Journal of Al-Azhar University Engineering Sector

Vol. 20, No. 74, January 2025, 228 - 242

A Numerical Study on PV Panels Integrated with Hybrid ZnO-MgO/Water-Ethylene Glycol Nanofluid-Based Solar Spectrum Filters

Yasser M. Safan[1,2,*], Mohamed R. Salem [1,3], S.A. Abdel-Moneim[1], Ashraf E. Elmohlawy[1]

[1] Mechanical Engineering Department, Faculty of Engineering at Shoubra, Benha University, 108 Shoubra St., 11629, Cairo, Egypt
[2] Industrial Engineering Department, Faculty of Engineering, October University for Modern Sciences and Arts, 6th October City, Egypt
[3] Department of Mechanical Engineering, Faculty of Engineering, Al Baha University, 65527, Al Baha, Saudi Arabia

***Correspondence:** Eng.yassersaafan@gmail.com

Citation:

Y.M. Safan, M.R. Salem, S.A. Abdel-Moneim and A.E. Elmohlawy, "A Numerical Study on PV Panels Integrated with Hybrid ZnO-MgO/Water-Ethylene Glycol Nanofluid-Based Solar Spectrum Filters", Journal of Al-Azhar University Engineering Sector, vol 20, pp. 228 - 242, 2025.

Received: 15 August 2024

Revised: 04 October 2024

Accepted: 15 October 2024

ABSTRACT

This study investigates the effect of using a hybrid nanofluid filter on the performance of a PV system. The ZnO-MgO/Water-Ethylene Glycol (W-EG)-based filter presents an economic and green optical filter. This study compares the effects of using a hybrid filter against other filters under a variable optical fluid mass flux (0-10 kg/s.m^2), a maximum radiation intensity (1000 W/m^2), and a fixed filter thickness (10 mm). The results show that a dynamic W-EG (60:40) filter with mass flux (1-6 kg/s.m^2), can reduce the temperature of the PV cells by 45% of that for a stationary filter. In addition, the performance of the spectral splitting filter-PV (SSF-PV) system shows an average enhancement ratio in the electrical efficiency by 28% more than that of the reference PV panel, and an average improvement in the cooling effect by 26%, relative to the fixed inlet temperature (20°C) of optical fluid. The proposed nanofluid-based SSF-PV system achieves an optimum electrical efficiency and enhanced cooling effect compared with investigated nanofluids.

KEYWORDS: Solar Spectrum Filter, Hybrid Nanofluid, ZnO-MgO, Water-Ethylene Glycol, PV Panels.

دراسة عددية لألواح كهروضوئية مدمجة بمرشح طيف شمسي نانوي هجين قائم على أكسيد الزنك وأكسيد المغنيسيوم مع خليط من الماء وإيثيلين جلايكول

ياسرمحمد سعفان[1,2] ، محمد رضا سالم[1,3] ، سيد أحمد عبد المنعم[1]، أشرف السيد المحلاوي[1]

[1] قسم الهندسة الميكانيكية، كلية الهندسة بشبرا، جامعة بنها، القاهرة، مصر

[2] قسم الهندسة الصناعية، كلية الهندسة، جامعة اكتوبر للعلوم الحديثة والآداب، القاهرة، مصر

[3] قسم الهندسة الميكانيكية، كلية الهندسة، جامعة الباحة، الباحة ، المملكة العربية السعودية

***البريد الاليكتروني للباحث الرئيسي :** Eng.yassersaafan@gmail.com

الملخص

تتناول هذه الدراسة أداء النظام الشمسي الكهروضوئي المزود بمرشح هجين من السوائل النانوية لتعزيز الأداء للمنظومة. ويعتبر المرشح النانوي المدمج المكون من جزيئات أكسيد الزنك – أكسيد المغنيسيوم (ZnO-MgO)/ماء-إيثيلين جلايكول (W-EG) مرشحًا اقتصاديًا وصديقا للبيئة . تتناول هذه الدراسة مقارنة بين المرشح الهجين المقترح و مرشحات أخرى أثناء التعرض لمعدل تدفق سطحي متغير للسائل النانوي (0-10 كجم/ثانية.م^2) لكثافة إشعاع قصوى (1000 وات/م^2)، ، وسمك مرشح ثابت (10 مم). وفقًا للنتائج، فإنه يمكن للمرشح الديناميكي W-EG (60:40) أن يخفض درجة حرارة الخلايا الكهروضوئية بنسبة 45% بالمقارنةً بالمرشح الثابت أثناء معدل تدفق سطحي (1-6 كجم/ثانية.م^2). بالإضافة إلى ذلك، فإن أداء المرشح الكهروضوئي يُظهر معدل تحسن في الكفاءة الكهربائية بقيمة 28% أكثر من اللوح الكهروضوئي القياسي وأيضا معدل تبريد بقيمة 26% بالنسبة إلى درجة حرارة السائل النانوي القياسية عند مدخل المرشح. لذا يعتبر اللوح الكهروضوئي المدمج مع مرشح طيف شمسي نانوي هجين قادرعلى تحقيق كفاءة كهربائية مثلى و معدل تبريد محسن بالمقارنة بالسوائل النانوية التي تم دراستها.

الكلمات المفتاحية: مرشح الطيف الشمسي، الموائع النانوية الهجينة، أكسيد الزنك وأكسيد المغنيسيوم، الماء وإيثيلين جلايكول، الألواح الكهروضوئية.

1 Introduction

Solar energy is a vital clean and sustainable energy resource. Conventional Photovoltaic (PV) panels convert solar radiation directly into electricity. However, in hot and harsh climates, these panels experience a significant drop in their electrical conversion efficiency. This efficiency can decrease by up to 0.6% for each degree of temperature rise above the standard nominal operating temperature for the widely used crystalline silicon PV panels [1-4]. The most challenging conditions for PV panel operation occur when solar radiation is at its peak and wind speeds are minimal [5]. The primary reason for the temperature increase in PV panels is that PV cells cannot convert all incident solar radiation into electricity. They can only utilize a limited range (about 15%-20%) of the solar spectrum (visible light and near-infrared) for electricity generation. The rest of the spectrum, such as ultraviolet and infrared radiations, are absorbed, which contributes to the heat build-up of the PV module [6, 7]. Therefore, various cooling techniques have been employed to reduce the temperature of PV cells. However, these methods often subject the cells to recurrent thermal stress and generate hot spots due to uneven cooling. Thermal stress and hot spots can lower energy output and shorten the lifespan of PV panels [8]. To address this issue, Spectral Splitting Filters (SSFs) were developed to fully utilize the sun's spectrum for more efficient electrical energy generation.

Among the SSFs, liquid filters are flexible and can be easily adjusted [9, 10]. Furthermore, the properties of the liquid can be modified by adding nanoparticles [9]. Spectral filtration nanomaterials are divided into four categories: metals, metal-oxide, core@shell, and carbon-based nanoparticles [11]. Numerous studies have explored metal-based nanofluid filters using various base fluids, particularly water and cobalt sulphate [12-18]. Gold (Au) and silver (Ag) were the most frequently used metals. Research on water-based metal nanofluids demonstrated a 5% increase in overall efficiency when a 0.0002 wt% gold/water nanofluid was used instead of a deionized water filter [12]. Another study found that, compared to a standalone PV system, the electrical efficiency improved by approximately 5% at ambient temperatures above 34°C when silver/water nanofluid was employed [13]. Zhang et al. [14] identified the optimal silver/water nanofluid as having a 20 nm particle radius and a volume concentration of 2.5 ppm at a 10 mm optical path, resulting in an electrical efficiency of 11.85% and a merit function value of 1.61 for Si cells. Investigations into metal/cobalt sulphate nanofluids revealed a fill factor of 0.633 and a 4% increase in thermal efficiency when silver-cobalt sulphate (Ag–$CoSO_4$) nanofluid was used instead of a deionized water filter. However, a slight decrease in electrical efficiency (0.3-1%) was noted [15]. Han et al. [16] reported a peak merit function of 1.37 with an Ag/$CoSO_4$ nanofluid filter at 37 ppm Ag nanoparticles. In conclusion, although Ag/$CoSO_4$ nanofluid exhibited strong absorption over a broader spectrum than water-based nanofluid, leading to higher temperature reduction, it resulted in lower electrical output at the same Ag nanoparticle loadings [16]. Fernandes et al. [17] explored the optimal combinations of various metallic nanoparticles and base fluids. They tested gold-copper/water, gold-indium tin oxide/ethylene glycol, copper/water, and copper-indium tin oxide/ethylene glycol nanofluids, achieving spectral filtration efficiencies of 39.7%, 39.1%, 39.1%, and 37.1%, respectively, using silicon solar cells. Zhang et al. [18] introduced a spectral splitting Photovoltaic/Thermal (PV/T) system to enhance the electrical efficiency of photovoltaic modules by filtering part of the energy with Ag nanofluid. Their indoor experiments indicated that increased solar radiation had minimal impact on electrical efficiency, while increased optical thickness or mass fraction improved heat harvest. Additionally, Abdelrazik [6, 19] identified that water containing a core-shell silver-silica nanofluid was the most effective filter for monocrystalline silicon photovoltaic cells, whereas pure water was the best filter for three different types of cells in numerical analyses.

Researchers have also focused on metal-oxide nanomaterials. Qi et al. [20] and Jing et al. [21] examined the effectiveness of silica (SiO_2)-water nanofluid as a spectral filter with various nanoparticle sizes (5 nm, 10 nm, 20 nm, 25 nm, and 50 nm). Their findings revealed that the optical properties: transmittance, scattering, and absorption, were influenced by nanoparticle size, while concentrations below 0.10 wt% had minimal impact on optical transmission. The optimal SiO_2 nanoparticle size was 20 nm at 0.05 wt%, and 5 nm at a 2% volume fraction [20, 21]. Other studies [22-24] explored the use of ZnO due to its cost benefits over Au and Ag. Elharoun et al. [22] and Huaxu et al. [23] assessed the optical transmittance of a water-ZnO filter, finding average transmittance values between 81.4% and

71.9% at different concentrations. Elharoun et al. [22] then applied the water-ZnO filter to a compound parabolic concentrated PV cell with various nanofluid loadings (50, 100, 150, and 200 ppm). Their results showed a maximum PV temperature reduction of 10.7% at 200 ppm, with electrical efficiency and power increasing by 87.8% and 37.8% at 1 cm thickness, respectively. Thermal efficiency reached 21.5%. In contrast, Huaxu et al. [24] focused on glycol-based ZnO instead of water, achieving a thermal efficiency of 47% at an 89.2 ppm concentration. The electrical conversion efficiency was comparable to that of the water-Ag-SiO_2 nanofluid as the optimal filter. Additionally, Cui et al. [25] experimentally tested a 0.02 wt% MgO-water nanofluid filter with 10 nm nanoparticles, demonstrating electrical and thermal efficiencies of 14.7% and 47.2%, respectively.

Furthermore, the Ag@SiO_2 nanofluid is frequently studied due to its strong localized surface plasmon resonance (LSPR) in the ultraviolet-visible band and its stability under high temperatures and radiation for 60 days, especially when combined with cobalt sulfate ($CoSO_4$) and propylene glycol (PG) instead of water [26-30]. Researchers have reported merit functions of 1.4053, 1.51, and 1.12, respectively, when using a Si solar cell filtered by Ag@SiO_2 nanofluid [26-28]. Huang et al. [26] achieved the highest electrical and total efficiencies of 9.2% and 84.3%, respectively, with silver nanoparticles of 30 nm core diameter and 5 nm silica thickness. Additionally, Huang et al. [27] recorded the maximum merit function of 1.51 with a nanofluid concentration of 30 mg/L and an optical path distance of 42 mm. Additionally, carbon-based nanofluids have been used to enhance the absorption of ultraviolet light bandwidth.

Some studies have focused on combining carbon-based nanoparticles with metallic nanoparticles, such as carbon nanotubes (CNT) with silver (Ag) [31, 32], and with core-shell silver-silica (Ag@SiO_2) [33]. In the studies by Xia et al. [31, 32], the electrical and thermal efficiencies of Ag, CNT, and Ag-CNT were evaluated as spectral filters. The CNT-Ag nanofluid, at its optimal concentration of 5×10^6 μg/m^3, achieved electrical and thermal efficiencies of 11.77% and 38.7%, respectively. These efficiencies represented improvements of 15% and 9.9% compared to the Ag filter alone, and 1.4% and 7.2% compared to the CNT filter alone, at a CNT:Ag ratio of 1:4. Additionally, Hjerrild et al. [33] reported a 30% increase in combined efficiency when using the Ag@SiO_2-CNT filter compared to a water filter.

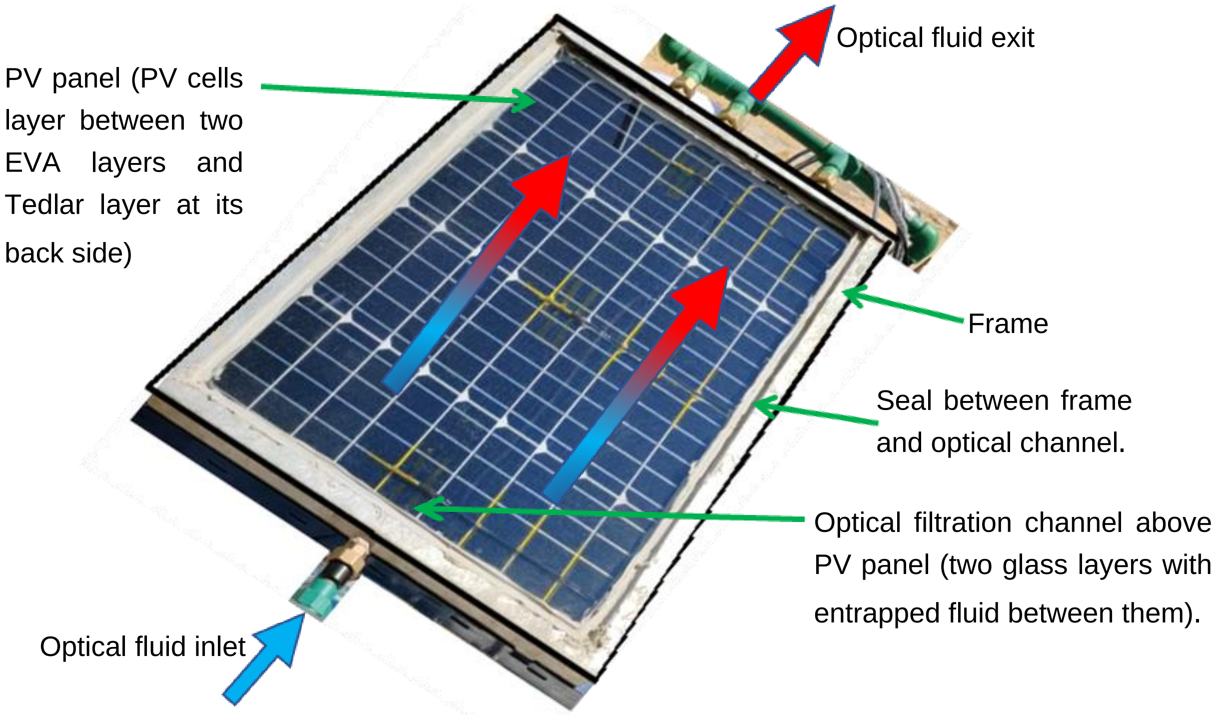
Previous research has primarily focused on single nanofluid filters with varying concentrations, nanoparticle sizes, and diameters, with limited investigation into hybrid nanofluid filters. To the best of our knowledge, no studies have explored the performance of a hybrid ZnO-MgO nanofluid filter using a water-EG mixture as the base fluid. Given the high cost of precious metal nanoparticles such as silver (Ag) and gold (Au) and the complexity of core-shell structures, large-scale industrial applications are limited. Additionally, the long-term stability of nanofluids remains a significant challenge. Thus, the present study addresses this research gap by developing and testing a hybrid ZnO-MgO/Water-Ethylene Glycol-based nanofluid as a solar spectrum filter, which could present a more feasible solution for real-world applications. Vidhya et al. [34] investigated the thermophysical properties and heat transfer performance of different concentrations (0-0.10%) of this nanofluid ZnO-MgO and showed a significant improvement at the 0.10% volume concentration. Therefore, 0.10% concentration is selected. The proposed hybrid nanofluid is based on a hybrid base fluid, a mixture of water and ethylene glycol in a 60:40 ratio. This mixture is chosen in the present study due to its enhanced absorption properties across both ultraviolet and infrared bandwidths, as well as its favorable heat transfer characteristics and reduced pumping power requirements [35-38]. In conclusion, the present study aims to investigate and evaluate the electrical performance characteristics and cooling effectiveness of the SSF-PV system utilizing the proposed hybrid nanofluid, ZnO-MgO/W-EG, as an optical filtration fluid. Furthermore, we compare its performance results with existing literature covering various concentrations (0.002–0.20%v) and a reference conventional PV panel.

2 SSF-PV System

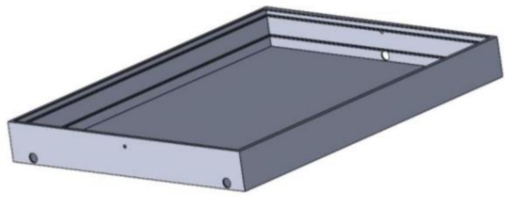
2.1 SSF-PV system description

The proposed SSF-PV system is shown in Fig. 1a. It includes three primary components: a system frame (Fig. 1b), an optical filtration channel above the PV panel, and a 50 W monocrystalline

PV panel (Solarex MSX-50), shown in Fig. 1c and its characteristics are listed in Table 1. The PV panel utilizes visible and near-infrared wavelengths for photoelectric generation, which are transmitted through the optical filtration channel after solar radiation hits the top glass layer. While the ultraviolet and infrared wavelengths, which generate heat through photothermal conversion, are absorbed by the nanofluid filter. This absorption helps maintain the optimal operating conditions for the PV panel. However, some heat is transferred through the SSF-PV system layers, causing the PV layer to warm up.



a) SSF-PV panel



b) The frame of the SSF-PV panel

c) A monocrystalline PV panel (Solarex MSX-50)

Fig. 1: Representation of SSF-PV system.

Table 1: Panel characteristics (at 1000 W/m² and 25°C).

Max. Power (P_m)	50 W
Voltage at Max. Power (V_m)	17.1 V
Current at Max. Power (I_m)	2.92 A
Open circuit voltage (V_{oc})	21.1 V
Short circuit current (I_{sc})	3.17 A
Current-Temperature coefficient	0.065±0.005 A/°C
Dimensions	734 x 535 x 35 mm

2.2 SSF-PV system model

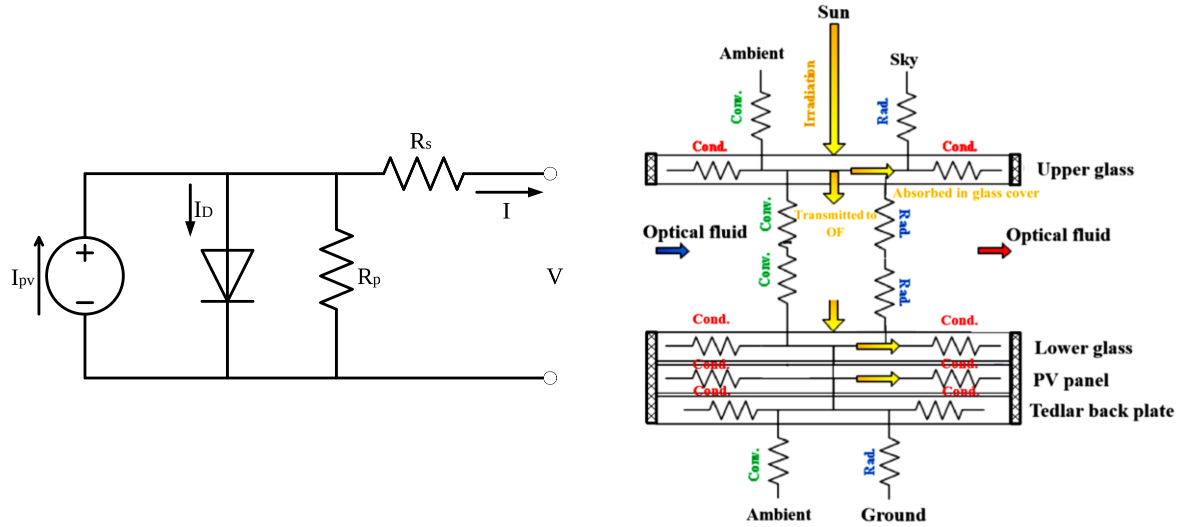
The present SSF-PV system model incorporates both the PV panel and the heat transfer mechanisms of the thermal system. In this study, a five-parameter model is employed as an equivalent model to more accurately represent a typical PV cell, as described in Eq. (1) [39]:

$$I = N_p I_{ph} - N_p I_0 \left[\exp\left(\frac{q}{a K_b T_{pv}} \cdot \left(\frac{V}{N_s} + \frac{I R_S}{N_p} \right) \right) - 1 \right] - \left(\frac{\frac{N_p V}{N_s} + I R_S}{R_P} \right) \quad \textbf{(1)}$$

These parameters are determined either through real measurements obtained during field testing or by using the average temperature of PV cells from COMSOL thermal simulations. Additionally, the heat transfer mechanisms across the various layers of the SSF-PV system can be summarized as follows [10]:

- Natural convection and radiation occur between the top glass layer and its surroundings.
- Forced convection and radiation take place between the optical fluid and the glass layers.
- Pure conduction is present between the PV panel and the glass layers.
- Pure conduction also happens between the Eva and PV layers.
- Pure conduction is found between the PV panel and the back plate (Tedlar).
- Natural convection and radiation are observed from the back plate to the ambient environment, with a convection heat transfer coefficient of 10 $W/m^2.K$ [40] for the upper glass and the backside of the Tedlar layer.

The equivalent model of the PV cell and the heat transfer network are illustrated in Fig. 2. The performance characteristics of the proposed system are the temperature reduction (ΔT) corresponding to the cooling effectiveness, temperature distribution, electrical efficiency (η), and efficiency enhancement ratio, as detailed in Eqs. (2-4) [39, 41]. The reflection of incident solar radiation from the optical filtration nanofluid layer can significantly influence the performance characteristics of the SSF-PV system. Specifically, increased reflection can reduce the transmittance of the optical filter and enhance the scattering of incident light, which may lead to decreased energy absorption and overall efficiency. To mitigate the effects of reflection on system performance, nanoparticles with sizes less than 50 nm are employed in this study, as supported by the findings in [13]. Additionally, the optical filter thickness to 10 mm is optimized, as recommended by [10], to further enhance light transmission and minimize reflection losses.



a) PV equivalent electrical circuit. **b) Heat transfer network across layers of SSF-PV system.**

Fig. 2: Equivalent model of electrical and thermal networks of SSF-PV system [10].

$$\Delta T\ \% = \left[\frac{T_{of,outlet\ (\dot{m})} - T_{of,ref.\ inlet}}{T_{of,outlet\ (\dot{m}=0)} - T_{of,ref.\ inlet}}\right] * 100 \quad \textbf{(2)}$$

$$\eta = \eta_{ref}[1 - \zeta(T - T_{ref})] \quad \textbf{(3)}$$

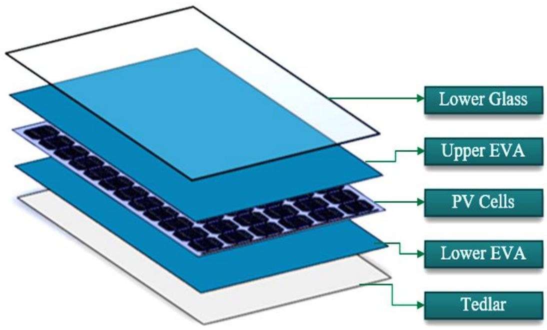
$$\text{Efficiency Enhancement Ratio} = \left[\frac{\eta}{\eta_{PV}}\right] \quad \textbf{(4)}$$

3 SSF-PV System Simulation Model

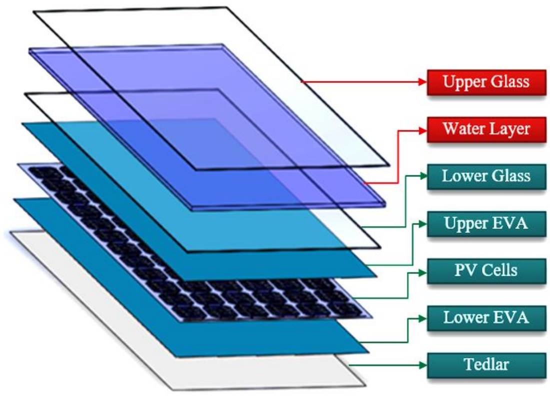
The system simulation in this study initiates with a thermal simulation using COMSOL Multiphysics. Primarily, the effect of the suggested base fluids; water, EG, and water-EG, on the temperature of the SSF-PV system is investigated at a fixed fluid inlet temperature (20°C) with variable flow rate (0-0.05 kg/s) corresponding to a mass flux (0-10 kg/s.m^2) at a maximum radiation intensity (1000 W/m^2). Subsequently, the proposed ZnO-MgO/W-EG hybrid nanofluid filter is compared with various ZnO and MgO filters of different lower and higher concentrations. The present numerical results using Matlab/Simulink for the proposed filter are then compared with the aforementioned nanofluids at a constant mass flux (2 kg/s.m^2). The experimentally evaluated nanofluid properties used in this numerical study were obtained from [42 - 49]. Table 2 illustrates the contents and properties of the different layers, which are depicted in Fig. 3a and 3b, where boundary conditions and heat transfer mechanisms are predetermined. Inputs of ambient temperature and solar radiation intensity generate the operational temperature forecast for each system stratum. Finally, the electrical behavior of the SSF-PV system model is analyzed using Matlab/Simulink, as shown in Fig. 3c, building upon the results from COMSOL Multiphysics.

Table 2: Configuration and properties of modeled and simulated SSF-PV system [34, 42 - 48].

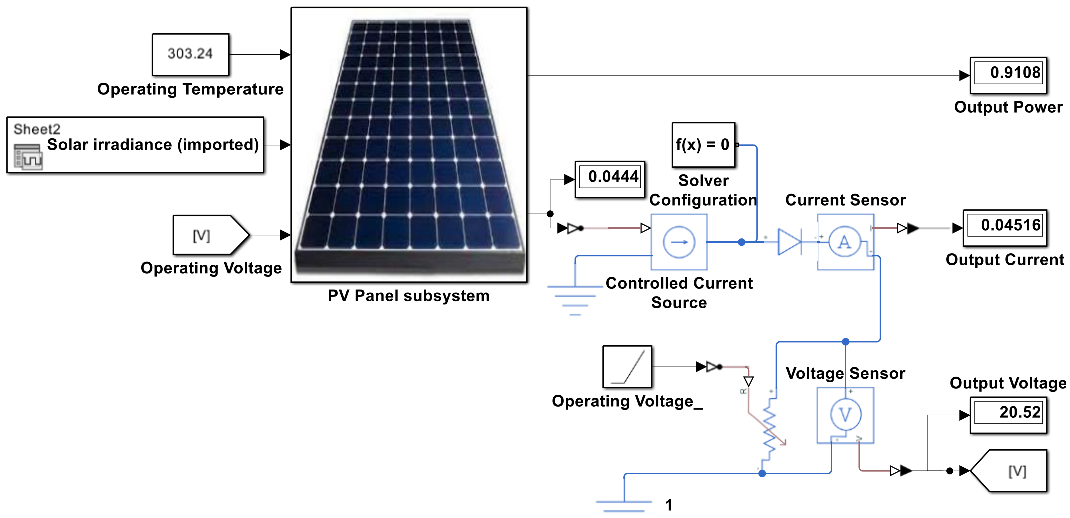
Layer	Nanofluid	Concentration	Thickness (mm)	Thermophysical properties			Optical Absorbance (a.u.)
				Density (kg/m^3)	Thermal conductivity (W/m.K)	Specific heat (J/kg.K)	
Glass	-	-	3	2450	2	500	0.02-0.06
Optical fluid	ZnO/W [42,43]	0.002%v	10	1067-1099	0.6376 - 0.9488	3043 - 3262	0.12-0.49
	ZnO/W-EG [44]	0.20%v			0.3938 - 0.4214	3168 - 3348	0.59-0.78
	MgO/W [45,46]	0.04%v		998-1022	0.6270 - 0.6317	4064 - 4084	0.40-0.56
	MgO/W-EG [47]	0.20%v			0.4486 - 0.5242	2560 - 2850	0.38-0.78
	ZnO-MgO/W-EG [34,48]	0.10%v		1079-1087	0.4920 - 0.5040	3242 - 3417	0.81-1.50
EVA	-	-	0.8	950	0.311	2090	-
PV cells	-	-	0.1	2330	130	677	-
Tedlar	-	-	0.05	1200	0.15	1250	-



a) Exploded view of the layers of the conventional PV panel.



b) Exploded view of the layers of the nanofluid-based SSF-PV system.



c) Simulation model for PV panel using MATLAB/Simulink

Fig. 3: Simulation models.

4 Validation of Simulation Model

Initially, a mesh-independence test is performed to verify the reliability of the results. Various mesh sizes for the SSF-PV system model are evaluated under a solar irradiance of 1000 W/m^2, as shown in Table 3. The discrepancies between the mesh sizes are minimal, all within 0.01%. Therefore, the normal mesh size is chosen to minimize computational time. In the validation phase, the effective irradiance is incrementally adjusted from 600 to 1000 W/m^2. The COMSOL results demonstrate a maximum discrepancy of 3.1%, which is consistent with the findings of Fayaz et al. [49], as shown in Table 4.

Table 3: Mesh independence test.

Mesh Type	Number of Elements	Min. Temperature (K)	Max. Temperature (K)
Normal	233048	304.99	314.37
Fine	252645	304.99	314.37
Finer	409328	304.98	314.70

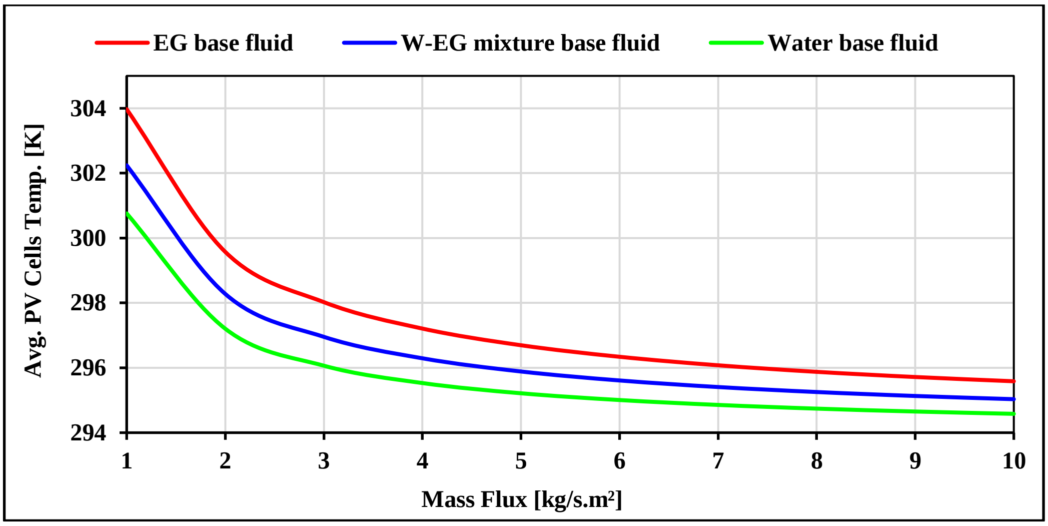
Table 4: Comparison between results of the present simulation model and Fayaz et al. [49].

Radiation Intensity (W/m^2)	Max. Temperature (°C)		Percentage Difference (%)
	Fayaz et al. [49]	Present Work	
600	57.5	59.3	+3.1
800	67.5	68.4	+1.3
1000	77.9	76.5	-1.8

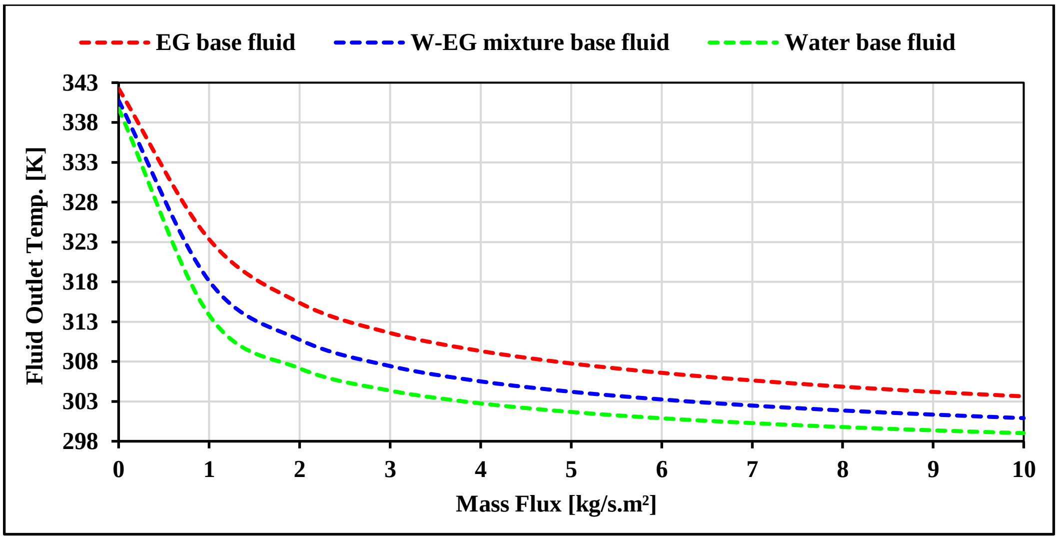
5 Results and Discussion

5.1 Results of using pure base fluids

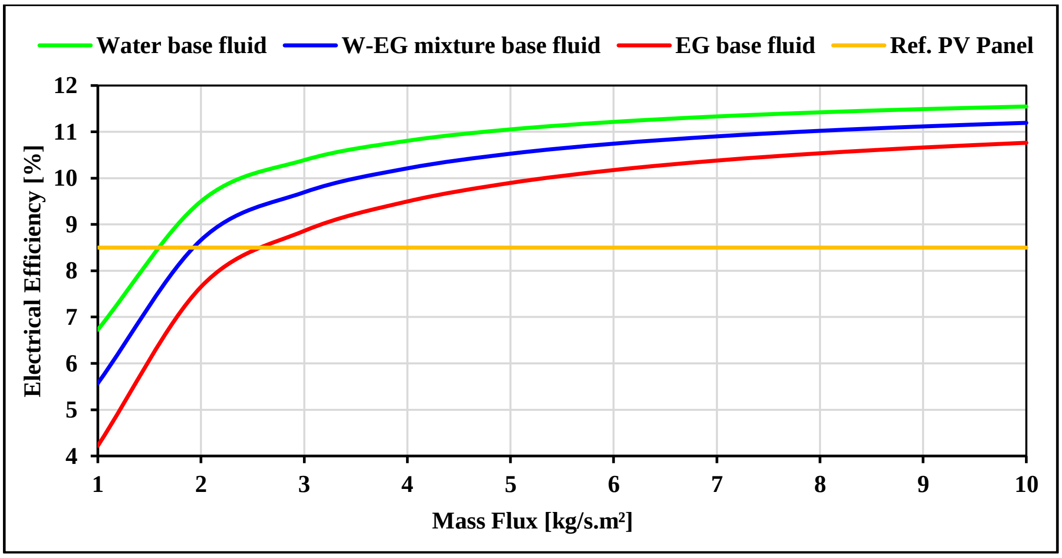
In this analysis, the effect of incorporating three different pure optical filtration fluids; water, ethylene glycol (EG), and a water-ethylene glycol mixture (W-EG, 60:40%), is numerically explored at various mass fluxes (0-10 kg/s.m^2) and constant solar intensity (1000 W/m^2). The inlet temperature of the fluids is fixed at 20°C. The resulting performance characteristics are shown in Fig. 4, while Table 5 presents a sample of these characteristics at a mass flux of 2 kg/s.m^2. These measures indicate that pure EG exhibits the highest cooling effect by (39%) increase in the outlet temperature of the optical fluid. This is explained by the high absorptivity of the pure EG for the ultraviolet light during the photothermal energy conversion process. However, the pure EG recorded the highest PV cells' temperature, and accordingly the lowest electrical efficiency (7.65%). This can be attributed to two reasons; the pure EG has a limited optical absorption of the visible light, which negatively affects the photoelectrical conversion process performed by the PV cells, and also a limited absorbance of the infrared wavelength [50], which results in a heat buildup in the PV cells, and reduced their conversion efficiency. On the contrary, pure water showed the lowest cooling effect (26%) increase in the outlet temperature of the optical fluid, and the highest electrical efficiency (9.5%). According to Eq. (2), Figs. 4 and 5, it can also be revealed that an optical filter at the minimum applied mass fluxes (1 kg/s.m^2), as shown in Figs. 5b, 5d, 5f, results in a significant cooling effect in terms of a temperature reduction by 54%, 45%, and 37% for EG, W-EG, and water, respectively, compared with a stationary optical filter with zero mass flux, as shown in Figs. 5a, 5c, 5e. Therefore, a dynamic filter is highly preferred over a stationary filter (zero mass flux). However, the impact of the mass flux on the temperature reduction diminishes to less than 10% at a transition mass flux of 6 kg/s.m^2. Thus, to attain a good cooling effect, and an optimum electrical efficiency greater than that of the conventional PV panel, it is recommended to use the SSF-PV system with a hybrid base fluid of W-EG. This can be achieved at a mass flux of 2 kg/s.m^2 or higher, which prevents the heat buildup that may arise at low velocities of the optical fluid, and allows the hybrid base fluid to absorb both the ultraviolet and the infrared lights, transmit the visual light and near-infrared wavelengths.



a) Temperature of PV cells in the SSF-PV system.



b) Temperature of optical base fluids in the SSF-PV system.

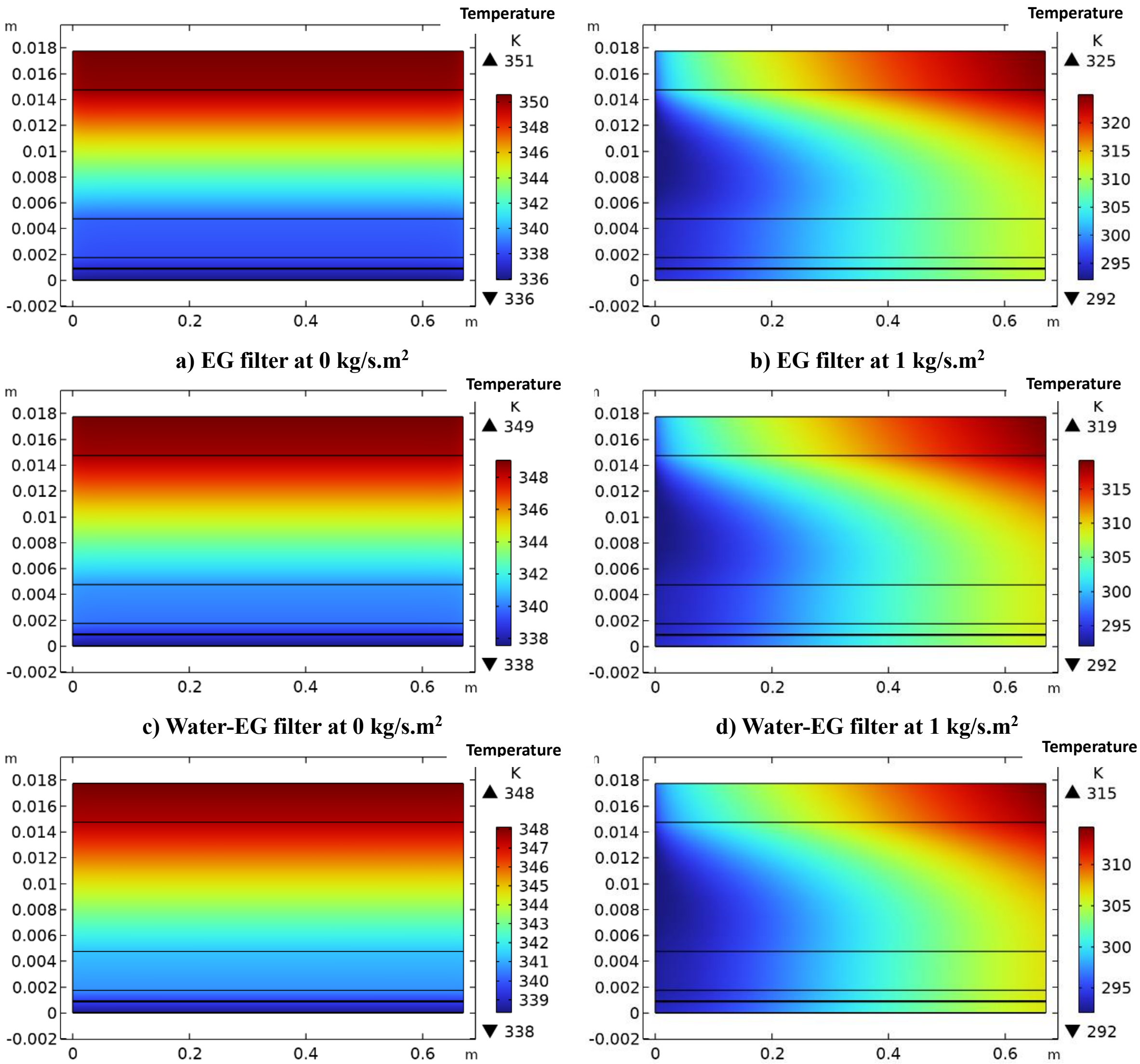


c) Electrical efficiency of the SSF-PV system and the reference PV panel

Fig. 4: Performance of SSF-PV system and reference PV panel at different mass flux and 1000 W/m^2.

Table 5: Performance analysis of SSF-PV system using different base fluids at 1000 W/m² solar irradiance and 2 kg/s.m² mass flux.

Base Fluid	Cooling Effectiveness			Electrical Performance		
	Outlet Fluid Temp. [°C]	ΔT [°C]	ΔT [%]	PV Cell Temp. [°C]	ΔT [°C]	η [%]
EG	42.45	22.45	39	31.10	11.10	7.65
Water - EG	37.80	17.80	32	29.25	9.25	8.70
Water	34.20	14.20	26	27.70	7.70	9.50

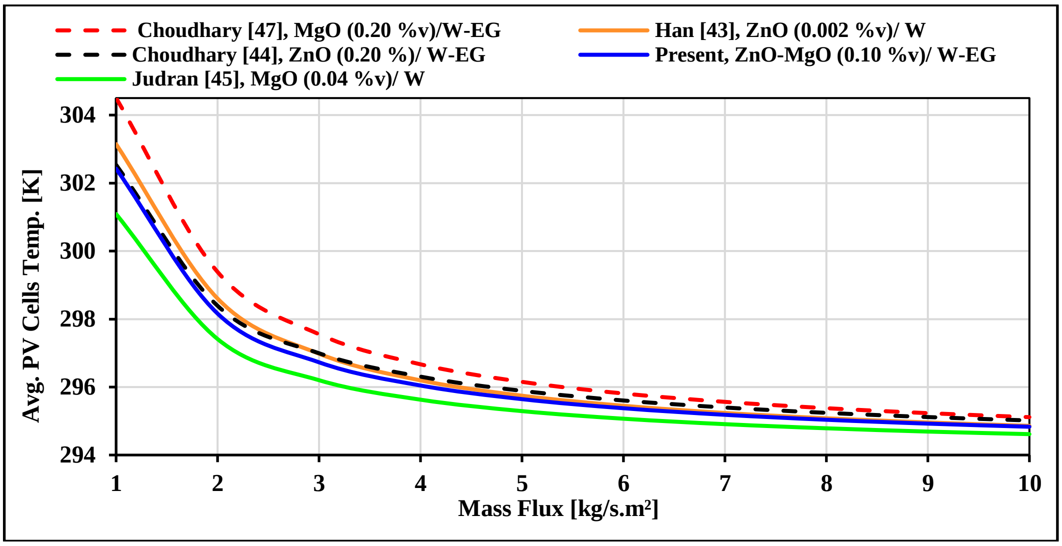


a) EG filter at 0 kg/s.m²
b) EG filter at 1 kg/s.m²
c) Water-EG filter at 0 kg/s.m²
d) Water-EG filter at 1 kg/s.m²
e) Water filter at 0 kg/s.m²
f) Water filter at 1 kg/s.m²

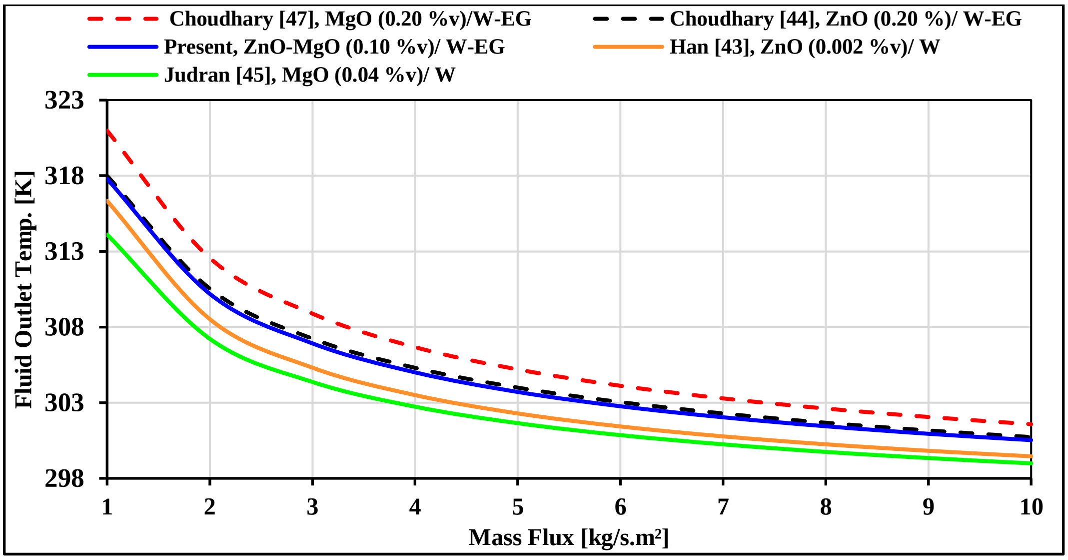
Fig. 5: Temperature distribution of SSF-PV system using different base fluids and mass flux.

5.2 Results using hybrid optical filtration nanofluids

In this analysis, the proposed nanofluid is compared to other literature with low (0.002-0.04%v) and high (0.20%v) concentrations. At first, the filtration effectiveness of the filter is evaluated. The proposed hybrid filter shows a higher ability to maintain the temperature of the PV cells near the reference temperature in comparison to other nanofluids, except for the water-based (0.04%) MgO nanofluid as shown in Fig.6a. This can be attributed to the high transmittance of the water-based nanofluid compared to the limited transmittance of the EG-based and W/EG-based nanofluids. However, water-based nanofluids have limited long-term stability and suffer from high precipitation rates. Secondly, the cooling effectiveness of investigated filters is evaluated using Eq. (2) and Fig.6b. It can be shown that the W-EG-based nanofluids with high concentration (0.20%v) can achieve more effective cooling than low-concentration nanofluids (0.002-0.04%v). The cooling of the investigated nanofluids is enhanced by 29%, 26%, 23%, and 21% for the MgO (0.20%v), proposed ZnO-MgO (0.10%v) and ZnO (0.20%), ZnO (0.002%v), and MgO (0.04%v), respectively. Thus, the proposed nanofluid with only an intermediate concentration (0.10%v) can achieve comparable cooling effectiveness to the high-concentration nanofluids. This is because of the ability of the hybrid ZnO-MgO nanofluid to absorb and benefit from both ultraviolet and infrared wavelengths, in addition to the enhanced thermophysical properties of the ZnO-MgO nanofluid. Finally, the electrical efficiency of the SSF-PV system using the proposed hybrid nanofluid is compared to the reference PV panel in Fig.7. It can be observed from Fig.7 and Eq. (4) that the MgO (0.04%v), the proposed ZnO-MgO (0.10%v), ZnO (0.002%v), ZnO (0.20%), and MgO (0.20%v) achieved an average enhancement ratio in the electrical efficiency by 32%, 28%, 26%, 26%, and 22%, respectively, more than that of the reference PV panel. This is because of the ability of the hybrid nanofluid to maintain the PV layer temperature near the nominal temperature. In conclusion, the proposed nanofluid achieves optimum electrical efficiency and cooling effectiveness, in comparison to other investigated nanofluids which can enhance only a single performance characteristic at a time, either electrical or thermal.



a) Average temperature of PV cells using different nanofluids.



b) Outlet temperature of different optical nanofluids.

Fig. 6: Temperature of PV cells and outlet nanofluids' temperature in SSF-PV system at different mass flux and 1000 W/m².

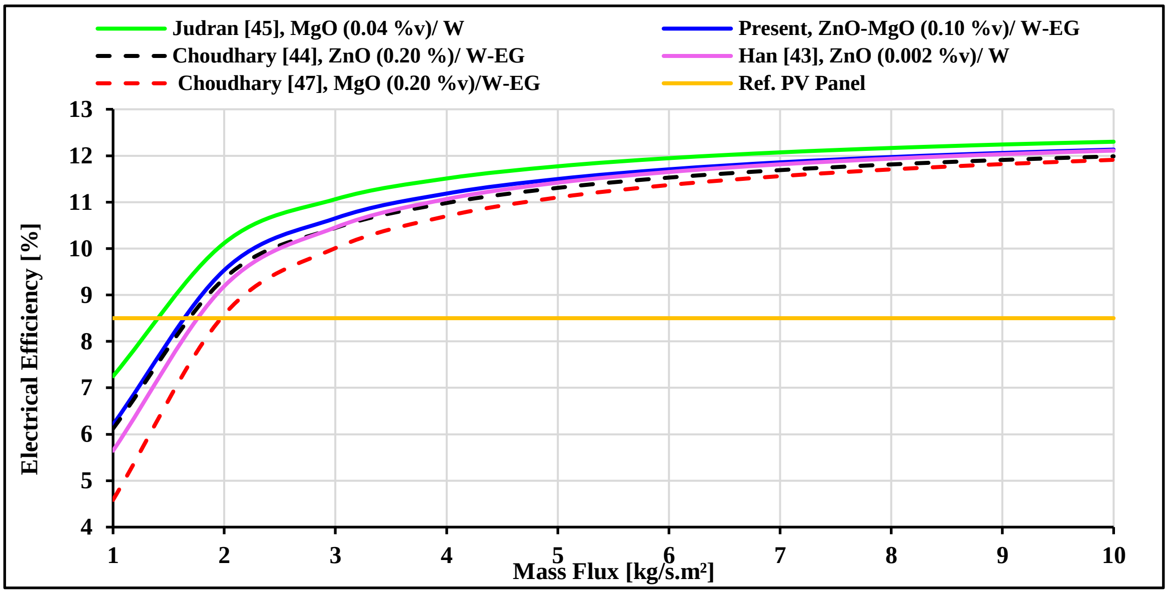


Fig. 7: Electrical efficiency of SSF-PV system using different nanofluids and reference PV panel at different mass flux and 1000 W/m^2.

Conclusion

This study aims to enhance the performance of conventional PV panels using nanofluid SSFs to reduce the PV panels' degradation rate, increase their life cycle, and benefit from the photoelectrical energy conversion process. Based on the present results and discussion, the following conclusions can be withdrawn:

- A hybrid ZnO-MgO/W-EG (60:40) nanofluid is proposed as a spectral splitting filter.
- The highest percentage of temperature increase in the base fluids at the filtration channel is 39%, 32%, and 26, recorded by the EG, W-EG mixture, and water, respectively, relative to the fixed fluid inlet temperature (20°C) at a mass flux of 2 kg/s.m^2 and a maximum solar intensity of 1000 W/m^2.
- The largest electrical efficiency is recorded by the water base-fluid (9.5%), followed by the proposed W-EG mixture (8.7%), and finally the EG (7.65%), at a mass flux of 2 kg/s.m^2 and a maximum solar intensity of 1000 W/m^2.
- A dynamic optical filter at a mass flux of 1 kg/s.m^2 can enhance the PV cooling effect by 54%, 45%, and 37%, using EG, W-EG, and water, respectively, relative to a stationary filter with zero mass flux.
- The effect of variable mass flux on the cooling of the SSF-PV system is reduced to less than 10% at a transition mass flux of 6 kg/s.m^2.
- The hybrid ZnO-MgO(0.10%v) nanofluid, ZnO (0.20%), ZnO (0.002%v), and MgO (0.04%v) exhibit an average cooling effect of 26%, 26%, 23%, and 21%, respectively, relative to the fixed fluid inlet temperature (20°C).
- The SSF-PV system has approached an average enhancement ratio in the electrical efficiency of 32%, 28%, 26%, 26%, and 22%, respectively, more than that of the reference PV panel using MgO (0.04%v), the proposed ZnO-MgO (0.10%v), ZnO (0.002%v), ZnO (0.20%), and MgO (0.20%v), respectively.
- The proposed nanofluid achieves optimum electrical efficiency and effective cooling, compared with the investigated nanofluids.

Conflict of Interest

The authors have no financial interest to declare in relation to the content of this article.

References

[1] Hamzat, A.K., Sahin, A.Z., Omisanya, M.I. and Alhems, L.M., 2021. Advances in PV and PVT cooling technologies: A review. Sustainable Energy Technologies and Assessments, 47, 101360.

[2] Salem, M.R., Ali, R.K. and Elshazly, K.M., 2017. Experimental investigation of the performance of a hybrid photovoltaic/thermal solar system using aluminium cooling plate with straight and helical channels. Solar Energy, 157, 147-156.

[3] Salem, M.R., Elsayed, M.M., Abd-Elaziz, A.A. and Elshazly, K.M., 2019. Performance enhancement of the photovoltaic cells using Al2O3/PCM mixture and/or water cooling-techniques. Renewable Energy, 138, 876-890.

[4] Browne, M.C., Norton, B. and McCormack, S.J., 2015. Phase change materials for photovoltaic thermal management. Renewable and sustainable energy reviews, 47, 762-782.

[5] Abdelrazik, A.S., 2023. The potential of liquid-based spectrally-selective optical filtration and its use in hybrid photovoltaic/thermal solar systems. Solar Energy, 249, 569-605.

[6] Browne, M.C., Norton, B. and McCormack, S.J., 2016. Heat retention of a photovoltaic/thermal collector with PCM. Solar Energy, 133, 533-548.

[7] Han, X., Xue, D., Zheng, J., Alelyani, S.M. and Chen, X., 2019. Spectral characterization of spectrally selective liquid absorption filters and exploring their effects on concentrator solar cells. Renewable energy, 131, 938-945.

[8] Brekke, N., Dale, J., DeJarnette, D., Hari, P., Orosz, M., Roberts, K., Tunkara, E. and Otanicar, T., 2018. Detailed performance model of a hybrid photovoltaic/thermal system utilizing selective spectral nanofluid absorption. Renewable Energy, 123, 683-693.

[9] Ju, X., Xu, C., Liao, Z., Du, X., Wei, G., Wang, Z. and Yang, Y., 2017. A review of concentrated photovoltaic-thermal (CPVT) hybrid solar systems with waste heat recovery (WHR). Science bulletin, 62(20), 1388-1426.

[10] Safan, Y.M., Abdelrazik, A.S., Elmohlawy, A.E., Abdel-Moneim, S.A. and Salem, M.R., 2024. Investigating the performance of photovoltaic panels using optical water spectral splitting filter: An experimental and computational analysis. Journal of Renewable and Sustainable Energy, 16(4).

[11] Jiao, Y., Xing, M. and Estellé, P., 2024. Efficient utilization of hybrid photovoltaic/thermal solar systems by nanofluid-based spectral beam splitting: A review. Solar Energy Materials and Solar Cells, 265, 112648.

[12] Chawrey, S., Kumar, S., Chander, N. and Kumar, N., 2023. Thermal management of a mono-crystalline PV/T system using gold plasmonic nanofluid based optical filter. Materials Today: Proceedings, 84, 57-60.

[13] Abdelrazik, A.S., Saidur, R. and Al-Sulaiman, F.A., 2021. Investigation of the performance of a hybrid PV/thermal system using water/silver nanofluid-based optical filter. Energy, 215, 119172.

[14] Zhang, C., Shen, C., Yang, Q., Wei, S. and Sun, C., 2020. Blended Ag nanofluids with optimized optical properties to regulate the performance of PV/T systems. Solar Energy, 208, 623-636.

[15] Wang, G., Chen, X., Lin, J., Xu, C. and Ju, X., 2023. Experimental study on a concentrating solar photovoltaic/thermal system using different fluid spectral beam filters. Journal of Cleaner Production, 429, 139549.

[16] Han, X., Chen, X., Wang, Q., Alelyani, S.M. and Qu, J., 2019. Investigation of CoSO4-based Ag nanofluids as spectral beam splitters for hybrid PV/T applications. Solar Energy, 177, 387-394.

[17] Fernandes, M.R. and Schaefer, L.A., 2021. Multiparticle nanofluid optimization for spectral-splitting energy harvesting. Renewable Energy, 173, 849-860.

[18] Zhang, C., Shen, C., Zhang, Y., Sun, C., Chwieduk, D. and Kalogirou, S.A., 2021. Optimization of the electricity/heat production of a PV/T system based on spectral splitting with Ag nanofluid. Renewable Energy, 180, 30-39.

[19] Abdelrazik, A.S., 2023. Water liquid compatibility as a spectral splitting optical filtration fluid to six types of photovoltaic solar cells under high solar concentrations. Energy Conversion and Management, 294, 117557.

[20] Qi, Y., Liu, Z., Shi, Y., Yu, X. and Yang, B., 2023. Size optimization of nanoparticle and stability analysis of nanofluids for spectral beam splitting hybrid PV/T system. Materials Research Bulletin, 162, 112184.

[21] Jing, D., Hu, Y., Liu, M., Wei, J. and Guo, L., 2015. Preparation of highly dispersed nanofluid and CFD study of its utilization in a concentrating PV/T system. Solar Energy, 112, 30-40.

[22] Elharoun, O., Tawfik, M., El-Sharkawy, I.I. and Zeidan, E., 2023. Experimental and numerical study of photovoltaic performance integrated with a nanofluid-based optical filter and a compound parabolic concentrator. Energy Conversion and Management, 291, 117278.

[23] Huaxu, L., Fuqiang, W., Dong, L., Jie, Z. and Jianyu, T., 2019. Optical properties and transmittances of ZnO-containing nanofluids in spectral splitting photovoltaic/thermal systems. International Journal of Heat and Mass Transfer, 128, 668-678.

[24] Huaxu, L., Fuqiang, W., Dong, Z., Ziming, C., Chuanxin, Z., Bo, L. and Huijin, X., 2020. Experimental investigation of cost-effective ZnO nanofluid based spectral splitting CPV/T system. Energy, 194, 116913.

[25] Cui, Y. and Zhu, Q., 2012, March. Study of photovoltaic/thermal systems with MgO-water nanofluids flowing over silicon solar cells. In 2012 asia-pacific power and energy engineering conference (1-4). IEEE.

[26] Huang, J., Han, X., Ma, Y. and Khosa, A.A., 2024. Multi-parameter study and two-step optimization of the nanofluid-filtered photovoltaic/thermal systems. Applied Thermal Engineering, 241, 122417.

[27] Huang, J., Han, X., Zhao, X., Khosa, A.A. and Meng, C., 2022. The stability, optical behavior optimization of Ag@ SiO2 nanofluids and their application in spectral splitting photovoltaic/thermal receivers. Renewable Energy, 190, 865-878.

[28] Crisostomo, F., Hjerrild, N., Mesgari, S., Li, Q. and Taylor, R.A., 2017. A hybrid PV/T collector using spectrally selective absorbing nanofluids. Applied energy, 193, 1-14.

[29] Huang, J., Han, X., Zhao, X. and Meng, C., 2021. Facile preparation of core-shell Ag@ SiO2 nanoparticles and their application in spectrally splitting PV/T systems. Energy, 215,119111.

[30] Zhao, X., Han, X., Yao, Y. and Huang, J., 2022. Stability investigation of propylene glycol-based Ag@ SiO2 nanofluids and their performance in spectral splitting photovoltaic/thermal systems. Energy, 238, 122040.

[31] Xia, X., Wei, W., Yu, B., Li, N. and Ji, J., 2024. Experiment and numerical investigation on a spectral splitting PV/T system for electrical energy and thermal output. Energy, 288, 129911.

[32] Xia, X., Cao, X., Li, N., Yu, B. and Liu, H., 2023. Study on a spectral splitting photovoltaic/thermal system based on CNT/Ag mixed nanofluids. Energy, 271, 127093.

[33] Hjerrild, N.E., Mesgari, S., Crisostomo, F., Scott, J.A., Amal, R. and Taylor, R.A., 2016. Hybrid PV/T enhancement using selectively absorbing Ag–SiO2/carbon nanofluids. Solar Energy Materials and Solar Cells, 147, 281-287.

[34] Vidhya, R., Balakrishnan, T. and Kumar, B.S., 2021. Investigation on thermophysical properties and heat transfer performance of heat pipe charged with binary mixture based ZnO-MgO hybrid nanofluids. Materials Today: Proceedings, 37, 3423-3433.

[35] Zhang, J., Zhang, P., Ma, K., Han, F., Chen, G. and Wei, X., 2008. Hydrogen bonding interactions between ethylene glycol and water: density, excess molar volume, and spectral study. Science in China Series B: Chemistry, 51, 420-426.

[36] Sundar, L.S., Ramana, E.V., Singh, M.K. and De Sousa, A.C.M., 2012. Viscosity of low volume concentrations of magnetic Fe3O4 nanoparticles dispersed in ethylene glycol and water mixture. Chemical physics letters, 554, 236-242.

[37] Said, Z., Sajid, M.H., Alim, M.A., Saidur, R. and Rahim, N.A., 2013. Experimental investigation of the thermophysical properties of AL2O3-nanofluid and its effect on a flat plate solar collector. International communications in heat and mass transfer, 48, 99-107.

[38] Nabil, M.F., Azmi, W.H., Hamid, K.A., Mamat, R. and Hagos, F.Y., 2017. An experimental study on the thermal conductivity and dynamic viscosity of TiO2-SiO2 nanofluids in water: ethylene glycol mixture. International Communications in Heat and Mass Transfer, 86, 181-189.

[39] Masters, G.M., 2013. Renewable and efficient electric power systems. John Wiley & Sons.

[40] Abdelrazik, A.S., Al-Sulaiman, F.A. and Saidur, R., 2022. Feasibility study for the integration of optical filtration and nano-enhanced phase change materials to the conventional PV-based solar systems. Renewable Energy, 187, 463-483.

[41] Hissouf, M., Najim, M. and Charef, A., 2020. Numerical study of a covered Photovoltaic-Thermal Collector (PVT) enhancement using nanofluids. Solar Energy, 199, 115-127.

[42] Li, Y., Fernández-Seara, J., Du, K., Pardiñas, Á.Á., Latas, L.L. and Jiang, W., 2016. Experimental investigation on heat transfer and pressure drop of ZnO/ethylene glycol-water nanofluids in transition flow. Applied Thermal Engineering, 93, 537-548.

[43] Han, X., Lu, L., Yan, S., Yang, X., Tian, R. and Zhao, X., 2021. Stability, thermal conductivity and photothermal conversion performance of water-based ZnO nanofluids. Journal of Thermal Science, 30, 1581-1595.

[44] Choudhary, S., Sachdeva, A. and Kumar, P., 2020. Influence of stable zinc oxide nanofluid on thermal characteristics of flat plate solar collector. Renewable Energy, 152, 1160-1170.

[45] Judran, H.K., Al-Hasnawi, A.G.T., Al Zubaidi, F.N., Al-Maliki, W.A.K., Alobaid, F. and Epple, B., 2022. A high thermal conductivity of MgO-H2O nanofluid prepared by two-step technique. Applied Sciences, 12(5), 2655.

[46] Ghanbari, R. and Heyhat, M.M., 2022. Experimental Study of the Effect of Magnesium Oxide and Multi-Walled Carbon Nanotubes Hybrid Nanofluid on Increasing the Absorption Efficiency of Solar Radiation. Amirkabir Journal of Mechanical Engineering, 54(5), 1101-1124.

[47] Choudhary, S., Sachdeva, A. and Kumar, P., 2020. Investigation of the stability of MgO nanofluid and its effect on the thermal performance of flat plate solar collector. Renewable Energy, 147, 1801-1814.

[48] Anandan, K., Siva, D. and Rajesh, K., 2018. Structural and optical properties of (ZnO/MgO) nanocomposites. Int. J. Eng. Res. Technol, 7(8), 493-499.

[49] Fayaz, H., Rahim, N.A., Hasanuzzaman, M., Rivai, A. and Nasrin, R., 2019. Numerical and outdoor real time experimental investigation of performance of PCM based PVT system. Solar Energy, 179, 135-150.

[50] Sajid, M.U. and Bicer, Y., 2020. Nanofluids as solar spectrum splitters: a critical review. Solar Energy, 207, 974-1001.

Nomenclatures

a	Diode ideality factor
I	Electrical current, A
Kb	Boltzmann constant ≈ $1.38\text{x}10^{-23}$ J/K
N	Number of cells in PV panel
q	Electron charge ≈ $1.602\text{x}10^{-19}$ C
R	PV cell resistance, Ω
T	Temperature, °C or K
V	Voltage, V

Greek letters

ζ	PV cell current-temperature coefficient, A/°C
η	Efficiency

Superscripts and subscripts

conv	Convection
o	Reverse saturation
p	Parallel
ph	Photocurrent
PV	Photovoltaic panel
rad	Radiation
ref	Reference or Nominal value
s	Series

Acronyms and abbreviations

EG	Ethylene Glycol
EVA	Ethylene Vinyl Acetate
PV	Photovoltaic
PV/T	Photovoltaic/Thermal
SSF	Spectral Splitting Filter
W	Water