SEBHA UNIVERSITY CONFERENCE PROCEEDINGS, VOL.03 NO. 2 2024
DOI: 10.51984/SUCP.V3I2.3375

وقائع مؤتمرات جامعة سبها
Sebha University Conference Proceedings

Confrence Proceeeding homepage: http://www.sebhau.edu.ly/journal/CAS

Comprehensive Study of The Impact of Water and Nanofluid Cooling on the Performance of Hybrid Photovoltaic Panels at Varied Irradiation Values

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Keywords:
Coolant
Electrical efficiency
Nanofluid
Photovoltaic cell
Thermal efficiency

ABSTRACT

High solar irradiation and ambient temperatures in regions like Libya can significantly decrease the electrical output of solar cells. This study investigates the impact of water and nanofluid cooling on the performance of a novel hybrid photovoltaic (PV) panel prototype. The prototype incorporates a water-based cooling system utilizing a water and Al_2O_3-water nanofluid within a rectangular collector at the rear of the PV panel. A comparative analysis is conducted using this collector technique. The closed-loop, passive cooling system directly contacts the PV panel through its rear side with varying nanofluid concentrations. Results demonstrate significant improvements in thermal efficiency, with increases of 48 % observed at nanofluid concentrations of 5 % volume. Electrical efficiency rises to 12.7 % and overall efficiency and total efficiency also exhibit a notable rise, reaching 60 % and 79.2% respectively at nanofluid concentrations of 5 % volume. additional enhancement of efficiency before and after using nanofluid as coolant increases to 5.5 %. In this study, a new style collector design was developed in addition to the suction plate. Additionally, the cooling cycle in the flow duct is carried out continuously using the water and water + Al_2O_3 as coolant. Therefore, the performance of the parallel channel of the plate, excluding PV/T and intermediate metal, was evaluated numerically. 3D numerical simulation was performed using finite element modeling (FEM) based on ANSYS Fluent software. Thus, the performance of PV/T obtained by the numerical simulation method was verified by external research.

دراسة مقارنة لتأثير التبريد بموائع النانو و الماء على أداء الألواح الكهروضوئية الهجينة عند قيم مختلفة للأشعاع الشمسي

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الملخص

دراسة حديثة تبحث في مقارنة تأثير التبريد بالماء و السوائل النانوية على أداء نموذج جديد للوحة ضوئية حرارية هجينة .فكما هو معلوم تعاني الخلايا الشمسية في مناطق ذات إشعاع شمسي مرتفع ودرجات حرارة محيطة عالية، مثل ليبيا، من انخفاض كبير في إنتاجها الكهربائي مما يقلل كفاءتها الكهربائية مع مرور الوقت . يقترح هذا البحث تصميمًا مبتكرًا يتكون من مجمع حراري مثبت فوقه الواح كهروضوئية مع نظام تبريد بالماء و السوائل النانوية التي تتكون من محلول مائي بأكسيد الألومنيوم (Al_2O_3) تتدفق داخل مجمع مستطيل الشكل يوضع خلف اللوح الضوئي .أظهرت نتائج التحليل المقارن باستخدام تقنية التبريد بالماء أولا ثم بموائع النانو ان استخدام موائع النانو كمبردات ساهم في تحسين الكفاءة الكهربائية و الحرارية ، حيث لوحظ ارتفاع بنسبة 48 % عند استخدام سائل نانوي بنسبة تركيز 5% بالحجم .كما ارتفعت الكفاءة الكهربائية إلى % 12.7 ، وكذلك الكفاءة الكلية والكفاءة الإجمالية للوحة بشكل ملحوظ لتصل إلى % 60 و 70.2% على التوالي عند استخدام سائل نانوي بنسبة تركيز % 5 بالحجم. تم تحقيق تحسن بنسبة 5.5% في الكفاءة بعد استخدام سائل نانوي

الكلمات المفتاحية:
التبريدد
الخلايا الكهروضوئية
الكفاءة الكهربائية
الكفاءة الحرارية
موائع النانو

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Article History : Received 20 June 2024 - Received in revised form 26 September 2024 - Accepted 06 October 2024

كمبرد، يقدم هذا البحث تصميمًا مبتكرًا للالوح الكهروضوئية الهحينية و الي هي عبارة عن دمج بين الالواح الكهروضوئية العادية مع المجمعات الحرارية التي تعمل على الاستفاذة من الحرارة المستخلصة من التبريد في تطبيقات الحياة ، كما يتم الحفاظ على دورة تبريد السائل بشكل انسيابي داخل قناة التدفق باستخدام فرق الارتفاع للماء .وتم تقييم أداء الالواح الكهروضوية الهجينة باستخدام اقوى برامج المحاكاة المعروف باسم Ansys الذي يدرس بدقة في نظام ثلاثي الابعاد جريان الموائع و تأثيرها على التصاميم المقدمة .

1. Introduction

Fossil fuels currently dominate the global energy landscape, despite their rapid depletion and well-documented environmental impact [1, 2]. Projections indicate that fossil fuels (oil, gas, and coal) will still comprise a significant portion (78%) of the energy mix by 2040, even with the growing adoption of non-fossil fuel alternatives like renewable and nuclear energy [2]. This dependence on fossil fuels poses a severe challenge: securing a sustainable and reliable energy supply while mitigating environmental damage caused by greenhouse gas emissions [3].

Renewable energy sources, particularly solar energy, offer a promising solution towards a more sustainable future. Solar energy can be harnessed in two primary forms: heat and electricity. Solar thermal collectors capture heat, while photovoltaic (PV) modules convert sunlight directly into electricity. However, the demand for heat and electricity often coincides. Hybrid photovoltaic/thermal (PV/T) systems address this by combining PV modules and solar thermal collectors in a single unit, enabling the simultaneous generation of both electricity and heat [4].

The development of PV/T technology stemmed from the observation that a significant portion of solar radiation absorbed by PV modules generates unwanted heat within the cells, leading to efficiency losses. Commercially available solar cells typically exhibit efficiencies between 6% and 16% at a reference temperature of 25°C, with efficiency further declining by 0.4-0.65% for every degree Celsius increase in temperature [5,11]. Removing this heat not only improves PV cell efficiency but also allows for the captured heat to be utilized for other applications. This synergy underpins the value proposition of PV/T systems: they offer a more efficient way to utilize solar energy by achieving higher overall system efficiency.

PV/T systems boast several key advantages. They can generate both electricity and heat with minimal additional cost and space requirements. Additionally, their inherent flexibility allows them to cater to both heating and cooling needs [6]. This research delves deeper into the potential of PV/T systems, specifically focusing on the impact of different cooling methods on their performance.

The introduction of PV/T research began with earlier work by Wolf [6], and Kern and Russell [7], followed by research on design and design by Hendrie [8], Florschuetz [9], and Cox and Raghuraman [10]. The operation of photovoltaic thermal system is cold. However, research efforts to improve the performance of photovoltaic thermal systems gained moderate momentum in 2000. The authors found that daily heating efficiency can be up to 40%, with better energy savings than traditional water heater collection systems. Robles-Ocampo et al. [12] Tiwari and Sodha [13] tested four different hybrid PV/T systems.

A 3D heat transfer method for flat solar panels using water/copper nanofluid as the heat transfer fluid was developed by Rehena et al. [14]. The authors investigated the effect of the Prandtl number on the heat transfer rate and collection efficiency and found that at higher Prandtl number values, the nanofluid performed better than the base fluid. Siddiqui et al. [15] The results showed that the temperature of cells decreased from 41.1 to 30.6 Celsius with increasing water inlet pressure. However, the high-water velocity (0.01-0.1 m/s) adopted in this study may consume high pumping power and also affect the performance of PV module.

From the above-mentioned literature, most studies have focused on the performance and design of optimal geometric PV/T systems. In addition, importance is given to examining the effects of the selected systems. There are many studies [32,33,34,35,37] in the literature focusing on PV/T systems, most of which are done in the same way and confirmed by experimental data. Few studies have been reported using comprehensive 3D analysis and validation studies.

The literature also shows that two types of PV/T collectors have been extensively studied and analyzed; one of them is the plate configuration Chow et al., [16], Chow, [17], Zondag et al. [18]; Etiga et al. [19,37] and another similar record Tiwari and Sodha, [13]; Huang et al., [21]; Prakash, [22]. However, in most of the experiments, a conventional heat exchanger consisting of a suction plate and flow pipe was used.

Numerous recent studies have focused on employing various types of nanomaterials for cooling hybrid solar panels. These investigations have demonstrated enhanced thermal and electrical properties of photovoltaic panels when nanofluids are utilized as coolant [23,24,25,26,27,28]

The main aim of This study investigates the performance of a photovoltaic/thermal (PV/T) collector with a parallel plate flow channel excluding an intermediate absorber plate. The coolant circulation within the flow channel relies solely on the principle of elevation head, achieving a passive cooling approach. (CFD) simulations, utilizing ANSYS Fluent software, were employed to numerically evaluate the PV/T collector's performance. The simulations leveraged the finite element method (FEM) capabilities within ANSYS Fluent for a three-dimensional analysis.

2. Methodology

2.1. Numerical Model

The process of finding a numerical solution to complex physical problems, particularly in fluid dynamics, is known as Computational Fluid Dynamics (CFD). CFD software is employed to analyze these intricate physical processes, providing a more efficient and less time-consuming alternative to experimental setups. CFD allows for a comprehensive examination of fluid flow, considering its various physical properties simultaneously [3].

The analysis involves three primary equations that describe the relationships among the physical properties of interest. The formulation of these mathematical models depends on the specific physical situation under consideration, whether it involves heat transfer, mass transfer, phase transfer, etc. Validating the model against theoretical or experimental data is crucial for obtaining accurate solutions. In this study, the numerical analysis utilized ANSYS 2018 academic software.

The following equations are applied [20,30,32].

1- $\eta_{el} = \eta_{ref}\left[1 - \beta_{ref}\left(T_c - T_{ref}\right)\right]$

2- enhancement of efficiency $= \frac{\eta_{with\,nano} - \eta_{without\,nano}}{\eta_{with\,nano}}$

3- $\eta_{th} = \frac{E_{th}}{E_c}$

4- $\eta_{tol} = \frac{E_{th} + E_{el}}{E_c}$

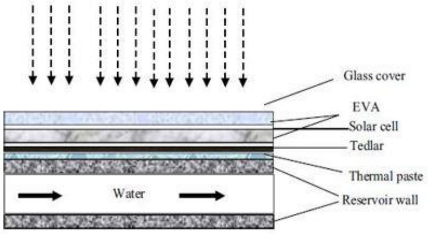
5- $\eta_o = \eta_{el} + \eta_{th}$

2.2. Boundary condition

Several calculations were made to evaluate the performance of the PV/T module. The analysis considered several parameters, including an inlet velocity of 0.0001 m/s, a radiation of 1000 W/m^2, an inlet temperature of 35°C, and an ambient temperature of 35°C.

2.3. PV/T Flat plate solar collector geometry

The model consisted of five main areas for the PV module: inner cover (glass), encapsulation (Ethyl Vinyl Acetate (EVA), PV cell, backplate (Tedlar), and thermal paste (as heat conductor). The flow channel consisted of two areas: the area (made of aluminum) and the water area (water and water + Al_2O_3). A cross-section of the PV/T model is shown in Figure 1. Generally, the panel of the PV/T module consists of nine parts, including solid and liquid parts. Simulations were created using ANSYS Fluent software, which solves the governing equation in a non-stationary 3D case. Data regarding the relationship between cell temperature and external temperature is obtained from the software and relevant graphs are displayed.



ector [30].

To fully comprehend the refrigeration mechanism, it is imperative to conduct an energy balance analysis of the PV/T system. As illustrated in Figure 2, this analysis provides a detailed breakdown of energy flows and facilitates a comparative study with a conventional PV system operating without a cooling mechanism

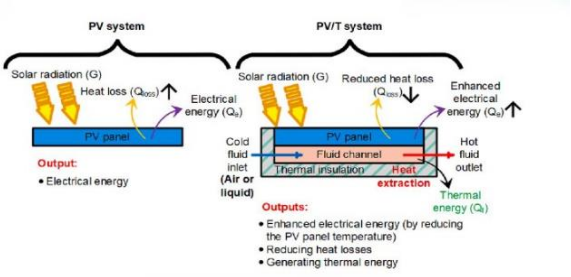


Fig. 2: Energy balance on PV and PV/T system [29].

2.5. Mesh generation, quality and statics

In the present simulation software, mesh generation is employed to subdivide a domain into a set of subdomains. The PV/T module was meshed using the physics-controlled mesh sequence setting available in the meshing setup, as illustrated in Figure 3. The number of mesh elements increases at each boundary to ensure accurate resolution of the heat transfer and flow fields. CFD achieved mesh quality with orthogonal quality equal to 1 (best orthogonal quality value is from 0.8 to 1), aspect ratio equal to 1, and skewness equal to 1.3063e-010. mesh statics were nodes equal to 622080, elements equal to 593021, and mesh size 3.5 mm with size function is curvature.

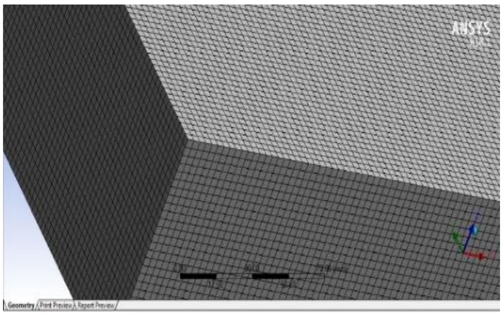


Fig. 3: Mesh generation

2.6. Mesh independence test

The CFD software divides the domain into numerous small subdomains known as cells, collectively forming the mesh, in order to attain a precise solution for the physical problem. Essentially, the domain of interest undergoes discretization into these small cells, allowing the application of mathematical equations under the assumption of linear behavior within each cell. Consequently, in regions where a parameter exhibits high sensitivity, a finer mesh is essential. It's noteworthy that the mesh often contributes to errors in the computed solution. In cases where the mesh lacks refinement in areas with highly fluctuating parameters, there is a heightened risk of obtaining results deviating significantly from reality.

To identify the most suitable mesh for the given physical problem, a mesh independence test is imperative. This test aims to strike a balance between achieving a competitive simulation runtime and obtaining the most accurate results. In this context, a mesh independence study was conducted to explore which type of mesh yields results closest to the theoretical value for the geometry. The study involved varying the element size, number of nodes, and number of elements one at a time as shown in Figure 4.

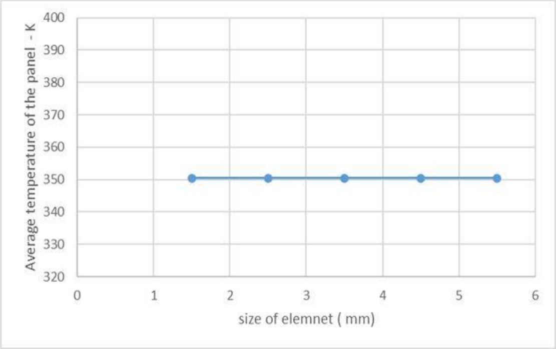


Fig. 4: Mesh independence test

2.7. Validation

In this investigation, the CFD model was validated using air coolant fluid in a PV/T flat plate collector with eight cases. These cases encompassed various heat flux irradiance conditions and operational scenarios of the PV/T flat plate collector. The selected cases were run under steady-state conditions, assuming a controlled volume for simulation. The inlet velocity was held constant at 1.5 m/s, and the inlet temperature was set at 25°C. Solar radiation, with a normal component, was applied to the outer surface of the panel, and the heat flux was varied within the range of 200–1000 W/m2.

The surface wall temperature, calculated using the proposed CFD model, exhibited a high level of agreement with the experimental data obtained by Setyohandoko et al. [36], as outlined in Figure 5.

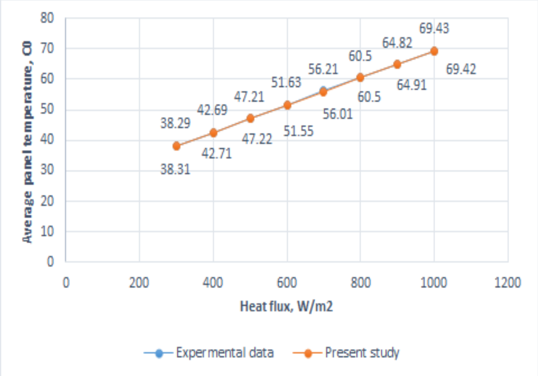


Fig. 5: Validation of the CFD results with experimental data

3. Results And Discussions

This study investigated five cases of cooling a PV/T system using Al_2O_3 + water nanofluid at five different volume concentrations: 1%, 2%, 3%, 4%, and 5%. To ensure accuracy and comprehensiveness, the five cases were examined at five solar radiation values: 200, 400, 600, 800, and 1000 W/m^2, with an inlet temperature of 308 K, an ambient temperature of 308 K, and a coolant inlet velocity of 0.0001 m/s.

In each case, the surface temperature of the photovoltaic panels used in the PV/T system was measured and compared to the surface temperature of the photovoltaic panels when water was used as a coolant. The comparison was made at a solar radiation of 1000 W/m^2. In case 1, using nanofluid as a coolant at a volume concentration of 1%, the surface temperature of the PV/T system was 353.43 K, while the surface temperature of the PV/T system when water was used as a coolant was 354.44642 K, resulting in a temperature difference of 1.01 K, as shown in Figure 6. In case 2, the nanofluid concentration was increased to 2% volume, increasing the temperature difference to 2.00149 K, as shown in Figure 7. In Figure 8, case 3, using a 3% volume concentration of nanofluid, the temperature difference between using nanofluids and using water as a coolant for the PV/T system reached 2.96 K.

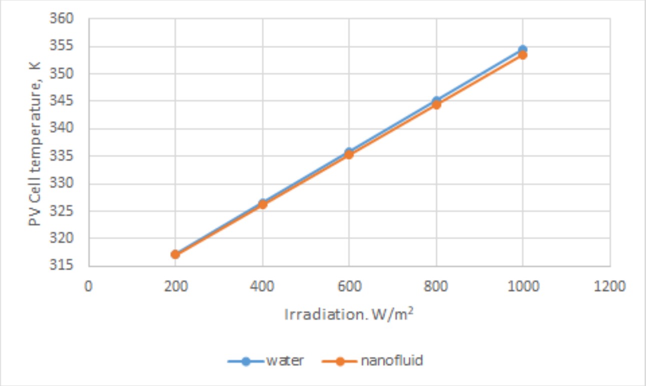


Fig. 6: Effect of 1 % volume nanofluid concentration on the PV cell temperature compared to the effect of water as coolant

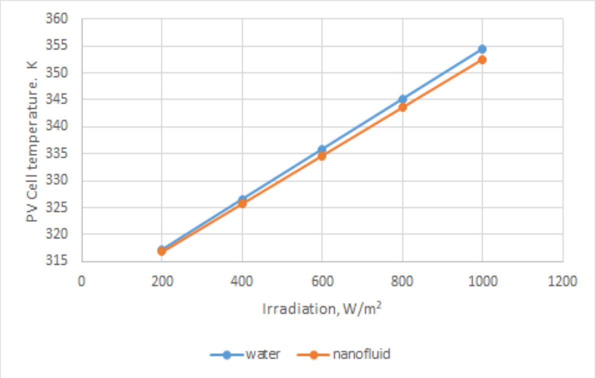


Fig. 7: Effect of 2 % volume nanofluid concentration on the PV cell temperature compared to the effect of water as coolant

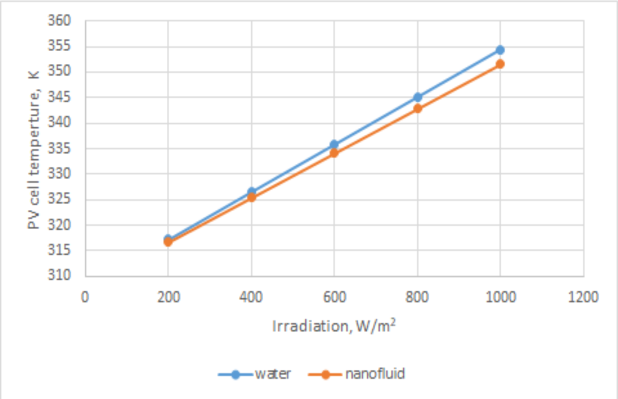


Fig. 8: Effect of 3 % volume nanofluid concentration on the PV cell temperature compared to the effect of water as coolant

In case 4, as shown in Figure 9, the difference was 3.91 K when using nanofluid at a volume concentration of 4% compared to using water as a coolant. In Figure 10, representing case 5, the volume concentration of nanofluid was increased to 5%, resulting in a difference of 4.83 K. This means that the surface temperature of the PV/T system when using nanofluid at a volume concentration of 5% was 349.60 K, while it was higher when using water as a coolant, 354.44 K, proving that nanofluids are more efficient in cooling PV/T systems, contributing to improved electrical and thermal efficiency.

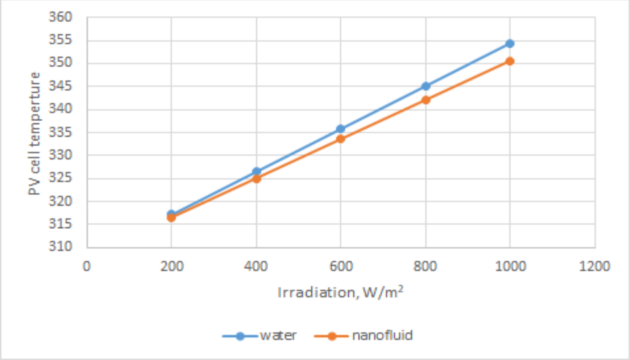


Fig. 9: Effect of 4 % volume nanofluid concentration on the PV cell temperature compared to water as coolant

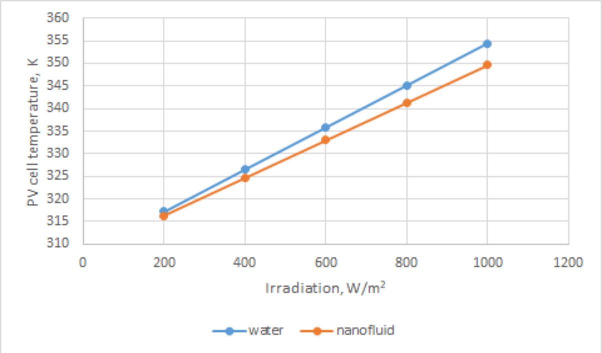


Fig. 10: Effect of 5 % volume nanofluid concentration on the PV cell temperature compared to the effect of water as coolant

Figure 11, at a constant solar radiation of 1000 W/m^2, summarizes the previous results. It shows that the temperature of PV/T systems remained constant at 354.44 K when water was used as a coolant, while the temperature decreased when nanofluids were used as a coolant. The lower the temperature, the higher the volume concentration of nanofluids used, reaching 349.60 K at a volume concentration of 5%.

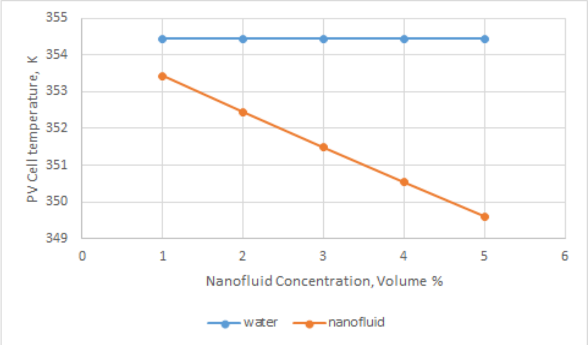


Fig. 11: Effect of varied nanofluid concentration on the PV cell The temperature at constant irradiation 1000 W/m^2

The electrical and thermal efficiency of PV/T systems was investigated in the five cases where five volume concentrations of nanofluid were used as a coolant for the system. It was found that the electrical efficiency increased from 12% when water was used as a coolant to 12.7% when nanofluid was used as a coolant at a volume concentration of 5%, as shown in Figure 12.

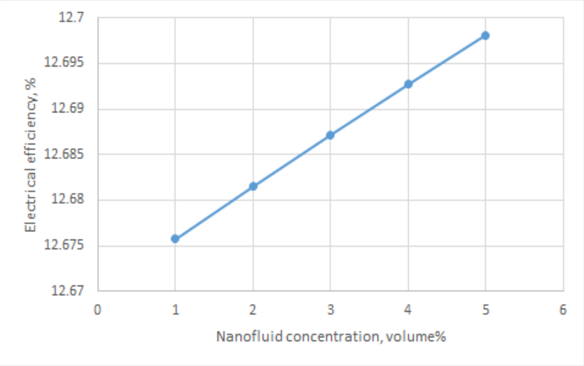


Fig. 12: Effect of varied nanofluid concentrations on PV/T system electrical efficiency

The thermal efficiency of the PV/T system when using nanofluids as coolants at the previous volume concentrations was 44%, 45%, 46%, 47%, and 48%, respectively, as shown in Figure 13.

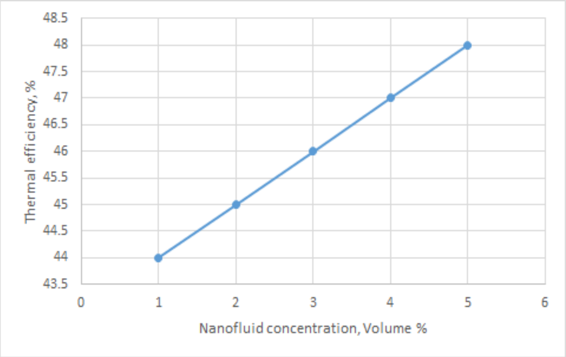


Fig. 13: Effect of varied nanofluid concentrations on PV/T system thermal efficiency

To further confirm that using nanofluids as coolants in PV/T systems improves efficiency, the enhancement efficiency was studied. This efficiency represents the electrical efficiency before and after using nanofluids. This efficiency was studied at the five nanofluid concentrations and compared to water. An increase in enhancement efficiency was found with increasing nanofluid concentration, as shown in Figure 14. Also from Figures 15, 16, and 17, we observed enhancement and improvement in overall and total efficiency when using nanofluids coolant. In Figure 18, we observed enhancement in the Prandtl number of nanofluid from 7.3 to 9.4 compared to the water constant at 6.96.

Based on the above, it can be concluded that nanofluids are more efficient in cooling PV/T systems. They have a high capacity to absorb incident solar radiation and transfer heat compared to water.

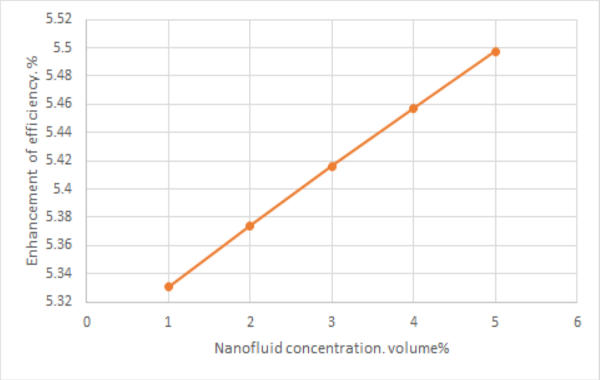


Fig. 14: Effect of varied nanofluid concentrations on PV/T enhancement efficiency

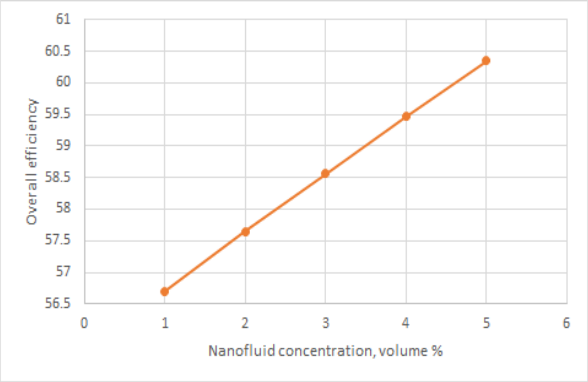


Fig. 15: Effect of varied nanofluid concentrations on PV/T overall efficiency

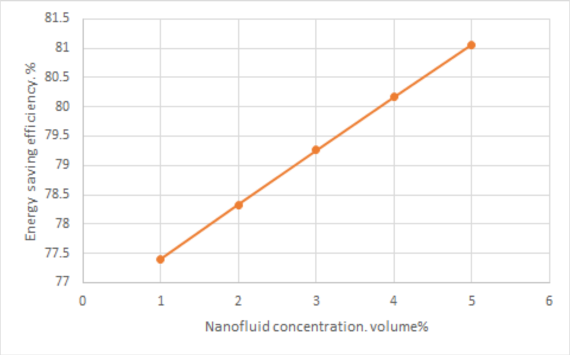


Fig. 16: Effect of varied nanofluid concentrations on PV/T energy save efficiency

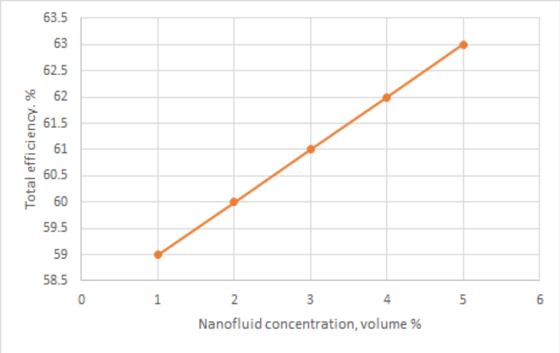


Fig. 17: Effect of varied nanofluid concentration on PV/T total efficiency

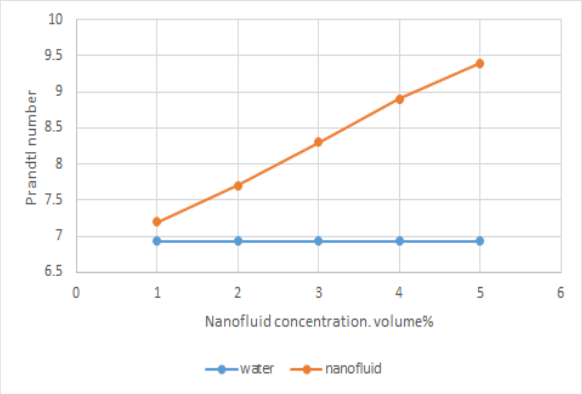


Fig. 18: Effect of varied nanofluid concentrations on Prandtl number

4. Conclusion

This study investigated the effectiveness of Al_2O_3-water nanofluid as a coolant for photovoltaic thermal (PV/T) systems. Five different volume concentrations (1%, 2%, 3%, 4%, and 5%) of the nanofluid were examined under various solar radiation levels (200, 400, 600, 800, and 1000 W/m^2). The results demonstrate that Al_2O_3-water nanofluid offers significant advantages over traditional water cooling for PV/T systems.

Key Findings:

- Reduced Surface Temperature: The use of nanofluid coolants resulted in a notable decrease in the surface temperature of the photovoltaic panels compared to water cooling. The temperature difference increased with increasing nanofluid concentration, reaching a maximum of 4.83 K at a concentration of 5%.
- Enhanced Electrical Efficiency: The electrical efficiency of the PV/T system improved with the application of nanofluid coolants. An increase of 0.7% in electrical efficiency was observed when using a 5% volume concentration nanofluid compared to water cooling.
- Improved Thermal Efficiency: The thermal efficiency of the PV/T system also showed a significant improvement with nanofluid coolants. Thermal efficiency increased progressively from 44% with water cooling to 48% with a 5% concentration of nanofluid.
- Enhanced Overall Performance: The study confirmed an overall enhancement in the performance of the PV/T system when using nanofluids. This enhancement is attributed to the superior heat transfer characteristics of nanofluids compared to water.
- Increased Prandtl Number: The Prandtl number, a key thermophysical property, also showed improvement with nanofluid coolants. This indicates a better balance between thermal conductivity and viscosity, leading to more effective heat transfer.

In conclusion, this study provides strong evidence that Al_2O_3-water nanofluids are a promising solution for cooling PV/T systems. Their ability to reduce operating temperatures, improve electrical and thermal efficiencies, and enhance overall system performance makes them a valuable advancement in PV/T technology.

5. Abbreviations and Acronyms

CFD	Computational fluid dynamics
PV/T	Photovoltaic thermal system
η_{el}	Electrical efficiency
η_{th}	Thermal efficiency
η_{tol}	Total efficiency
η_{o}	Overall efficiency
E_{el}	Electrical power
E_{th}	Thermal power
E_{c}	Absorbed power
T_{c}	Photovoltaic cell temperature
T_{ref}	Reference cell temperature
η_{ref}	Reference efficiency
β_{ref}	Temperature coefficient at reference cell temperature

6. Acknowledgement

The authors extend their sincere gratitude to the esteemed reviewers for their insightful comments and suggestions, which significantly contributed to enhancing the quality of this manuscript.

7. References

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