IR spectrum and it only allowed the radiation in range of PV absorptivity spectrum (400-1200 nm). Whereas, optical filter containing water could only absorb IR spectrum. Saroha et al. [27] tested the effect of silver and gold based nanofluid working as optical filters in PV/T system. The results revealed that unwanted wavelengths were more absorbed by silver as compared to gold based nanofluid. Silver/water nanofluid based PV/T system approached 9.6% electrical, 67.8% thermal and 78.4% overall efficiency. Whereas, gold/water nanofluid based PV/T system achieved 9% electrical, 67.6% thermal and 76.6% overall efficiency. Jin et al. [28] investigated the effect of liquid optical filter based on magnetic electrolyte nanofluid for PV/T system. Electrolyte nanofluid is prepared by dispersing Fe_3O_4 nanoparticle in 50% water and 50% EG solutions containing methylene blue or copper sulfate, in this way they obtained two stable ENF filters. By adjusting the volume fraction of nanoparticles and molar fraction, more optimized ENF is produced. This ENF presents more better results compared to the simple liquid filters. Merit function of this newly developed ENF is found to be much more than the conventional liquid optical filter.

An arrangement in which nanofluids flows in separated channels outperforms the single channel through which the nanofluid is set to flow. In this arrangement a channel is placed underneath the rear surface of PV panel whereas, a separate channel is held above the front surface of the module. Upper channel nanofluid is made to achieve high liquid filter performance whereas the nanofluid flowing beneath the surface achieves higher thermal performance (working as a coolant). This technique achieved 8.5% higher electrical efficiency as compared to the double pass channel in which fluid flows in a single channel [29].

3. Efficiency improvement using nanofluid

Integrating the heat receivers with the conventional PV system is found to elevate both electrical and thermal efficiencies. Several fluids such as water or nanofluids can be used in these receivers to remove heat so as to improve the efficiency of the system. Studies have proved that nanofluid based PV/T system outperforms conventional PV system and water-based PV/T system. Soltani et al. [30] used five different methods for PV cooling (natural cooling, forced air cooling, water cooling, SiO_2 -water nanofluid cooling and Fe_3O_4 -water nanofluid cooling) to improve the performance. They found that SiO_2 -water nanofluid cooling increased the efficiency by 3.35% and Fe_3O_4 -water nanofluid cooling increased the efficiency by 3.13% as compared to the natural cooling. Hussien et al. [31, 32] found enhancement in the thermal and electrical efficiency of PV/T system by application of Al_2O_3 /water nanofluid as a coolant. Experimentation was carried out at constant flow rate of 0.2L/s and nanoparticles concentration of 0.3%. Results showed the increase in thermal and electrical efficiency when temperature was decreased from 79.1 to 42°C. Thermal and electrical efficiency of system enhanced up to 34.4% and 12.1% respectively

using nanofluid. Ebaid et al. [33] used TiO_2 water-polyethylene glycol nanofluid and Al_2O_3 water cetyltrimethylammonium bromide nanofluid (with 0.01, 0.05, and 0.1 wt% concentration at a flowrate of 500–5000 ml/min) to test the efficiency enhancement of PV module via the cooling process. Pertaining to the results, Al_2O_3 nanofluid decreased the cell temperature by 13.83% and TiO_2 reduced the temperature by 11.2% at 5000 ml/min relative to water cooling. The best performance was witnessed in case of TiO_2 nanofluid cooling, it produced 50% more average efficiency compared to the water cooling (0.82% for TiO_2 and 0.48% for water cooling compared with no cooling). Karami and Rahimi [34] performed experiments to investigate the enhancement in the efficiency of PV module being cooled by the Boehmite ($AlOOH \cdot xH_2O$) based nanofluid flowing inside microchannel at the rear end of the PV module. The results showed that the maximum increase in the electrical efficiency due to cooling as compared to the without cooling power output was found to be 27.12% at a concentration ratio of 0.01 wt.% and 300 ml/min flow-rate. Similarly, Sardarabadi et al. [64] observed as much as 9.75% electrical efficiency increment for silica/water nanofluid based PV/T system as compared to uncooled system. **Figures 3 and 4** depict the maximum efficiencies of PV/T systems obtained by different researchers.

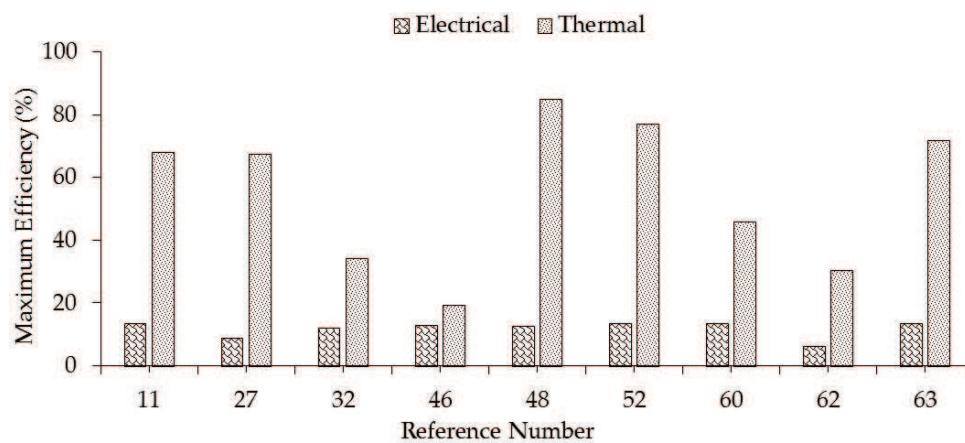


Figure 3. Maximum efficiency for obtained by researchers with Nanofluid cooling.

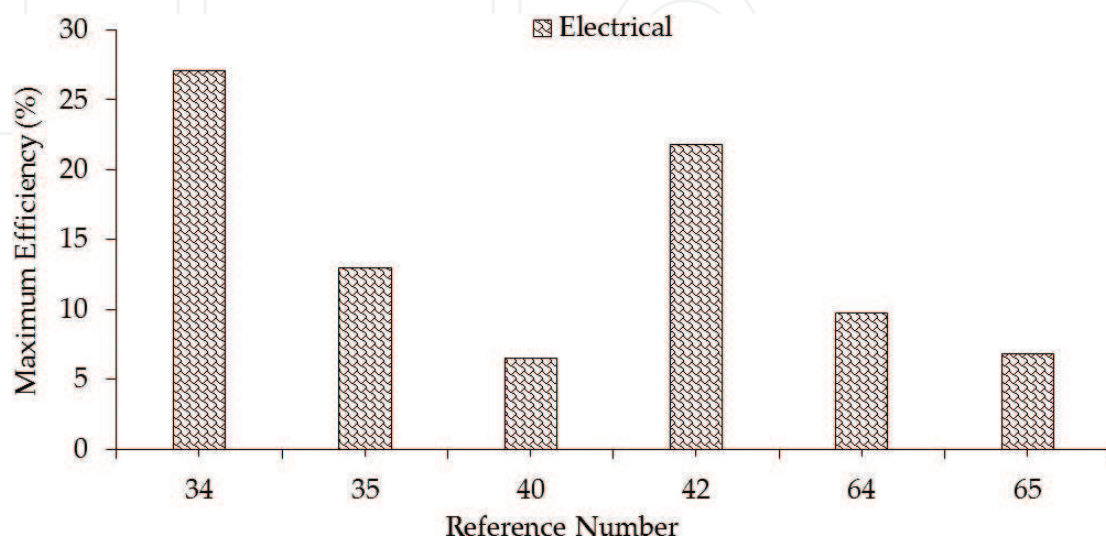


Figure 4. Maximum efficiency improvement by Nanofluid cooling compared to conventional PV.

Authors	Nanoparticle	Base Fluid	Concentration	Flowrate	Module Type, Irradiation (W/m ²)	Ambient Temp	Module Temp	Electrical Efficiency	Thermal Efficiency	Overall Efficiency	
										Energy	Exergy
Al-Waeli et al. [16]	SiC	Deionized Water	3 wt%	—	—	—	—	100.19% Increase compared to Water Cooled PV System	24.1% increase compared to Water Cooled PV System	88.9% increase compared to conventional PV	—
Sardarabadi et al. [19]	No Cooling	—	—	—	845.42, Monocrystalline	—	—	—	—	—	10.90%
	—	Deionized Water	—	—		—	—	—	—	—	12.23%
	ZnO	Deionized Water	—	—		—	10°C Reduction compared to conventional PV	—	—	—	12.29%
	—	PCM + Deionized water	—	—		—	6°C Reduction compared to conventional PV	—	—	—	13.17%
	PCM + ZnO	Deionized Water	—	—		—	—	—	—	—	13.42%

Authors	Nanoparticle	Base Fluid	Concentration	Flowrate	Module Type, Irradiation (W/m ²)	Ambien Temp	Module Temp	Electrical Efficiency	Thermal Efficiency	Overall Efficiency	
										Energy	Exergy
Soltani et al. [30]	—	Water	—	—	Silicon Crystalline PV Module	—	—	—	—	3.051% increase compared to natural cooling	—
	Fe ₃ O ₄	Water	0.5 wt. %	—			—	—	—	3.13% increase compared to natural cooling	—
	SiO ₂	Water	0.5 wt. %	—			—	—	—	3.35% increase compared to natural cooling	—
Hussien et al. [32]	—	—	—	—	1000, Monocry-stalline	—	79.1 °C	8%	—	—	—
	Al ₂ O ₃	Water	0.30wt. %	0.2 L/s			42.2 °C	12.10%	34.40%	—	—
Ebaid et al. [33]	—	Water	—	5000 ml/min	750, Monocry stalline	—	16.58% Decrease compare to conventional PV	.61% Increase compared to conventional PV	—	—	—
	Ti ₂ O ₃	Water-polyethylene glycol	0.1 wt%	5000 ml/min			22.9%% Decrease compare to conventional PV	0.82% Increase compared to conventional PV	—	—	—

Authors	Nanoparticle	Base Fluid	Concentration	Flowrate	Module Type, Irradiation (W/m ²)	Ambient Temp	Module Temp	Electrical Efficiency	Thermal Efficiency	Overall Efficiency	
										Energy	Exergy
Karami and Rahimi [34]	AlOOH-XH ₂ O	Water	0.01 wt. %	300 ml/min	1000 Monocrystalline	25°C	Decrease from 62°C to 32.5°C	27.12% Increase compared to conventional PV	—	—	—
Sardarabadi et al. [37]	No Cooling	—	—	—	855, Monocrystalline	33°C	—	—	—	11%,	11.53%
	—	Deionized Water	—	30L/h			—	8.2% Increase compared to conventional PV	35.60%	47.20%	13.54%
	SiO ₂	Water	1 wt%	—			—	9.01% Increase compared to conventional PV	—	49.80%	13.85%
	SiO ₂	Water	3 wt. %	—			—	9.75% Increase compared to conventional PV	—	52.40%	14.02%
Sardarabadi and Passandideh. [40]	TiO ₂	Deionized Water	0.2 wt. %	30 kg/h	917 Monocrystalline	33.4 °C	11.48°C Reduction as compared to Conventional PV	6.54% Increase compared to conventional PV	—	—	—
	ZnO	—	0.2 wt. %	30 kg/h			11.85°C Reduction as compared to Conventional PV	6.46% Increase compared to conventional PV	—	—	—
	Al ₂ O ₃	—	0.2 wt. %	30 kg/h			11.03°C Reduction as compared to Conventional PV	6.36% Increase compared to conventional PV	—	—	—

Authors	Nanoparticle	Base Fluid	Concentration	Flowrate	Module Type, Irradiation (W/m ²)	Ambient Temp	Module Temp	Electrical Efficiency	Thermal Efficiency	Overall Efficiency	
										Energy	Exergy
Abd-Allah et al. [42]	Boehmite (ALOOH·xH ₂ O)	Water	0.1 wt. %	200 ml/min	—	—	21.6°C Reduction compared to without cooling	21.87% Increase compared to without cooling	—	—	—
Sathieshkumar et al. [46]	No cooling	—	—	—	Monocrystalline	—	—	11.31%	—	—	—
	—	Water	—	0.02 kg/s		—	—	12.42%	18.43%	—	—
	CuTiO ₂	Water	0.2 wt. %	0.02 kg/s		—	—	12.87%	19.50%	—	—
Hasan et al. [48]	—	Water	—	0.167 kg/s	1000 Polycrystalline	30 °C	Decreased from 87–57°C	11.40%	—	—	—
	SiC	Water	1 wt. %	0.167 kg/s			Decreased from 87–41°C	12.75%	85%	97.75%	—
	TiO ₂	Water	1 wt. %	0.167 kg/s			Decreased from 87–45°C	12.30%	—	—	—
	SiO ₂	Water	1 wt. %	0.167 kg/s			Decreased from 87–50 °C	11.80%	—	—	—
	—	—	—	—			—	—	—	—	—
Maadi et al. [54]	Al ₂ O ₃	Water	10 wt%	30 kg/h	Monocrystalline	—	—	6.23% Increase compared to pure water	—	—	—
	TiO ₂	Water	10 wt%	30 kg/h		—	—	6.02% Increase compared to pure water	—	—	—
	ZnO	Water	10 wt. %	30 kg/h		—	—	6.88% Increase compared to pure water	—	—	—
	SiO ₂	Water	10 wt. %	30 kg/h		—	—	5.77% Increase compared to pure water	—	—	—

Authors	Nanoparticle	Base Fluid	Concentration	Flowrate	Module Type, Irradiation (W/m ²)	Ambient Temp	Module Temp	Electrical Efficiency	Thermal Efficiency	Overall Efficiency	
										Energy	Exergy
Sahini et al. [58]	—	Deionized Water	—	0.026 kg/s	Polycrystalline PV Module	—	—	8.5% Increase compared with conventional PV system	—	—	—
	Silver with 1 vol.% potassium oleate surfactant	Deionized Water	0.5 vol.%	0.026 kg/s		—	—	0.9% Increase compared to water cooled system	—	—	—
Sardarabadi et al. [61]	No Cooling	—	—	—	917 Monocrystalline	34.42°C	—	12.73%	—	12.73%	10.29%
	—	Water	0.2 wt%	30 kg/h			11% decrease compared to conventional PV	13.41%	34.12%	47.53%	11.56%
	ZnO	Water	0.2 wt%	30 kg/h			11.85% decrease compared to conventional PV	13.59%	46.05%	59.64%	12.17%
	TiO ₂	Water	0.2 wt%	30 kg/h			11.48% Decrease compared to conventional PV	13.63%	44.34%	57.97%	11.93%
	Al ₂ O ₃	Water	0.2 wt%	30 kg/h			11.03% Decrease compared to conventional PV	13.44%	36.66%	50.10%	11.88%

Authors	Nanoparticle	Base Fluid	Concentration	Flowrate	Module Type, Irradiation (W/m ²)	Ambient Temp	Module Temp	Electrical Efficiency	Thermal Efficiency	Overall Efficiency	
										Energy	Exergy
J.J. Michael and S. Inyan. [62]	No Cooling	—	—	—	—	—	—	8.98%	—	—	—
	—	Water	—	0.01 kg/s	Without Glazing	—	—	8.77%	19.36%	—	—
	—	—	—	0.01 kg/s	With Glazing	—	—	6.40%	21%	—	—
	CuO	Water	0.05%	0.01 kg/s	Without Glazing	—	—	7.62%	28.22%	—	—
	—	Water	0.05%	0.01 kg/s	With Glazing	—	—	6.18%	30.43%	—	—
Al-Waeli et al. [63]	—	—	—	—	—	25°C	68.3°C	7.11%	—	—	—
	—	Water	—	0.175 kg/s	—	—	45.22°C	9.92%	35.40%	—	—
	—	PCM + Water	—	0.175 kg/s	—	—	42.22°C	12.32%	50.50%	—	—
	PCM + SiC	Water	—	0.175 kg/s	—	—	39.52°C	13.70%	72%	—	—
Hamdan and Kardasi [65]	No Cooling	—	—	—	—	—	46.9	10.04%	—	—	—
	—	Water	—	—	—	—	25.47	11.20%	—	—	—
	Al ₂ O ₃	—	0.4 wt. %	—	—	—	22.67	12.06%	—	—	—
	No Cooling	—	—	—	—	—	48.49	12.57%	—	—	—
	—	—	—	—	—	—	24.93	11.39%	—	—	—
	CuO	—	0.6 wt. %	—	—	—	22.13	10.23%	—	—	—

Table 1. Effect of Nanofluids on PV/T System's performance.

Gangadevi et al. [35] experimentally examined that the electrical, thermal and overall efficiency of PV module being cooled by Al_2O_3 /water nanofluid got increased by 13%, 45% and 58% respectively as compared to water based and 1 wt% Al_2O_3 nanofluid based cooling. Mustafa et al. [36] numerically tested the effect of mass flowrate and concentration of nanofluid (TiO_2 /water) on the efficiency of PV/T system. As per the results, electrical and thermal efficiency of this system is linearly proportional to mass flowrate. Best results are obtained at low concentration of nanofluid.

Electrical, thermal and overall efficiencies of the various PV/T systems working with different nanofluids is expressed in the **Table 1**.

Efficiency enhancement of PVT systems being cooled by the nanofluids is due to the enhanced thermal conductivity of the nanofluids. Increase in thermal conductivity is dependent on concentration, size and type of the nanoparticle [4].

4. Factors affecting efficiency of nanofluid-based PV/T systems

Various factors such as the concentration of nanofluid, flowrate of nanofluid, size of the nanoparticle, geometry of microchannel, type of base fluid and irradiance influence the efficiency of nanofluid-based PV/T system. Effects of these factors are discussed in the subsequent sections.

4.1. Irradiance

Increase in irradiance cause the module temperature to escalate as more heat reaches the surface. Khanjari et al. [2] investigated environmental parameters that affect the efficiency of a PV/T system cooled by nanofluids (Al_2O_3 /water) via CFD simulation. As the absorbed solar radiation increased from 200 W/m^2 to 800 W/m^2 the electrical efficiency of system decreased from 11.41% to 10.12% for pure water and 11.4% to 10.23% for alumina nanofluid whereas, thermal efficiency increased from 65–79% for pure water and 76–91% for alumina nanofluid. As the absorber plate temperature increased from 291 K to 324 K the electrical efficiency decreased from 11.1% to 9.4% for water and 11.2% to 9.5% for alumina nanofluid whereas, the thermal efficiency did not change with increasing inlet temperature of fluid after reaching a primary value. Similarly, the system efficiency was found to escalate with decreasing irradiation i.e. the maximum overall efficiency of the system was found to increase from 78.60% to 80.58% and 73.58% to 75.93% for 1 wt% and 3 wt% respectively, when the irradiation value decreased from 1100 W/m^2 to 600 W/m^2 [37]. Effect of irradiance found by Al-Waeli et al. [38] has been presented in **Table 2**.

4.2. Concentration

Researchers have found contradictory results when it comes to concentration enhancement of nanofluids. Manikandan and Rajan [39] harnessed sand for the cooling of PV/T system in order to enhance the efficiency. They tested 0.5, 1 and 2 vol% concentration and the collection efficiency ratio for these concentrations was found to be 3.6%, 11.2% and 26.9% whereas the solar collection efficiency increased by 9% and 16.5% for 0.5% and 2% respectively. Sardarabadi and Fard [40] also examined that increasing the mass fraction of nanoparticles from 0.05 to 10 wt%, the thermal performance of the system increased by four times. Wei An. [24] examined the

effect of nanofluid concentration in spectral splitting filter based PV/T system. They observed that increasing the concentration of the nanofluid increased the nanofluid temperature and system's electrical efficiency, but the thermal efficiency gets decreased in this way.

The maximum overall efficiency of the system was found to be 75.93% and 80.58% when the ferrofluid concentration was increased from 1 wt% to 3 wt% respectively [37]. Khanjari et al. [41] observed that increasing volumetric concentration of the nanoparticle (from 1–5%) increased the heat transfer coefficient and thus the overall efficiency (from 1.33% to 11.54% for silver and 0.72% to 4.26% for alumina). Radwan et al. [20] observed efficiency escalation with increasing concentration. But some researchers witnessed contradictory results. Karami and Rahimi [34] examined that increasing concentration of nanoparticles reduces the efficiency because of agglomeration or clustering of the suspended particles. Abd-Allah, [42] found best results at 0.1 wt% amongst (0.01, 0.1, 0.5 wt%).

Cieslinski et al. [43] found no impact of nanoparticle concentration on the performance of the PV/T system. They observed that 1 wt% of Al_2O_3 /water rather decreased the thermal efficiency compared to the distilled water and 3 wt% and 3 wt% did not change the thermal efficiency as compared to the distilled water thermal efficiency. Whereas, the overall efficiency of the system reached up to 80%.

In order to obtain best results, there is always a need to determine the optimum concentration of nanoparticles in base fluid instead of using high volume fraction of nanofluid [43, 44]. However, instead of increasing the concentration of the same kind of nanoparticle, blending a different kind of nanoparticles can help improve the efficiency of PV module in a more efficient way [45].

4.3. Flowrate

Sathieshkumar et al. [46] concluded that both electrical and thermal efficiency of the PV/T system increases with increasing flow rate but after a certain flowrate magnitude the efficiencies of the system start to decline. Overall energy efficiency is found to be higher in turbulent regime whereas overall exergy efficiency is higher in laminar regime [47]. Mustafa et al. [36] numerically tested the effect of mass flowrate and concentration of nanofluid (TiO_2 /water) on the efficiency of PV/T system. As per the results, the electrical and thermal efficiency of this system was found to be linearly proportional to mass flowrate.

Hasan et al. [48] observed that increasing the mass flowrate increased the cell efficiency linearly. As the mass flowrate increased from 0 to 1.666 kg/s the electrical efficiency of the cell increased from 8% to 16.5% at 500 W/m² solar irradiance in case of SiC-water nanofluid. Mean photovoltaic temperature decreased from 87° C to 41° C as the mass flowrate changed from 0 to 1.666 kg/s at 1000 W/m² solar irradiance in case of SiC. Karami and Rahimi. [34] observed that temperature of the module decreased from 62° C to 32.5° C when the flow rate increased from zero to 300 ml/min. Khanjari et al. [41] observed that increase in inlet fluid velocity (from 0.05 m/s to 0.23 m/s) increase the first law (energy) efficiency but decreases the second law (exergy) efficiency (from 15.40% to 12.50% for silver). Lelea et al. [14] observed lower maximum module temperature for nanofluid based cooling as compared to water cooling at lower Re number. Whereas, at higher Re (Re > 1000) the maximum module temperature overlaps for nanofluid based cooling and water-based cooling of PV module.

PV/T system in laminar regime outperforms turbulent regime. More PV efficiency can be achieved in turbulent regime but it requires higher pumping power thus making the overall system efficiency lesser [15]. Although heat transfer in case of higher Reynolds numbers is seemed to increase because of greater Brownian motion of particles but too high a Reynolds number requires higher pumping power which eventually reduces the overall performance of the microchannels containing nanofluids [49]. Xu and Kleinstreuer [50] concluded that increased concentration elevates the system efficiency when cooled by Al_2O_3 /water nanofluid. Higher inlet Reynolds number yields higher cell efficiency but too high a Reynolds number is not favorable. Low inlet temperature of nanofluid is capable to produce pronounced cooling effect. Height of channel containing nanofluid is also of much consideration, slight variation in channel height varies the required pumping power and significant change in entropy generation rate.

4.4. Nanoparticle size

Due to the smaller size, nanoparticles have large surface area which is attributed to higher heat transfer rates. Nanoparticles have high thermal conductivity, but heat capacity is low. Nanoparticles are stable in the base fluid at high temperatures and they do not agglomerate in the water as well [51]. Energy and exergy efficiency of the system can be increased by increasing the size of the nanoparticle in the turbulent regime but in laminar regime the case is opposite. Yazdanifard et al. [15] interestingly found no effect of particle size on the efficiency. They used Titanium dioxide nanofluid and Aluminum oxide nanofluid for the cooling purpose but no significant efficiency alteration was observed. Whereas, Al-Shamani et al. [4] observed that heat transfer of the nanofluid decreased with a decrease in size of the nanoparticle. Therefore, there is still a need for further experimentation to conclusively narrate the effects of nanoparticle size on the efficiency of the solar systems.

4.5. Base fluid

Not only the type of nanoparticle affects the performance of the PV/T system but the type of base fluid is also of same significance while predicting the performance of the system. Using base fluids such as ethylene-glycol, polyethylene glycol, cetyltrimethylammonium bromide water mixtures instead of water can considerably elevate the cell efficiency [15]. Addition of surfactant and selection of suitable pH of nanofluid can display pronounced effects [44]. Rajeb et al. [52] examined both numerically and experimentally the effect of variation in concentration (0.1, 0.2 and 0.4 wt%), type of nanoparticle (Al_2O_3 and Cu) and type of base fluid (water and ethylene glycol) on the efficiency of PV/T system being cooled by nanofluid. They observed that increasing the concentration of nanofluid increased the efficiency of the system. The system best performed when water was used as base fluid as compared to ethylene glycol base fluid. According to the drawn results, maximum electrical and thermal efficiency was found to be 13.55% and 77% respectively for Cu/water nanofluid based PV/T system, at 0.4 wt%. Whereas, they found 13.54% electrical and 60% thermal efficiency for Cu/ethylene glycol based PV/T system, at 0.4 wt%. Conclusively, Cu/water nanofluid based system outperformed Al_2O_3 /water based system in terms of electrical and thermal efficiency. Hosseinzadeh et al. [53]

found that a PV system being cooled by water only, performed better than the systems cooled by either ethylene glycol only and water-ethylene glycol (50% water and 50% ethylene glycol).

4.6. Nanoparticle type

Maadi et al. [54] stated that for metalloids the viscosity of the nanofluids gets increased and the specific heat capacity is decreased, which is not favorable. This is because, at a given mass fraction the volume of the metalloid nanofluids is increased due to high density. Hasan et al. [48] observed that cooling the PVT by impinging SiC, TiO₂, SiO₂ nanofluids and pure water improved the maximum power output by 62.5%, 57%, 55% and 50% as compared to the conventional PV module. Al-Shamani et al. [55] tested SiO₂, TiO₂ and SiC based nanofluid for the cooling purpose to analyze the efficiency betterment. Following the experimental results, SiC/water nanofluid outperformed rest of the nanofluids. At 1000 W/m² irradiance and 0.170 kg/s mass flowrate, SiC/water nanofluid based PV/T system showed 13.529% electrical efficiency whereas, TiO₂/water and SiO₂/water nanofluid based PV/T systems depicted 10.978% and 10.302% electrical efficiency respectively. PV/T system utilizing water solely for cooling, approached 9.608% electrical efficiency.

Kolahan et al. [56] examined the entropy generation in PV/T system due to the addition of nanoparticles both numerically and experimentally. They used Al₂O₃/water, TiO₂/water and ZnO/water by 0.2 wt% and SiO₂/water by 1 wt% and 3 wt% nanofluids (along with acetic acid as a surfactant). Following the results, ZnO/water produced least frictional entropy, SiO₂/water produced maximum pressure drop and frictional entropy generation and Al₂O₃/water produced least thermal and total entropy generation. Thermal entropy generation was found to be maximum at inlet, turning points and outlet, due to high temperature differences. For metallic nanofluids, increase of mass fraction caused density and viscosity elevation. Increased mass fraction reduced the velocity which in turns reduced the frictional entropy generation. For metalloid nanofluids, reverse is the case. For ZnO the frictional entropy was decreased by 10.87% at 10 wt%, whereas, for SiO₂/water the frictional entropy was increased by 0.94% compared to pure water. Addition of nanoparticles causes more prominent reduction in thermal entropy generation compared to the frictional entropy generation. Considering the entropy generation view point, metallic nanofluids produce better results than the metalloid nanofluids.

Extensive experimentation has been conducted to examine the effect of magnetic on the performance of nanofluids [66–70]. If the Ferro-nanoparticle is used in the system, employing alternating magnetic field around the channels can improve the efficiency of the system. Experimental results also depicted that the alternating magnetic field improved the system performance whereas, the constant field did not produce significant efficiency enhancement when compared with the no field condition. The system efficiency was found to be 71.91% when there was no field applied, whereas, the efficiency went up to 73.58% in the presence of alternating magnetic field (50 Hz) in case of 1 wt% and 1100 W/m² [37]. Shape of nanoparticle and type of magnetic field can influence the performance of nanofluid. Sheikholeslami et al. [66, 67] numerically analyzed the effect of non-uniform magnetic field on Fe₃O₄-H₂O nanofluid flowing in a porous cavity. Following the results, platelet shape of nanoparticles depicted

Intensity	Cooling Fluid	Electrical Efficiency	Thermal Efficiency
200	SiC-Water	16.90%	8%
1000	SiC-Water	10.90%	48%
200	CuO-Water	16%	6%
1000	CuO-Water	10%	41%
200	Al ₂ O ₃ -Water	13.50%	6%
1000	Al ₂ O ₃ -Water	9.80%	41%
200	Water	11.90%	4%
1000	Water	8.40%	31%

Table 2. Effect of irradiance on efficiency [38].

highest Nusselt number (i.e. optimum heat transfer) under the influence of non-uniform magnetic field. In the presence of magnetic field, addition of nanoparticles can improve the heat transfer properties of nanofluids [68].

4.7. Channel geometry

Narrow channels offer higher enhancement in the heat transfer coefficient whereas the wide channels depict instabilities in lateral heat transfer. Roughness in the pipes also affects the magnitude of heat transfer. Pipes with greater roughness magnitude offer greater heat transfer due to the increased contact surface. In order to achieve higher performance, the temperature distribution inside the channel should be held uniform, the temperature should be kept low and the pressure drop should also be as minimum as possible [49]. Considering the **Table 3**, helical channel performs best because of greater surface contact of nanofluid with the rear surface of PV unit.

Researcher	Nanoparticle	Base fluid	Concentration	Flowrate	Channel Geometry	Effect on Temperature	Effect on Electrical Efficiency
Karami and Rahimi [34]	Boehmite	Water	0.01 wt%	300 ml/min	Straight	Decreased from 62°C to 32.5°C for flowrate 0–300 ml/min	27.12% increase compared to Conventional PV System
Karami and Rahimi, [57]	Boehmite	Water	0.1 wt%	200 ml/min	Straight	18.33°C Temperature Reduction	20.57% increase compared to conventional PV System
	Boehmite	Water	0.1 wt%	200 ml/min	Helical	24.22°C Temperature Reduction	37.67% increase compared to Conventional PV System

Table 3. Effect of channel geometry on efficiency.

4.8. Circulation method

When cooling the PV module via nanofluid, the circulation method is also of much importance. If the circulation is done via passive method, the increasing intensity of light would cause a reduction in electrical efficiency and enhancement in thermal efficiency because natural convection is not that efficient. Thus, active convection cooling should be employed to obtain optimum results. Whereas, the elevation in thermal efficiency is due to the availability of enough time for the cooling fluid to exchange heat. However, the overall efficiency of the system gets increased if the cooling is employed. Pumping of nanofluid can further improve the efficiency compared to the passive cooling [38].

5. Advantages of nanofluid-based cooling

5.1. Environmental benefits

Fossil fuel based power plants emit tons of noxious gases that detriment the environment. Since the solar power plants are emission free, production of electricity via this method can eliminate the emission of 16,974,57 tons of CO_2 [58]. Hassani et al. [26] evaluated that nanofluid based PV/T systems can omit the emission of $448 \text{ kg CO}_2 \text{ m}^{-2} \text{ yr}^{-1}$.

5.2. Economic benefits

PV/T system can provide an economical solution for industrial and domestic power demands. Studies indicate a significant reduction in energy consumption produced from conventional resources due to the use of such system [23, 59]. Taylor et al. [60] also narrated that a solar thermal based power plant of 100 MW capacity can save about \$3.5 million per annum if the nanofluid receiver is incorporated with it. Nanofluids need a smaller area for heat transfer thus making the PV system compact and reducing the costs [51]. The economic analysis depicted that the cost of energy produced by nanofluid based PV/T system is 82% less than the current prices in Saudi Arabia [33]. Nanofluid system is predicted to takes only 2 years for pay-back [26]. Sardarabadi et al. [61] evaluated that size reduction by 21, 32,33 and 34 from energy viewpoint and 5,6,7 and 6 from exergy viewpoint for PVT/water, PVT/ TiO_2 , PVT/ ZnO and PVT/ Al_2O_3 respectively. By size reduction we mean the amount of material saved for the same required energy and exergy outputs at the same conditions.

6. Conclusion

Cooling of PV module by nanofluids significantly enhances electrical efficiency and thermal energy. Cooling causes the heat removal which in turns halts the development of thermal stresses, making the PV modules to last long and operate more efficiently. Employing nanofluids impedes entropy generation as well. Efficiency of this system escalates with increasing concentration of nanofluid up to a certain limit but as the concentration exceeds this optimum

limit, efficiency tends to decline because of the clustering and agglomeration of nanoparticles. Increasing flowrate of nanofluid increases the efficiency but as the flow gets into turbulent regime the instability issues arise and this also requires higher pumping power, in turns reducing overall system's efficiency. Using helical microchannel can increase the heat transfer and thus overall efficiency gets elevated. Using surfactant in the nanofluid can also surge the system's performance. Some of the measures that can refine the performance of these systems include,

1. Glazing can drastically improve the nanofluid based PV/T system's performance [46, 47].
2. Simultaneously using optical filters over the surface and thermal collector at the rear end can also elevate performance.
3. Applying alternating magnetic field around the flow channel can supplement the performance of system if the Ferro-nanoparticles are being used.

The unresolved challenges being faced by the researchers while using nanofluids include instability, agglomeration, high pumping power, and erosions. Stability improvement is the most important need of the hour in order to further proceed towards commercial use of nanofluids, as no perfect method of preparation and processing of stable nanofluid has been determined up-to-date.

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