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Enhance Photovoltaic/Thermal (PV/T) System Performance by Using Nanofluid

Khalid Salih Hamoudah[1*], Saleh Etaig[2], Esam Elabeedy[3].

[1]Department of renewable energy engineering, faculty of Engineering, Libyan Academy, Benghazi branch,
[2,3]Mechanical Engineering Department, Faculty of Engineering, University of Benghazi, Benghazi, Libya.

E-*mail:* [1]khalidsalih2010@yahoo.com ,[2]Saleh.Etaig@uob.edu.ly ,[3]Esam.Elabeedy@uob.edu.ly,

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KEYWORDS

Coolant, Efficiency,
Nanofluid, CFD,
Photovoltaic cell.

ABSTRACT

High temperatures significantly degrade the performance of photovoltaic (PV) panels, particularly in hot regions. To mitigate this issue, hybrid PV/thermal systems have emerged, combining PV panels with thermal collectors. These systems utilize a cooling fluid to remove excess heat from the PV panels, improving their efficiency and enabling the recovery of thermal energy. This study investigates the potential of nanofluids as a superior cooling medium for hybrid PV/thermal systems..

Nanofluids, engineered suspensions of nanoparticles in base fluids, offer enhanced thermal properties compared to conventional fluids. A numerical analysis using the finite volume method (FVM) based on Ansys software / CFD fluent was conducted to simulate the performance of a hybrid PV/thermal system under hot weather conditions. The study focused on natural convection cooling, eliminating the need for pumps and reducing energy consumption. Results indicate that decreasing the inlet velocity of the nanofluid significantly reduced the surface temperature of the PV panels. A reduction in inlet velocity to 0.0001 m/s led to a 4.5 K decrease in surface temperature, while a velocity of 0.00005 m/s resulted in a 6 K decrease. Conversely, the temperature of the nanofluid outlet increased by 16 K and 30 K for the respective velocities, signifying enhanced heat extraction. These findings demonstrate that optimizing the flow rate of the nanofluid can significantly improve the electrical and thermal performance of hybrid PV/thermal systems. This research contributes to the development of more efficient and sustainable solar energy technologies.

*Corresponding author.

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تحسين أداء النظام الكهروضوئي / الحراري (PV/T) بإستخدام الموائع النانوية

خالد صالح حمودة، صالح عتيق، عصام العبيدي.

ملخص: تؤثر درجات الحرارة العالية بشكل كبير على كفاءة الألواح الشمسية الكهروضوئية، خاصة في المناطق الحارة. للتخفيف من هذه المشكلة، ظهرت أنظمة هجينة تجمع بين الألواح الشمسية الكهروضوئية والمجمعات الحرارية. تستخدم هذه الأنظمة سائلاً تبريدياً لإزالة الحرارة الزائدة من الألواح الشمسية، مما يحسن كفاءتها ويسمح باستعادة الطاقة الحرارية. يدرس هذا البحث إمكانية استخدام السوائل النانوية كوسيلة تبريد متفوقة لأنظمة الطاقة الشمسية الحرارية الهجينة. تتميز السوائل النانوية، وهي جسيمات صلبة معلقة في سوائل الأساس، بخصائص حرارية محسنة مقارنة بالسوائل التقليدية مثل الماء . تم إجراء تحليل عددي باستخدام طريقة الحجم المحدد (FVM) اعتمادا على برامج Ansys software /CFD fluent لمحاكاة أداء نظام شمسي حراري هجين في ظل ظروف الطقس الحار. ركزت الدراسة على التبريد الحراري الطبيعي، مما يلغي الحاجة إلى المضخات ويقلل من استهلاك الطاقة. أظهرت النتائج أن تقليل سرعة دخول السائل النانوي يقلل بشكل كبير من درجة حرارة سطح الألواح الشمسية. أدى تقليل سرعة الدخول إلى 0.0001 م / ث إلى انخفاض درجة الحرارة بمقدار 4.8 كلفن، بينما أدى انخفاض السرعة إلى 0.00005 م / ث إلى انخفاض قدره 6 كلفن. على العكس من ذلك، ارتفعت درجة حرارة مخرج السائل النانوي بمقدار 16 كلفن و 30 كلفن للسرعات المذكورة، مما يشير إلى زيادة استخلاص الحرارة. توضح هذه النتائج أن تحسين معدل تدفق السائل النانوي يمكن أن يحسن بشكل كبير الأداء الكهربائي والحرارة لأنظمة الطاقة الشمسية الحرارية الهجينة. يساهم هذا البحث في تطوير تقنيات الطاقة الشمسية أكثر كفاءة واستدامة.

الكلمات المفتاحية – سائل التبريد، الكفاءة، الموائع النانوية، الخلية الكهروضوئية.

1. INTRODUCTION

Solar energy is a very attractive source of electricity because of its large amount. The solar energy captured by the Earth is about 1367 KW/m^2 [1]. About 30% of the sun's energy reaches the Earth, and every 20 minutes, the Sun provides enough energy to meet the Earth's needs for a whole year [2]. Solar energy is the energy that comes from the sun and can be converted into electricity and heat. It has produced energy for billions of years, so the use of solar energy and its materials technologies have received and attracted a lot of attention, especially in the last ten years [3,4,49,50]. For example, some studies have shown that approximately 1000 times the world's energy needs could be met with solar energy. The sun radiates a large amount of energy every day, and the hourly solar flux incident on the earth's surface is greater than the total human energy consumption in a year [10]; however, only 20% of this energy is currently used [5].
The increasing interests and activities in renewable energy are rapidly connected to the potential of renewable energy to complement and potentially substitute fossil fuels as energy sources [6,53]. The essential reasons for this strong attention to solar energy applications are due to the increasing demand for energy, limited availability of conventional energy sources such as fossil fuels and petroleum, and environmental problems associated with them such as acidic gas emissions. Moreover, the strong increase in the human population can be considered as an additional serious problem, since the global population has increased by nearly 2 billion with a major contribution from developing countries [7]. Furthermore, it is proved that the use rate of fossil fuels by humans is much faster than when they are replaced by geologic processes. Therefore, the use of renewable energy instead of fossil fuels in power generation is the future challenge to ensure a sustainable and secured energy supply as well as mitigate environmental issues [8]. Among the renewable energy resources, Solar energy is without emission during operation. Again, solar energy is the most sustainable, ubiquitous, and clean renewable energy source [9]. This explains the strong attention and focus on solar energy harvesting using different solar technologies including solar thermal systems and photovoltaic systems [11,12].

Solar energy can be gathered and utilized in two forms, thermal and electrical energy. Solar thermal energy is gathered by solar thermal collectors and photovoltaic (PV) modules produce electrical energy. However, the demand for heat and electricity is regularly supplementary.

Now, the commercial solar cell converts solar energy into electricity with low efficiency, less than 20% in the range of only 6 –16% at 25 OC temperature which again drops at a rate of 0.4 –0.65 % per each degree increase in temperature [13,45]. i.e., More than 80% of the absorbed solar energy is dumped into the surroundings again after electric energy conversion.

The undesirable heat thus produced drops the performance of the PV cells which can improved by removing the heat from the PV cell. The waste heat thus removed to cool the PV cell may be utilized in useful heating applications which led to the hybrid PV/T technology which introduced a better way of utilizing solar energy with higher overall efficiency [14].

Hybrid photovoltaic thermal (PV/T) system is a solar co-generation technology system combining PV cells and Solar Thermal collectors (STC) in one physical shape to produce both electrical and thermal energy simultaneously. The initiatory drive behind PV/T technology was that PV cells were found to absorb a substantial amount of solar radiation which produces undesirable heat that will be removed by using a coolant of the solar thermal collector at the same time [3,23,24,52,53].

The essential advantage of PV/T systems is that they produce twofold yields with a little extra cost and half of the space. Moreover, it is an efficient and flexible technology that can be used for both heating and cooling purposes [25,26].

Research on nanofluids focuses on their effectiveness in solar thermal applications (Nasrin and Alim, [15]; Hassani et al [16]; Zamzamian et al., [17]; An et al., [18]; Al-Waeli et al., [19]; Al-Shamani et al., [20]; Kalogirou et al., [21]]; Etaig et al.,[27,35]). Reviews highlight the advancements and applications of nanotechnology in boosting the efficiency of solar energy systems.

The economic benefits of nanotechnology include reduced manufacturing costs due to the use of low-temperature processes.

Numerical studies have investigated the impact of water-based nanofluids on PVT system performance (Xu and Kleinstreuer, [22]). These studies explore improved heat transfer using new models for nanofluid thermal conductivity. Additionally, thermal and electrical efficiencies along with the economic viability of PVT systems using silicon and multi-junction solar cells have been compared. Simulation results show PVT collectors achieving an overall efficiency of 70%, with contributions of 11% and 59% from electrical and thermal energy, respectively.

In Libya, many recent studies [47,49,51,53, 54] have begun to focus on improving the electrical efficiency obtained from photovoltaics by adopting PVT systems and PVT systems that use cooling fluid, the most important of which is cooling that have demonstrated great efficiency in improving the heat transmission process which contributes to improving electrical efficiency, reducing heat loss and utilizing heat extracted in various life applications.

In this research, as shown in Figure 1, the coolant circulation in the flow channel is passively maintained by using the coolant lift height. Therefore, the performance of PV/T with the parallel plate flow channel excluding the intermediate absorption plate is evaluated both numerically and experimentally. The 3D numerical simulation was performed by Ansys Fluent software based on the finite volume method (FVM). Thus, the PV/T performances obtained from the digital simulation model have been proven by experimental research in nature.

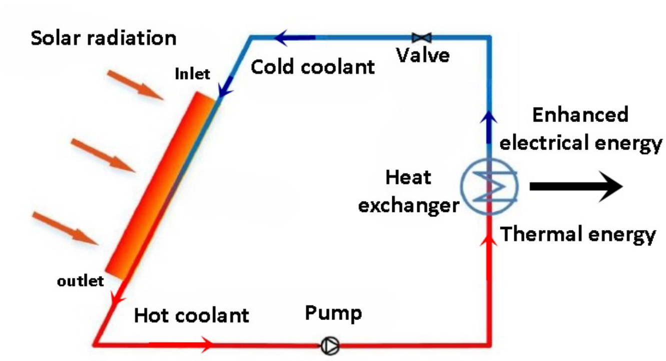

Figure 1. PV/T coolant circulating system.

2. MATERIALS AND METHODOLOGY

2.1. PV/T Flat Plate Collector Geometry

model comprised five solid domains for the PV module: front cover (glass), encapsulation (Ethyl Vinyl Acetate (EVA)), PV cells, back sheet (tedlar), and thermal paste (as a heat conductor). The flow channel was composed of two domains: a solid domain (made of aluminum) and a fluid domain (water and water + Alumina nanofluid). The cross-section of the PV/T model is illustrated in Figures 2 and 3 and Tables 1 and 2.
In total, the panel comprised nine layers, encompassing both solid and liquid layers, for the PV/T module. The simulations were performed using ANSYS Fluent software, solving the governing equations in a 3D steady-state condition. Data on the average cell surface temperature and average outlet temperature were extracted from the software, and corresponding graphs were presented.

Figure 2. Cross-sectional view of PV/T system.

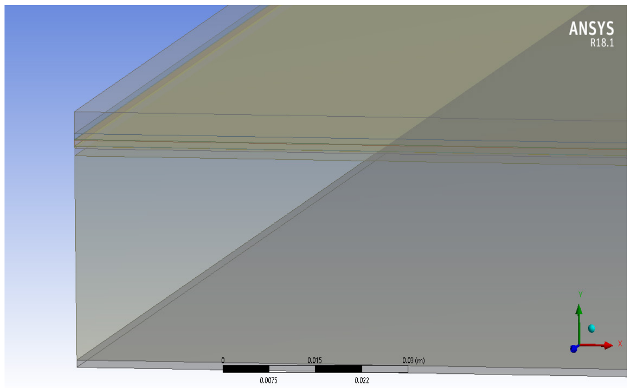

Figure 3. Layers of PV/T system.

Table 1. PV elements.

Material	Layer	Thickness, mm
glass	Top Cover	3
Eva	encapsulation	0.8
silicon	Solar cell	0.1
Eva	encapsulation	0.8
Tedlar	Bottom cover	0.05
Thermal paste	Conductor	0.3

Table 2. Thermal collector specification.

Material	Dimension	Thickness, mm
Aluminum	500×500×100	1

2.2. Boundary condition

Numerical simulations and analysis on the performance of the PV/T module considered various parameters, including various inlet velocities of 0.01 m/s, 0.0001 m/s, 0.00005 m/s, and irradiation ranges of 200, 400, 600, 800, 1000 W/m^2, inlet temperature at 35°C, and ambient temperature at 35°C. in this search used 5% volume (Al_2O_3 + water) nanofluid concentration as a suitable concentration to get the best results[47,51].

2.3. Study assumptions and limitations

Numerical simulations remain the most suitable approach for analyzing the thermal characteristics of PV/T collectors. The calculation of 3D temperature distributions involves the following assumptions:

• The transmissivity of ethyl vinyl acetate (EVA) is approximately 100%.
• The solar energy absorptivity is not affected by any dust on the surface.
• The flow is steady, fully laminar, and incompressible.
• Temperature variation along the thickness is considered negligible.
• The thermal-physical properties of the absorber duct are assumed to be constant concerning the operating temperature.
• The bottom side of the absorber duct is considered adiabatic.

2.4. Physical models

The presence of nanoparticles in nanofluids alters their physical properties. Unlike conventional fluids, where properties can be obtained from standard tables or equations [28], nanofluid properties depend on factors such as nanoparticle concentration [29]. In this context, the properties are regarded as temperature-dependent, and the correlations provided by Azmi et al. [30] can be applied. The objective of the model is to assess the collector's performance using a nanofluid compared to water as the base fluid under identical temperature conditions.
Lari [31] used the widely recognized Einstein's equation for viscosity calculation. This equation is suitable for spherical particles in volume fractions less than 5.0%, and it is defined as follows:

$$\mu_{nf} = (1 + 2.5\phi)\mu_w \tag{1}$$

Calculating the thermal conductivity was introduced by Yu and Choi [32], which is expressed in the following form:

$$k_{nf}=\left[\frac{k_p+2k_f-2\phi(k_f-k_p)}{k_p+2k_f-\phi(k_f-k_p)}\right] \quad (2)$$

The nanofluid density can be determined using the mixing theory developed by Pak and Cho [33]. The formula's applicability has been confirmed by the experimental findings of Sommer and Yerkes [34].

$$\rho_{nf}=(1-\phi)\rho_f+\phi\rho_p \quad (3)$$

The specific heat is obtained from Ozturk and Dincer [12] as:

$$(\rho C_p)_{nf}=(1-\phi)(\rho C_p)_f+\phi(\rho C_p)_p \quad (4)$$

The volume concentration of the nanoparticles is defined as this equation [34]:

$$\phi=\frac{V_{NP}}{V_T} \quad (5)$$

2.5. Thermal Models

The thermal energy extracted by coolant nano-fluid is defined by this equation:

$$E_{th}=\dot{m}C_p(T_{out}-T_{in}) \quad (6)$$

Where mass flow rate ($\dot{m}$) is calculated by the following equation:

$$\dot{m}=\rho U_0 A_{fc} \quad (7)$$

Where A_{fc} is the cross-sectional area of inlet velocity.
The Reynolds number is utilized to determine whether the flow is laminar or turbulent. For flow through a duct, the Reynolds number is calculated as:

$$D_h=\frac{4A_{fc}}{V_T\rho_f} \quad (8)$$

2.6. Electrical Models

The electrical efficiency η_{el} is calculated as follows [41,42]

$$\eta_{el}=\eta_{ref}\left[1-\beta_{ref}(T_c-T_{ref})\right] \quad (9)$$

Where η_{ref} is the reference efficiency at standard conditions (R =1000 W/m^2 and T_{ref} = 25^{O}C)
β_{ref} is the thermal coefficient of cell efficiency which is dependent on the materials of the PV module, here the value is taken 0.00045/K for silicon cell [38].
The PV cell's electrical efficiency can be calculated by this equation [36,37]:

$$\eta_{el}=\frac{V_{mp}I_{mp}}{E_c} \quad (10)$$

2.7. Mathematical Formulation

Heat loss Q of the top and bottom of the PV/T module due to convection can be determined by

$$Q_c=h_cA_c(T_c-T_{amb}) \quad (11)$$

The heat transfer coefficient hc is calculated from [39,45] which is valid for wind speeds ranging from 0 to 10 m/s.

$$h_c=5.67+3.86V \quad (12)$$

The actual amount of energy absorbed into the PV module can be calculated as follows [39, 40,52].

$$E_c = p_c \tau_g \alpha_c RA_c \quad (13)$$

Energy converted into electrical power calculated from this equation:

$$E_{el} = E_c \eta_{el} \quad (14)$$

The thermal efficiency is determined by:

$$\eta_{tol} = \frac{E_{th}}{E_c} \quad (15)$$

The total efficiency of the PV/T system is calculated as follows [42]:

$$\eta_{tol} = \frac{E_{th} + E_{el}}{E_c} \quad (16)$$

as shown in equation (17) [43]. This method provides a straightforward and easily interpretable measure of the system's overall performance.

$$\eta_o = \eta_{el} + \eta_{th} \quad (17)$$

For more accuracy in evaluating the PV/T system, we will compare efficiencies between using water and Al2O3 as PV/T system coolant by using enhancement of efficiency as follows [42].

$$\text{Enhancement of Efficiency} = \frac{\eta_{with\ nano} - \eta_{without\ nano}}{\eta_{with\ nano}} \quad (18)$$

2.8. CFD Model

The process of finding a numerical solution to complex physical problems, especially in fluid dynamics, is known as computational fluid dynamics (CFD). CFD software is used to analyze these complex physical processes, providing a more efficient and less time-consuming alternative to experimental setups. CFD allows a complete examination of the fluid flow, taking into account its different physical properties [44]. The analysis involves three main equations that describe the relationships between the physical properties of interest. The formulation of these mathematical models depends on the specific physical situation under consideration, be it heat transfer, mass transfer, phase transfer, etc. Model validation against theoretical or experimental data is essential to obtain accurate solutions. In this study, the numerical analysis used the academic software ANSYS 2018.

2.8.1. Governing equation of CFD

The governing equations of computational fluid dynamics are derived from the three fundamental conservation laws, emphasizing that mass, momentum, and energy are conserved in a closed system [44].

- Conservation of mass - expression from the continuity equation.
- Conservation of momentum - based on Newton's second law.
- Conservation of energy - follows from the first law of thermodynamics.

These equations, which represent the fundamental principles of fluid dynamics, work together to ensure that mass, momentum, and energy remain constant in the system being analyzed. To obtain a complete understanding of the physical flow, the velocity, pressure, and temperature variables must be determined simultaneously using these conservation equations. Pressure and temperature serve as the two independent thermodynamic variables required for this analysis. The resulting conservation equations also include key thermodynamic properties such as density (ρ), enthalpy (h), viscosity (μ), and thermal conductivity (k), which are determined by independent values of pressure and temperature In any fluid flow scenario, it is essential to analyze the velocity, pressure, and temperature at each point of the flow [30]. In the fields of solid PV/T sensors, heat transfer is studied mainly by conduction. Conduction represents the mechanism by which thermal energy is transferred through the body through particle vibrations. The heat transfer across the PV cell surface in the flow channel is treated using the heat conduction equation.

$$\nabla.(k\nabla T) = 0 \qquad (19)$$

In the fluid domain within the flow collector channel, the heat transfer mechanism has been investigated as a conjugate heat transfer involving both conduction and convection. The equation governing conjugate heat transfer in the fluid domain, considering nanofluid as the working fluid, is expressed in this equation.

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p .u.\nabla T = \nabla.(k\nabla T) + Q \qquad (20)$$

The mass and momentum conservations for the fluid flow are given by this equation:

$$\rho \frac{\partial u}{\partial t} + \nabla(\rho u) = 0 \qquad (21)$$

$$\rho \frac{\partial u}{\partial t} + \rho(u.\nabla)u = \nabla.\left[-\rho I + \mu(\nabla u + (\nabla u)^T) - \frac{2}{3}\mu(\nabla.u)I \right] + F \qquad (22)$$

2.8.2. Mesh generation, quality, statics

In the present simulation software, mesh generation is the technique 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 4 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) and aspect ratio equals to 1 and skewness equals 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.

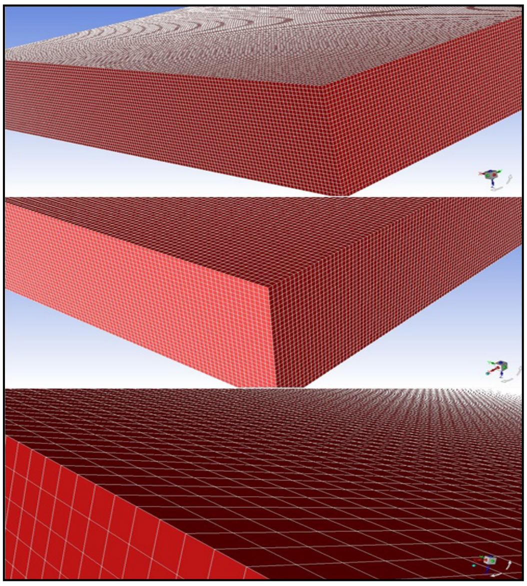

Figure 4. Mesh Element generation in PV/T flat plate collector system

2.8.3. Convergence

In CFD, achieving convergence is a crucial aspect. The convergence of a solution is influenced by factors such as the flow regime and mass transfer. Controlling convergence involves managing the error between the solutions obtained in the last two stages of computation, indicating the degree of solution fluctuation between these stages. A more stable and accurate solution is achieved when this error is minimized. However, it is essential to note that achieving convergence does not guarantee the correctness of the solution. Refining the mesh or implementing other modifications to it can be undertaken to enhance convergence. Additionally, repeating the solution is important to prevent uncertainties in the simulation process. In this project, a convergence range from 1e-06 to 1e-15 was employed. We applied the simulation at convergence 1e-06 and repeated it at convergence 1e-15 to make sure the solution was proven. after achieving the desired convergence, the error rate should be minimized to less than 0.5%.

2.8.4. 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 study, 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, and average PV/T system temperature as Figure 5 shows a plateau of values for project sizes between 1.5 mm and 5.5 mm. Considering the optimization of computational resources, we chose a value of 3.5 mm as the optimal point, beyond which diminishing returns were observed in terms of simulation efficiency.

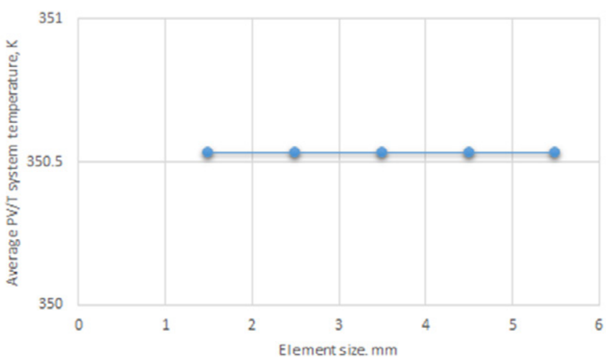

Figure 5. Mesh independence test.

2.8.5. Validation

In this study, the CFD model was validated using the air cooler on a flat PV/T sensor with eight cases. These cases include different heat flux radiation conditions and operational scenarios of the PV/T flat plate sensor. The selected cases were performed in steady-state conditions, assuming a controlled volume for the simulation. The CFD program and its accuracy were calibrated using real results obtained from a previous laboratory experiment [45], where the same laboratory trial conditions were applied and the surface temperature of the PV/T system was measured at a range of entry speeds for refrigeration fluid 0.0003, 0.0004, 0.0005, 0.0006 and 0.0007 m/s The results obtained from the CFD were very close to the results of the laboratory experiment by less than 1% error, as shown in Figure 6.

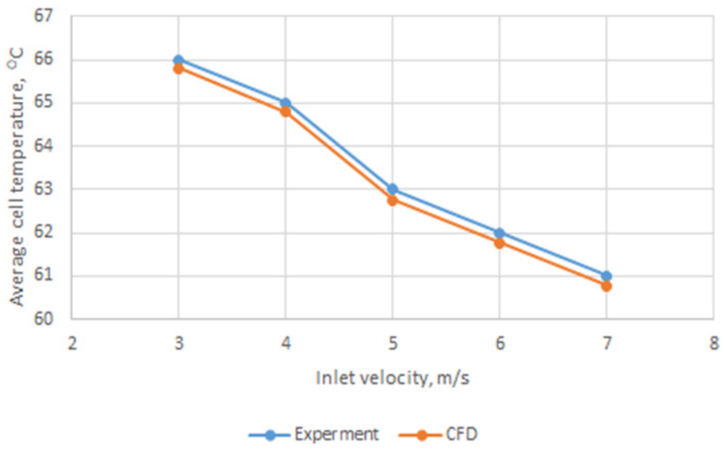

Figure 6. CFD Validation.

The congruency between the curve of the present study's results and that of the experimental study is striking. This remarkable alignment serves as compelling evidence of CFD's capacity to accurately mimic real-world phenomena. To further illuminate this point, we have juxtaposed the outcomes derived from the empirical investigation with those obtained from the CFD simulations

3. RESULTS AND DISCUSSION

3.1. Comparative Study of the Effect of Water and Nanofluid Rate on the Surface Temperature of a PV/T System

As shown in Figure. 7, in the case of 0.01 m/s inlet velocity and 1000 W/m^2 solar irradiation, the PV/T surface temperature was 315.4606 K when using nanofluids as coolant. and 314.9077 K when using nanofluid with a 5% volume, indicating a difference of 0.5 K.

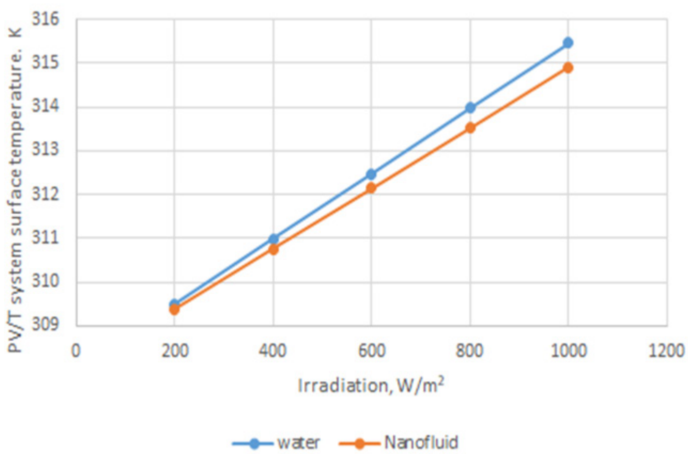

Figure 7. Effect of nanofluid inlet velocity on a PV cell temperature, 0.01 m/sec.

With an inlet velocity of 0.0001 m/s and 1000 w/m^2 solar radiation, Figure 8 shows a more significant temperature difference of 4.8 K, with the cooling system of water reaching 354.45 K and the nanofluid system cooled to 349.6089 K.

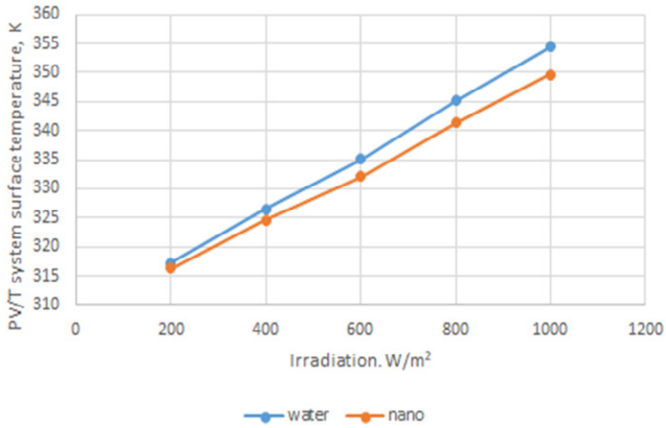

Figure 8. Effect of nanofluid inlet velocity on a PV cell temperature, v = 0.0001 m/sec.

Figure 9, with an inlet velocity of 0.00005 m/s, showed a temperature difference of 6.1019 K, with the water-cooling system reaching 367.7159 K and the system of nanofluid-cooled at 361,614 K.

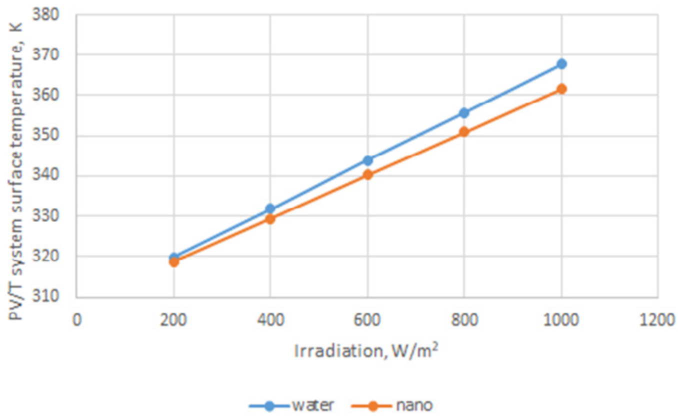

Figure 9. Effect of nanofluid inlet velocity on a PV cell temperature, v = 0.00005 m/sec.

3.2. Comparative Study of the Effect of Water and Nanofluid Cooling Rate on the Outlet Temperature of a PV/T System

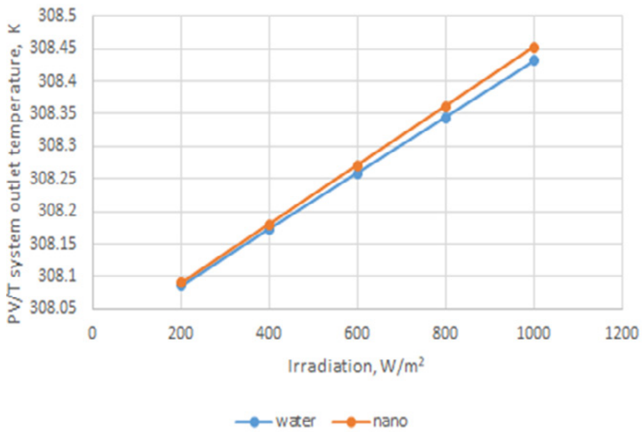

Figure 10: Effect of nanofluid inlet velocity on a PV cell outlet temperature, v = 0.01 m/sec.

Figure 10, with an inlet velocity of 0.01 m/s, solar radiation of 1000 W/m², and an inlet temperature of 308 K, shows that water and nanofluid with a volume concentration of 5% resulted in an exit temp. of 308.4515 K, which shows a slight increase of 0.4307 K compared to the inlet temperature. Figure 11, with an inlet velocity of 0.0001 m/s, shows a similar curve for the nanofluid and water indicates both coolers resulted in higher outlet temperatures compared to the inlet temperature, with a difference of 16.1015 K .

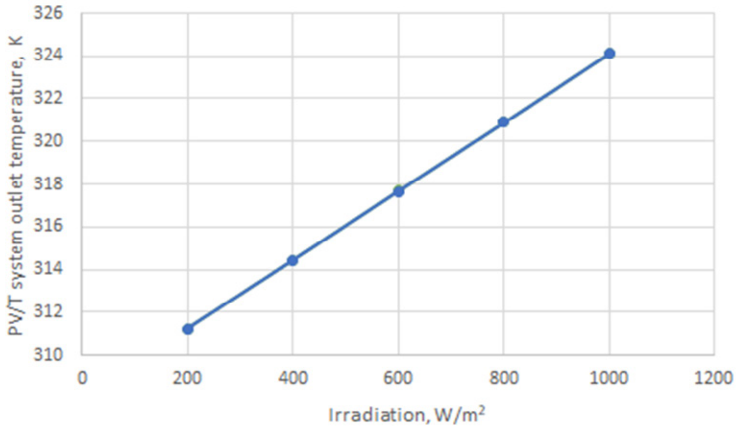

Figure 11: Effect of nanofluid inlet velocity on a PV cell outlet temperature, v = 0.0001 m/sec.

In the case of an inlet velocity of 0.00005 m/s, both coolers resulted in higher outlet temperatures compared to the inlet temperature, with a difference of 30 K as shown in Figure 12.

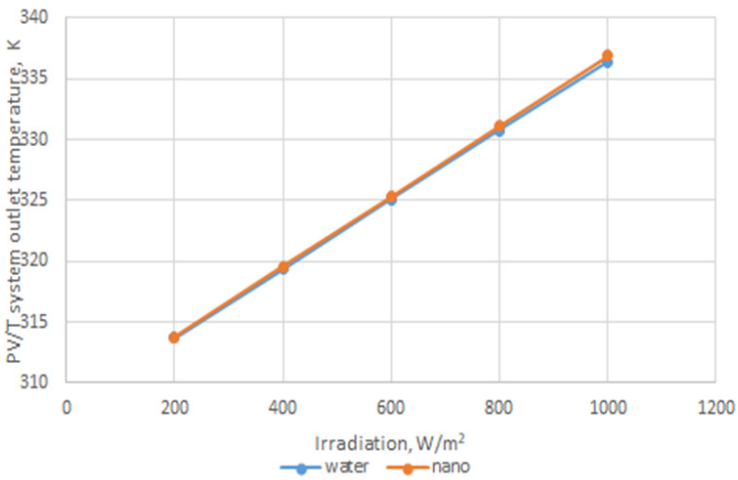

Figure 12: Effect of nanofluid inlet velocity on a PV cell outlet temperature, v = 0.00005 m/sec.

3.3. Comparative Study of the Effect of Water and Nanofluid Cooling Rate on Electrical, thermal, Overall Efficiency and Enhancement of Efficiency at 0.0001 m/s Inlet Velocity

As shown in Figure 13, the electrical efficiency of the PV/T system improved from 12% to 12.8%. Furthermore, Figure 14 shows an increase in thermal efficiency from 44% to 47.5%. These improvements together contribute to an increase in overall efficiency from 57% to 60%.

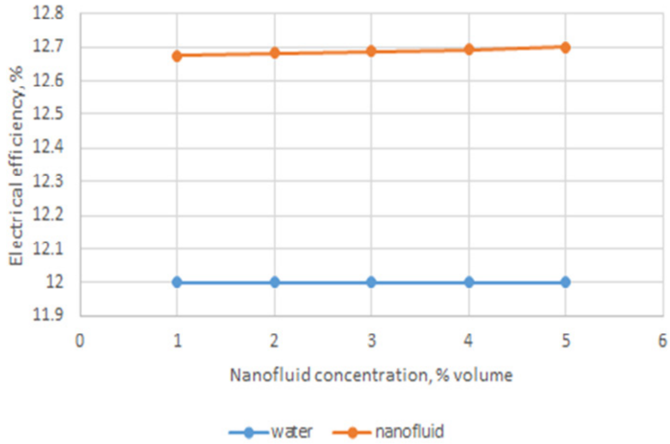

Figure 13. effect of 0.0001 inlet velocity on the electrical efficiency of the PV/T system.

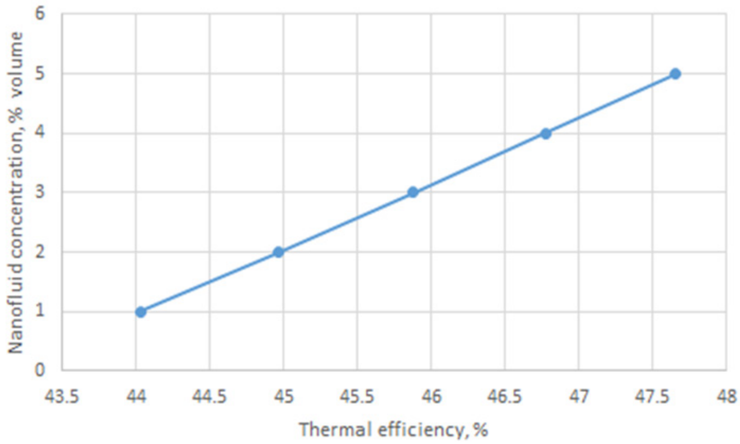

Figure 14 Effect of 0.0001 inlet velocity on the thermal efficiency of PV/T system.

Figure 15, clearly illustrates a degree of overall efficiency improvement when using nanofluids as coolants at an inlet velocity of 0.0001 m/s.

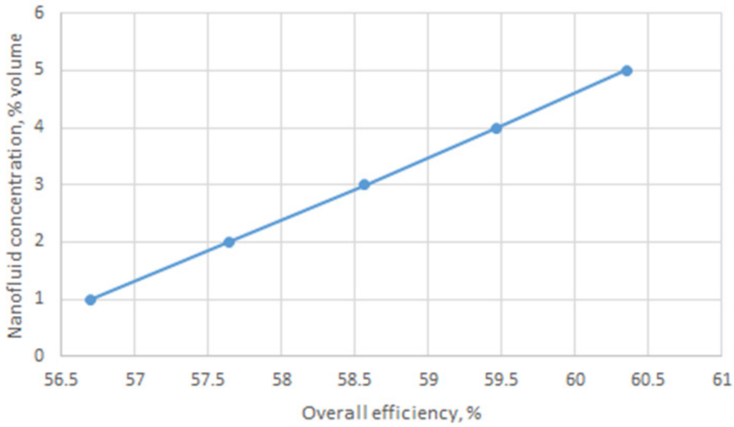

Figure 15 Effect of 0.0001 inlet velocity on the overall efficiency of the PV/T system.

In Figure 16, we can clearly observe a significant increase in the optimization efficiency when using nanofluids with an inlet velocity of 0.0001 m/s as coolant compared to water.

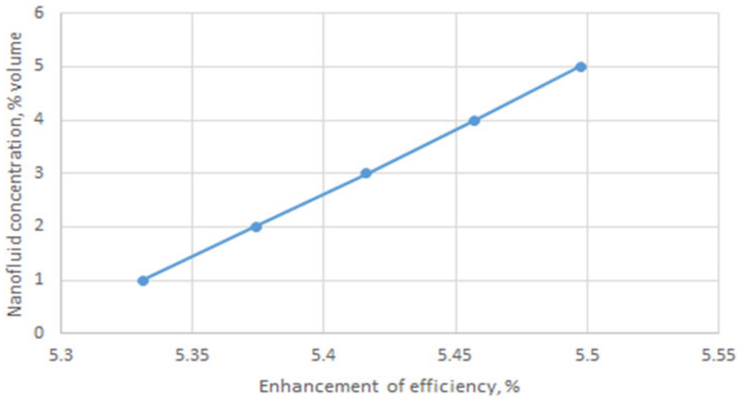

Figure 16 Effect of 0.0001 inlet velocity on an enhancement of efficiency of PV/T system.

4. CONCLUSION

From the above results, it can be seen that the inlet velocity of the coolant has a great effect on the surface temperature of the PV/T system and the outlet temperature of the coolant. The findings reveal that a decrease in inlet velocity contributes to a reduction in the PV/T system surface temperature. That is because some of the heat taken from the PV/T system is used to produce electrical energy, therefore increasing electrical efficiency and decreasing electrical losses. The rest raises the temperature at which the coolant leaves, which causes a large jump in thermal efficiency. Therefore, as the inlet velocity drops, the outlet temperature rises as much as 30 K below the inlet temperature, which is good for several applications.

The study also shows that nanofluid is a much better cooling agent than water itself. Nanofluid successfully lowered the PV/T system surface temperature at low inlet velocities, thereby increasing electrical efficiency by 12.8% compared to water. Additionally, it elevated thermal efficiency to 47.5%, resulting in an overall efficiency of 60%.

It has been proven that using nanofluid as a coolant cools the PV/T system surface more effectively and thus lowers the surface temperature, which in turn improves the PV/T system's electrical performance. Therefore, the percentage increase in efficiency was 5% better with nanofluid as a coolant than just water.

That is because at lower flow rates the coolant outlet temperature rises due to the increased convective heat transfer rate at higher flow velocities. This results in more heat being taken out of the PV/T system, and not enough time for thermal accumulation, which would in turn contribute to a temperature increase.

5. RECOMMENDATIONS

Based on the foregoing, it is recommended that where nanofluid or water is the coolant for the PV/T system a natural vertical flow may be used with no electrical pump to circulate the coolant. This is achieved by storing the coolant in tanks located above the PV/T system, allowing natural circulation (in low-velocity mode) of the fluid to flow through the system absorbing that thermal energy. Heat is then removed from the coolant after it has passed through the PV/T system and then returned to the tank. This repeats continuously to cool the PV/T system because of natural circulation. The recommendation calls for a PV/T system using nanofluid or water as the coolant that utilizes a passive cooling scheme. The system would eliminate the need for electric energy for propulsion, thereby, enhancing overall efficiency and diminishing the overall operational cost.

Main Advantages of Passive Cooling:

• Energy Efficient: Saves money on electricity as there are no pumps needed to circulate the fluid
• Reliability: Fewer moving parts result in higher system reliability
• Ease: The implementation is quite simple
• Cost-Effective: Can save money on both up-front investment and the operational costs of the system.
Some Considerations involving it would be:
• Energetic Thermal efficiency: The natural convection cooling is less efficient compared with forced convection cooling at high temperatures.
• System Design: Ensure good heat transfer and avoid overheating of the PV/T system
• Tank Size: Elevated tanks need to be big enough to store alongside having a head pressure to initiate natural circulation.
• Heat Rejection: A good heat exchanger is needed to remove the heat from the coolant before it gets sent back to the tank.
The recommendation to use a natural vertical flow for cooling PV/T systems is a promising approach that offers many advantages, especially in terms of energy efficiency and simplicity. However, a detailed technical analysis is required to assess the feasibility and performance of this approach for specific applications.

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NOMENCLATURE

A	Area (m^2)
Cp	Specific heat ($J\ kg^{-1}\ K^{-1}$)
D	Diameter (m^2)
E	Energy (W)
F	Fill Factor
h	Heat transfer coefficient ($Wm^{-2}K^{-1}$)
hT	conductive heat transfer coefficient from PV to coolant through tedlar ($Wm^{-2}K^{-1}$)
k	Thermal conductivity ($W\ m^{-1}\ K^{-1}$)
m	Mass flow rate ($Kg\ s^{-1}$)
n	Surface normal
P	Pressure (Pa)
Pc	Packing factor
Q	Total heat generation (W)
Qc	Convective heat loss (Wm^2)
q	Inward heat flux

R Solar irradiance (W/m^2)
Re Reynold number
t Time (minutes)
T Temperature ($^0C/K$)
U Velocity (m/s)
v Wind velocity (m/s)
V Volume (m^3)
V voltage
I current
K Boltzmann constant

GREEK SYMBOLS

∇ Vector differential operator
μ Dynamic viscosity (kg /m.s)
ρ Density (kg/ m^3)
η Efficiency
τ_g Glass emissivity
α Absorptivity
Ø Volume concentration of the nanoparticles

SUBSCRIPT

amb ambient
b back surface
c PV cell
el electrical
fc cross-sectional area
f base fluid
i inner diameter
in inlet
mp maximum power point
nf nanofluid
np nanoparticles
th thermal
out outlet
ref reference
w water

ABBREVIATION

PV Photovoltaic
PV/T Photovoltaic thermal
CFD Computational fluid dynamics