PENGARUH SUDUT KEMIRINGAN TERHADAP EFISIENSI SEL SURYA DAN ENERGI LISTRIK DARI SISTEM FOTOVOLTAIK-TERMAL (PV/T) YANG DI ISI NANOFLUIDA

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Diajukan Sebagai Salah Satu Syarat untuk Memperoleh Gelar Sarjana Teknik Pada Program Studi Teknik Elektro Fakultas Sains dan Teknologi

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UNIVERSITAS ISLAM NEGERI SULTAN SYARIF KASIM RIAU

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Effect of Tilt Angle on Solar Cell Efficiency and Electrical Energy of Nanofluid-Filled Photovoltaic-Thermal (PV/T) Systems

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ABSTRACT

This study aims to investigate the impact of nanofluid concentration and panel tilt angle on the efficiency of photovoltaic-thermal (PV/T) systems, with the goal of optimizing energy performance. Numerical simulations were conducted using the Finite Element Method (FEM) to analyze the effects of varying nanofluid concentrations and panel inclination angles on PV/T system performance. The findings revealed that a nanofluid concentration of 20% provided the most uniform fluid flow. At an inclination angle of π/6, increasing the concentration to 20% reduced the PV cell temperature and enhanced photovoltaic efficiency to 12.04%, while also achieving the highest electrical power output of 36.71 W. The highest thermal efficiency of 69.5% was observed at a 20% concentration with a π/6 tilt angle, whereas the highest total efficiency of 81.7% was achieved at a π/3 tilt angle. The study demonstrates that optimizing the combination of nanofluid concentration and panel tilt angle significantly enhances the energy efficiency of PV/T systems. This advancement contributes to the development of more efficient renewable energy technologies.

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1. INTRODUCTION

Energy is the main pillar in driving economic development and social welfare, both in supporting economic activities and daily needs [1]. Most energy resources come from fossil fuels. Dependence on fossil fuels causes challenges in the form of depletion of reserves, a global energy crisis, and negative environmental impacts such as global warming, excess carbon emissions, and significant climate change [2]. The development of renewable energy sources, especially solar energy, is a solution to overcome dependence on fossil fuels [3]. The main technology for converting solar energy into electricity is photovoltaic (PV) panels, which convert solar energy into electricity. However, only about 20% can be converted, while 80% is wasted as heat [4]. The accumulation of heat can decrease the efficiency and performance of PV cells. An increase in temperature above 25°C can degrade the performance of PV modules resulting in reduced power output and efficiency decreasing by about 0.5% per degree Celsius against temperature increase [5]. The reduction in PV efficiency caused by rising temperatures can be mitigated by incorporating a cooling system into the PV panel. This technology, known as a photovoltaic-thermal (PV/T) system, converts solar energy into both electricity and thermal energy at the same time [6].

Because of the high efficiency of PV/T systems, extensive research has been conducted to further develop and improve them [7]. Many studies have explored ways to improve electrical efficiency, as well as designing and optimizing the operational parameters of PV/T systems. Previous research shows

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that the temperature reduction of PV cells evaluated using PV/T technology with water as the cooling medium, results in a temperature reduction of up to 2°C, which contributes to a 3% increase in efficiency [8]. Furthermore, another investigation revealed that a PV/T cooling system employing water fluid in a laminar arrangement could decrease the PV cell temperature is reduted drop of 2°C [9]. The research additionally discovered that the base fluid (water) used in the solar collector outperforms the air system, the water temperature within the PV/T collector remains more stable despite variations in solar radiation levels, whereas the air-based collector is more prone to temperature fluctuations [10].

Cooling systems in PV/T can use various types of fluids, one of which is nanofluids. Nanofluids are fluids that have added nanoparticles with sizes between 1 and 100 nanometers, which can improve their thermal properties. Prior studies investigated the application of CuO-water nanofluids for cooling, resulting in a 51.22% overall efficiency and a 72.58% energy accumulation efficiency, surpassing that of Al_2O_3-water [11]. Moreover, additional studies discovered that CuO/water nanofluids exhibited superior performance compared to Al_2O_3/water and pure water [12]. Meanwhile, another study said that nanoparticles in nanofluids improve thermal conductivity and heat transfer, resulting in more optimal performance in PV/T systems [13]. The other research analyzed the combination of nanofluid flow rate and nanoparticle concentration to obtain maximum thermal efficiency [14].

In PV/T systems, the use of nanofluids shows a positive impact on the efficiency of panels installed with various tilt angles [15]. The amount of solar radiation received is significantly influenced by the tilt angle, which directly affects system performance. Previous research revealed that at optimal tilt angles, the use of nanofluids can increase thermal efficiency by up to 35% compared to systems using plain water as the cooling medium [16]. In addition, the optimal tilt angle is important to maximize the energy received, as it affects the heat transfer and performance of the PV/T system. When the inclination angle is not optimal, the received solar radiation decreases, thus lowering the electrical and thermal energy conversion efficiency [17]. This suggests that optimization of the inclination angle of solar cell panels, along with the use of nanofluids, can make a significant contribution to the efficiency of renewable energy systems.

A literature review indicates that utilizing nanofluids as a cooling medium in PV/T systems enchances thermal conductivity and energy efficiency compared to plain water, especially in the CuO/water nanofluid type [11, 12]. It was noted in earlier studies that the tilt angle of the panel influences the quantity of solar radiation it receives, thereby affecting system efficiency [16]. This research focuses on improving solar cell efficiency and electrical energy applied to PV/T systems through assessing the effects of nanofluid concentration and tilt angle variation. The Finite Element Method (FEM) was chosen for its ability to solve complex thermal analysis. The evaluation of the PV cell efficiency, electrical energy, thermal capability, and overall system efficiency will be grounded in the Second Law of Thermodynamics. This law elucidates that energy transitions from high to low states, offering insights into the system's overall efficiency.

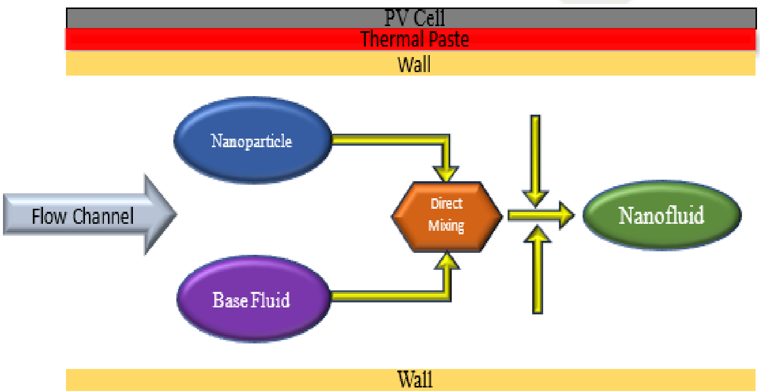

Figure 1. Schematic Model of PV/T Solar Panels and Flow Channels Filled with Nanofluids

2. RESEARCH METHOD

Figure 1 illustrates the photovoltaic-thermal (PV/T) solar panel model used in this study. The PV/T system consists of multiple layers: the PV cell layer, a thermal paste layer, the reservoir wall, and a flow

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channel within the reservoir that contains the nanofluid. The solar panel design features a side length of 30.5 cm and a thickness of 0.27 mm. Monocrystalline silicon (c-Si) was chosen for the PV cell layer due to its superior heat absorption capacity compared to polycrystalline silicon (p-Si). Typically, c-Si cells exhibit a photovoltaic conversion efficiency of approximately 13% and a heat coefficient of 0.54. The thermal paste layer, a conductive material, measures 30.5 cm in length and 0.3 mm in thickness. The reservoir wall is constructed from aluminum, with a length of 30.5 cm and a thickness of 1 mm. The flow channel within the reservoir, designed for fluid circulation, has a length of 30.5 cm and a thickness of 15 mm. The nanofluid was prepared using a direct mixing method, combining a base fluid (water) with nanoparticles (solid) to achieve a stable mixture. The nanofluid flow was assumed to be laminar, with a velocity of 0.01 m/s. The reservoir wall thickness was set at 0.015 m for simulation purposes. This study investigates the effects of varying tilt angles (π/6, π/4, and π/3) and nanoparticle concentrations (1%, 10%, and 20%) on the fluid velocity profile within the channel. These parameters were systematically analyzed to asses their effect on the total efficiency of the PV/T system.

The conjugate heat transfer approach has been used to develop heat transfer equations for the PV cell layer, thermal paste layer, reservoir structure, and flow channel. The temperature at the PV surface is considered fixed and uniform. In the analysis, the sky is assumed to be a black body that emits long-wave radiation according to the environmental conditions. In addition, it is assumed that the environment is dust-free allowing full transmission of solar energy. Table 1 lists the physical properties of solar radiation as well as the relevant environmental condition parameters.

Table 1. Nature of Incoming Energy from the Sun and Environmental Conditions

Quantity Name	Value	Distance (m)
Solar Irradiance	1.000	G (kg/m^2)
Heat Transfer Coefficient	6.5	Hc(W/(m2K))
Ambient Temperature	298.15	T_{amb} (K)
Radiation Emissivity	0.3	ε (kg/m^2)

PV panels, as shown in Figure 1, receive energy from sunlight. A portion of the radiative energy is transformed into electrical power through the photovoltaic process, whereas the remaining energy is converted into thermal energy. Radiation affects the entire surface of the plate. Thermal paste applied under the PV array serves to effectively distribute the heat, thereby helping to improve the efficiency of electrical conversion. The following formula describes the convection heat transfer process at the PV panel's top and bottom interfaces.:

$$q\_conv = -hc\,A + Tpv - Tamb \tag{1}$$

Hc represents the heat loss caused by convection, while A represents the surface area. Heat transfer at the PV/T panel's top and bottom interfaces as well as the energy carried by the nanofluid flow inside the reservoir are both included in the total conjugate convection. The following formula can be used to describe heat loss from infrared radiation, which is electromagnetic radiation released by the atmosphere and surface:

$$q_{lw} = \varepsilon.\,\sigma + \left(T^4{}_{pv} - T^4{}_{amb}\right) \tag{2}$$

Where σ stands for electrical conductivity and ε for radiation emissivity. An important consideration for modeling heat in participating media is the assessment of extinguishing, absorption, and scattering coefficients. The media extinguishing coefficient can be formulated as follows:

$$K_e = \frac{1.5\phi Q_e}{d} + (1 - \phi)\,\frac{4\pi\,K_{bf}}{\lambda} \tag{3}$$

Where Q is the nanoparticle attenuation coefficient, λ is the wavelength of radiation, and d denotes the diameter of the nanoparticle. The attenuation coefficient of water can be calculated using the following equation:

$$K_{bf} = K_a + K_s \tag{4}$$

Table 2. Basic Thermophysical Properties of Nanofluids

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Properties	Water	Copper
Cp (J/kgK)	4.179	383
ρ (kg/m^3)	997.1	8954
K (W/mK)	0.605	400
μ (Ns/m^2)	0.00108	-

Table 3. Nanofluid Physical Properties

Properties	Copper
Cp (J/kgK)	4027.2
ρ (kg/m^3)	1315.4
K (W/mK)	0.608027
μ (pas)	0.001196

In all layers, heat transfer occurs from the nanofluid to the solid, from the solid to the nanofluid, or flows through the solid layer via a conjugate convection mechanism. The nanofluid at the inlet is assumed to have a uniform temperature. This hybrid approach is applied to enable solar cells to convert transform solar radiation into electrical energy under optimal conditions. Most of the absorbed fraction of incident solar radiation is transformed into thermal energy, resulting in a rise in the solar cell temperatur. The increase in temperature is utilized through a cooling mechanism for the PV/T module using nanofluids, with the aim of maximizing the generated electricity. To calculate the efficiency, various equations are used. When PVs are exposed to solar radiation, the energy that is not fully utilized turns into thermal energy on the panel surface. The heat transfer across the PV cell, thermal paste, and reservoir wall is expressed by the following equation:

$$\nabla . (k\nabla T) = 0 \tag{5}$$

Inside the duct, heat transfer takes place through convection and conduction. The flow, at both inlet and outlet velocities, is assumed to be constant, incompressible, Newtonian, and laminar. The solid nanoparticles are assumed to have a uniform shape and size and maintain thermal equilibrium with the host fluid. The utilized particles are nano-sized aluminum oxide, with thermophysical values listed in Table 2. The difference in density versus temperature in relation to the gravitational force is considered linear according to the Boussinesq model. This model applies accurately when the density variation is small enough that it does not affect the convective flow, except for the gravitational effect. Taking these elements into account, the equations for continuity, momentum, and energy are articulated as follows:

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \tag{6}$$

$$U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = -\frac{1}{\rho_{nf}}\frac{\partial P}{\partial X} + \frac{\mu_{nf}}{\rho_{nf}}\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}\right) - \frac{1}{\rho_{nf}}(\rho\beta)_{nf}\, g \sin\varphi\,(T - T_C) \tag{7}$$

$$U\frac{\partial V}{\partial X} + V\frac{\partial V}{\partial Y} = -\frac{1}{\rho_{nf}}\frac{\partial P}{\partial Y} + \frac{\mu_{nf}}{\rho_{nf}}\left(\frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2}\right) - \frac{1}{\rho_{nf}}(\rho\beta)_{nf}\, g \cos\varphi\,(T - T_c) \tag{8}$$

$$U\frac{\partial T}{\partial X} + V\frac{\partial T}{\partial Y} = \alpha_{nf}\left(\frac{\partial^2 T}{\partial X^2} + \frac{\partial^2 T}{\partial Y^2}\right) + \frac{1}{(\rho C_p)_{nf}}\nabla . Q_r \tag{9}$$

Here, (U, V) refers to the velocity vector, T denotes the temperature, and P signifies the pressure. The subscript none indicates the bulk properties of the nanofluid, while g represents gravitational acceleration. Furthermore, μ, ρ, β, and α represent the dynamic viscosity, density, thermal expansion value, and thermal diffusion rate of the nanofluid at ambient temperature, correspondingly. The nanofluid density is expressed as the combined relationship between water and dispersed particles,

$$\rho_{nf} = (1 - \phi)\,\rho_{bf} + \phi\rho_{sp} \tag{10}$$

Where φ is the volume fraction of nanoparticles. The symbol bf refers to the base fluid or water. The viscosity of the base fluid affected by the addition of nanoparticles can be written:

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$$\mu_{nf} = \frac{\mu_{bf}}{(1-\phi)^{2.5}} \tag{11}$$

The thermal diffusivity of nanofluids, which is a measure of how quickly heat can spread through a material:

$$\alpha_{nf} = \frac{k_{nf}}{(\rho C_p)_{nf}} \tag{12}$$

Nanofluids' specific heat capacity is a combination of their base fluid and nanoparticles:

$$(\rho C_p)_{nf} = (1-\phi)\,(\rho C_P)_{bf} + \phi(\rho C_P)_{sp} \tag{13}$$

The thermal expansion coefficient of the nanofluid, which describes how much the volume of the nanofluid changes as the temperature changes, can be calculated:

$$\beta_{nf} = (1-\phi)\,\beta_{bf} + \phi\beta_{sp} \tag{14}$$

The heat transfer capability of the nanofluid was calculated based on Maxwell's equations:

$$k_{nf} = k_{bf}\left[\frac{k_p+2k_{bf}-2(k_p-k_f)\phi}{k_p+2k_{bf}+(k_p+k_p)\phi}\right] \tag{15}$$

Equations (5) to (15) are analyzed using the finite element method (FEM). After solving these equations, the power conversion efficiency of the PV cell is evaluated using the following equation:

$$\eta_{pv} = \eta_{ref}\left[1-\beta_{ref}\left(T_{pv}-T_{ref}\right)\right] \tag{16}$$

The electrical energy produced is the total electrical potential energy transformed into dynamic energy in SI units of Joules per second (Watt). For PV/T (Photovoltaic/Thermal) systems, the electrical energy output can be calculated with the following formula:

$$E_{pv} = \eta_{pv} \times A_m \times G \tag{17}$$

PV cell efficiency, surface area, and solar radiation intensity all affect the electrical output. The following formula can be used to express the electricity generated by a PV module under exposure to sunlight:

$$E_{in} = G.A_m \tag{18}$$

The thermal energy obtained by using nanofluid serving as a heat dissipation agent in the PV/T system is calculated by:

$$E_{nf} = m_{nf}C_p(T_{out}-T_{in}) \tag{19}$$

The percentage of thermal energy successfully converted into electrical energy can be calculated using:

$$\eta_{th} = \frac{E_{nf}}{E_{in}} \times 100\% \tag{20}$$

Total electrical and thermal energy output divided by total electrical energy received is the PV/T system's overall or global efficiency, and it is calculated as follows:

$$\eta_{glob} = \frac{E_{nf}+E_{PV}}{E_{in}} \times 100\% \tag{21}$$

The Finite Element Method (FEM) is used to numerically solve the continuity, momentum, and energy equations. This method operates by breaking down the problem domain into multiple smaller subdomains, making the computational process more manageable. In this study, the flow inside the solar collector is assumed to be an incompressible and laminar flow (spf) to solve equations (6)–(8), as well as heat transfer in fluids (ht) for equation (9). Irradiation is calculated assuming a constant heat flux as the boundary condition.

As a validation step, the temperature values obtained were compared with the research data of Fontenault and Gutierrez-Miravete (2012), as shown in Figure 2.

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(a) experiments conducted

(b) Fontenault dan Gutierrez-Miravete (2012)

Figure 2. Validation of current isotherms (a) with published work (b)

3. RESULTS AND DISCUSSION

Numerical calculations are carried out by considering an inlet temperature that is assumed to be uniform, which is equivalent to room temperature. This temperature selection aims to represent the condition the working fluid reached room temperature to facilitate heat transfer from the solar panel. Parametric studies were performed to examine different factors, such as PV cell temperature, efficiency PV cell, output electrical energy, efficiency thermal, and overall energy efficiency. The analysis was carried out with nanoparticle concentrations of 1%, 10%, and 20%.

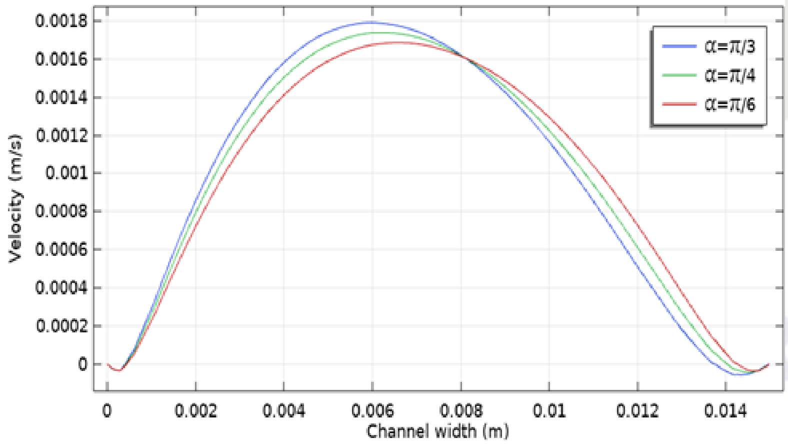

Figure 3. Fluid Velocity Profile

Figure 3. velocity profile of laminar flow in a closed channel, according to Navier-Stokes theory. The fluid velocity is zero at the walls due to the no-slip effect and increases parabolically towards the center, where the maximum velocity is reached. The variation in velocity profiles for the three angle variations reflects changes in pressure gradient, viscosity or channel geometry. Larger angle values result in higher peak velocities, while smaller angle values result in lower peak velocities but wider flow profiles, indicating a more even distribution of kinetic energy.

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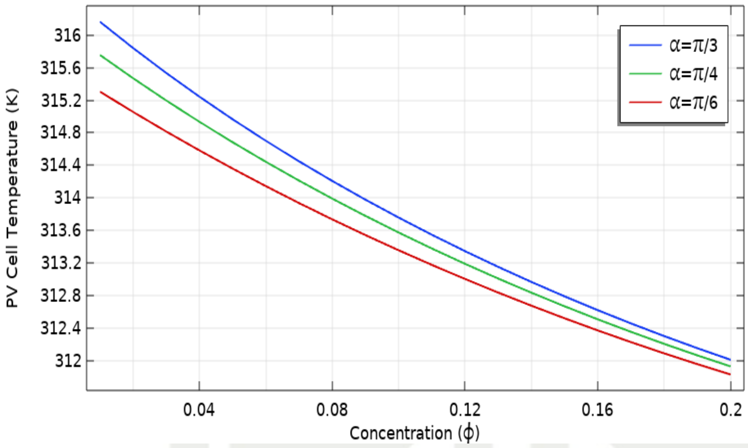

Figure 4. PV Cell Average Temperature

Figure 4. shows the correlation between concentration and PV cell temperature (Kelvin) for three angle values. Overall, the PV cell temperature decreases with increasing concentration values. This decrease in temperature is in accordance with heat transfer theory, where an increase in concentration ϕ often increases the efficiency of cooling or heat distribution, thereby reducing the heat trapped in the PV cell. Smaller α angles result in lower temperatures, which can be attributed to a more optimized radiation distribution, favoring thermal stability and improving PV cell performance. A slight drop in temperature will lead to a significant difference in thermal performance.

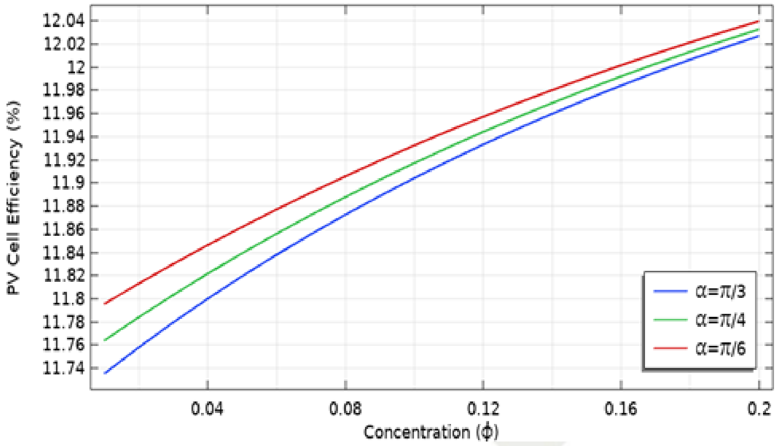

Figure 5. PV Efficiency

Figure 5. shows the correlation between concentration (ϕ) and photovoltaic (PV) cell efficiency in percent for three angle values. In general, the PV efficiency increases as the concentration increases reflecting that an increase in concentration enhances the conversion of light energy into electricity due to more optimized light absorption. In the three variations of tilt angle, it is seen that smaller angles result in higher efficiency. Thus, the efficiency of the PV cell is affected by the increase in nanoparticle concentration and the value of the flow inclination angle, where smaller angles provide more optimal efficiency.

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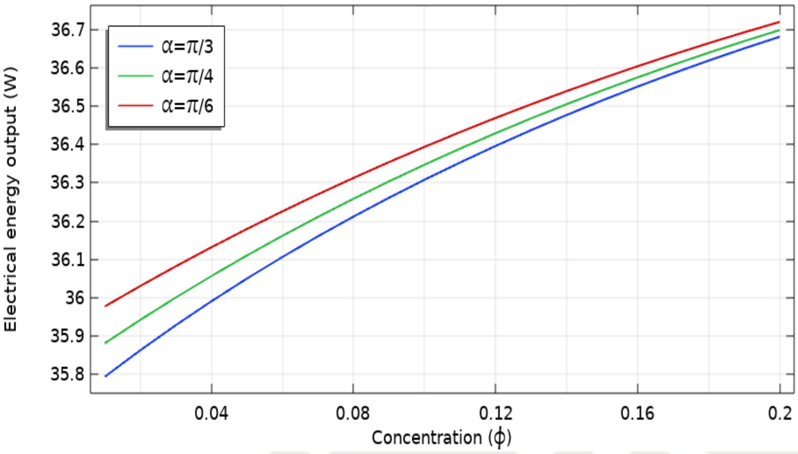

Figure 6. Electrical energy output of PV/T

Figure 6. shows the correlation between concentration (ϕ) and electrical power output (watts) of the PV cell for three angle values. The electrical power increases with increasing concentration. This increase in electrical power reflects that higher concentration allows more light energy to be converted into electrical energy. In addition, smaller angle α produces more power, this angle setting increases the efficiency of light incidence and heat distribution, supporting the theory that optical and thermal design have a significant impact on the performance of the PV system.

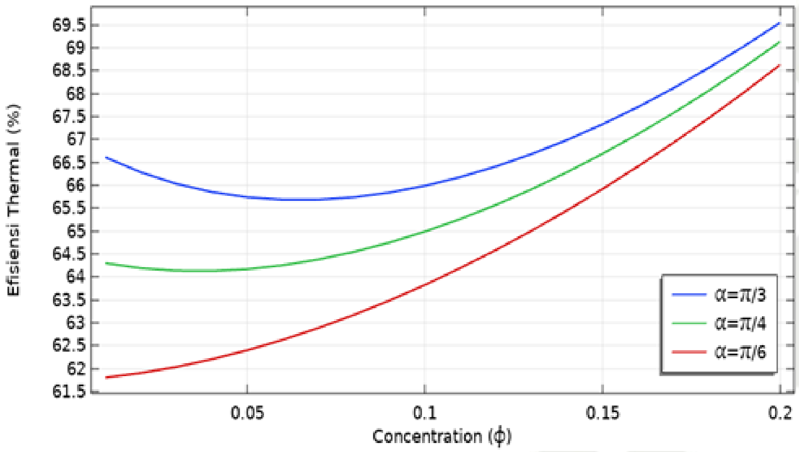

Figure 7. Thermal Efficiency

Figure 7. reflects that a higher concentration of ϕ allows for more optimal utilization of thermal energy, increasing the thermodynamic process efficiency. The higher efficiency at smaller angles α is in accordance with heat transfer theory, where a more focused energy path or optimal angle arrangement favors more effective heat transfer, thereby enhancing the system thermal efficiency.

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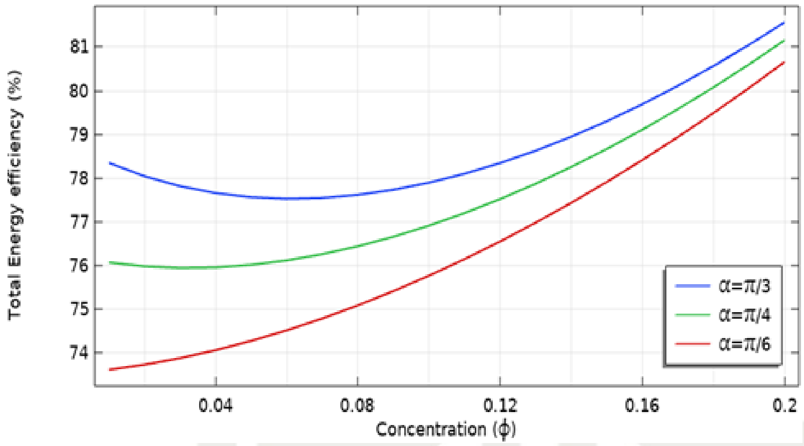

Figure 8. Total Efficiency of PV/T System

Figure 8. this increase in efficiency is in line with the theory of energy conversion, where higher concentration (ϕ) increases the density of energy converted into work. In addition, smaller values of angle α indicate more optimal thermodynamic performance, consistent with the theory that certain geometric arrangements angles can maximize efficient energy transfer and improve total thermal performance.

4. CONCLUSION

The main conclusion of this study shows that nanofluid concentration and panel tilt angle significantly impact the efficiency and performance of PV/T systems. An optimal concentration of 0.02 results in an even distribution of fluid flow, while increasing the concentration to 0.2 at an inclination angle of π/6 lowers the panel temperature, increases the photovoltaic efficiency by 12.04%, and produces the best electrical power of 36.71 W. The system thermal and overall efficiencies improve with higher nanofluid concentration and optimal inclination angle, reaching the highest total efficiency of 81.7% at an angle of π/3. This study shows a significant effect of nanofluid concentration and tilt angle on PV/T performance, but is limited to low concentration variations and has not considered environmental factors, long-term durability, and economic analysis. Future research needs to explore and test the system in real-world conditions for more optimized efficiency.

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