WATER-BASED COOLING IN PV SYSTEMS: A STATISTICAL COMPARISON OF MODIFIED PV-T AND CONVENTIONAL PV PANELS UNDER VARIABLE FLOW RATES

MÓDOSÍTOTT PV-T ÉS HAGYOMÁNYOS PV PANEL ÖSSZEHASONLÍTÁSA STATISZTIKAI MÓDSZER SEGÍTSÉGÉVEL, KÜLÖNBÖZŐ ÁRAMLÁSI SEBESSÉGEK ESETÉN

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Abstract

This study explores how well a modified photovoltaic (PV) panel with a water-based cooling system performs under various environmental conditions. We compared a standard PV panel to one enhanced with copper pipes and aluminium adhesive, testing two different flow rates (4 l/min and 7 l/min) to see how solar irradiance and ambient temperature affect the working temperature. Our findings revealed that lower flow rates made the panel more sensitive to environmental changes, with solar irradiance and ambient temperature accounting for up to 92.5% and 80.2% of the temperature variation, respectively. The ANCOVA analysis confirmed that flow rate, solar irradiance, and ambient temperature all significantly influence the working temperature, with flow rate having the strongest impact. The results also showed a significant interaction between flow rate and irradiance, indicating that cooling effectiveness changes with sunlight intensity. However, the interaction between flow rate and ambient temperature was not significant, suggesting that the effect of flow rate remains consistent across different air temperatures.
Keywords: *water-based cooling, flow rate, solar irradiance, ambient temperature, thermal performance, ANCOVA*
JEL code: *O13, Q4*

Összefoglalás

Ez a tanulmány azt vizsgálja, hogy egy módosított fotovoltaikus (PV) panel - víz alapú hűtőrendszerrel - hogyan teljesít különböző környezeti feltételek mellett. Összehasonlítottunk egy standard és egy rézcsövekkel és alumínium ragasztóval kiegészített napelemet, két különböző áramlási sebesség (4 l/perc és 7 l/perc) esetén. Megvizsgáltuk, hogyan befolyásolja a napsugárzás és a környezeti hőmérséklet az üzemi hőmérsékletet. Eredményeink azt mutatták, hogy az alacsonyabb áramlási sebesség érzékenyebbé teszi a panelt a környezeti változásokra, mert a napsugárzás és a környezeti hőmérséklet az üzemi hőmérséklet változás akár 92,5%-át, illetve 80,2%-át is befolyásolhatja. Az ANCOVA analízis megerősítette, hogy az áramlási sebesség, a napsugárzás és a környezeti hőmérséklet mind jelentősen befolyásolja az üzemi hőmérsékletet, és ezek közül az áramlási sebességnek van a legerősebb hatása. Az eredmények azt is kimutatták, hogy az áramlási sebesség és a besugárzás között jelentős kölcsönhatás van, ami azt jelzi, hogy a hűtési hatékonyság a sugárzás intenzitásával változik. Az áramlási

sebesség és a környezeti hőmérséklet közötti kölcsönhatás azonban nem volt szignifikáns, ami arra utal, hogy az áramlási sebesség hatása konzisztens marad a különböző levegő hőmérsékletek esetén.
Kulcsszavak: *PV-panel, PVT-panel; áramlási sebesség, globálsugárzás, termikus teljesítmény, ANCOVA*

Introduction

Water cooling systems have been shown to enhance the efficiency of photovoltaic (PV) panels by lowering their operating temperatures. For example, WAN ABDULLAH et al. (2021) integrated a copper pipe water-cooling system on the back of a PV panel, resulting in a 3% increase in efficiency at a flow rate of 300 *l*/h compared to uncooled panels. They noted a temperature reduction of 16°C after 60 minutes at a solar irradiance of 350 W/m². Similarly, JAILANY et al. (2016) utilized a forced-water spraying technique on the surface of PV modules, achieving a temperature decrease of 9.07°C and a 9.27% increase in power output over a day. Both studies indicated that higher water flow rates lead to greater temperature reductions and efficiency gains, underscoring the potential of water-cooling systems to improve PV panel performance by alleviating the adverse effects of elevated temperatures on solar cell efficiency.

Photovoltaic/thermal (PV/T) systems represent another effective approach to boosting the efficiency of photovoltaic modules by simultaneously reducing cell temperature and harnessing thermal energy. Two studies explored various water-based cooling configurations for PV/T systems. KAZEM et al. (2020) compared web, direct, and spiral flow channels in Oman, finding that the spiral flow design achieved the highest overall efficiency at 35.0%. All PV/T systems outperformed conventional PV modules, with temperature reductions of at least 3°C. Likewise, YILDIRIM et al. (2022) introduced an innovative thermal collector design that achieved 17.79% electrical efficiency and 76.13% thermal efficiency under optimal flow conditions. Both studies demonstrate the significant potential of water-based PV/T systems to improve both electrical and thermal performance compared to traditional PV modules, highlighting their suitability for high solar irradiance regions and their role in advancing solar energy utilisation.

Hybrid photovoltaic thermal (PVT) systems employ cooling techniques to enhance both electrical and thermal efficiency of solar panels. Water-based cooling methods, including front surface, back surface, and combined cooling, can significantly reduce PV panel temperatures by 22-27°C, improving performance (BHAKRE et al., 2021). HUSSEIN et al. (2017) demonstrated that active water cooling decreased panel temperature from 76°C to 70°C, increasing electrical efficiency to 6.5% at an optimal flow rate of 2 *l*/min. Furthermore, using Zn-H_2O nanofluid with a 0.3% concentration ratio further reduced the temperature to 58°C, boosting electrical efficiency to 7.8% (HUSSEIN et al., 2017). Front surface cooling also offers the added benefit of panel cleaning, enhancing optical efficiency. While dual cooling shows promise for hot arid regions, further research is needed to fully evaluate its potential (BHAKRE et al., 2021).

Recent studies have explored innovative cooling techniques for photovoltaic-thermal (PVT) systems to enhance their efficiency. MOSTAKIM et al. (2024) investigated a sprayed water PVT system that simultaneously generates electricity and hot water. Their research demonstrated significant improvements, including a peak thermal efficiency of 70.6% and a PV panel efficiency increase of up to 16.78%. The cooling technique consistently reduced panel temperatures from 45.08°C to 34.12°C. Similarly, AL-JAMEA et al. (2022) compared water immersion and spraying cooling methods for PV panels. They found that water spraying achieved a 60% temperature reduction, resulting in a 59% increase in power output and an 8%

efficiency improvement. Both studies highlight the effectiveness of water-based cooling techniques in optimising PV panel performance, with spraying methods showing particular promise. These findings contribute to the ongoing development of more efficient and sustainable PVT systems.

AWAD et al. (2022) compared air and water cooling in hybrid solar systems and found that air cooling at 2.5 m/s delivered better results, achieving 92.8 W of electrical power, 13% electrical efficiency, and 78.08% thermal efficiency, outperforming the water-based setup. Meanwhile, SMITH et al. (2014) showed that water cooling kept panel temperatures below 40°C (compared to 55°C without cooling), enhancing efficiency while also preventing power losses caused by dust accumulation. They concluded that the energy gained from improved panel output outweighed the energy required for water circulation.

Similarly, recent studies by SAMPURNA PANDA et al. (2023) and MALAIYAPPAN et al. (2022) highlight the effectiveness of water-based cooling systems. Front surface cooling and water circulation through ducts both led to noticeable improvements in panel output. For instance, MALAIYAPPAN et al. reported a 10.4% boost in performance under 866 W/m² solar irradiance. These studies also underscore the advantages of hybrid PVT systems, which not only increase electrical efficiency but also repurpose excess heat for thermal use, maximising total energy output.

Material and methods

In this study, we tested both a standard photovoltaic (PV) panel and a modified version (see Figure 1a). The modified panel featured copper pipes bonded with a synthetic resin adhesive containing 75% aluminium, which aimed to enhance thermal conductivity (see Figure 2 b). We varied the cooling flow rate to determine the optimal setup for maximising the system's overall efficiency. Throughout the experiment, we continuously monitored temperature, solar irradiance, and ambient conditions using sensors. Our primary objective was to develop a PV system that could maintain or even enhance its efficiency at higher temperatures, ultimately resulting in improved solar energy output.

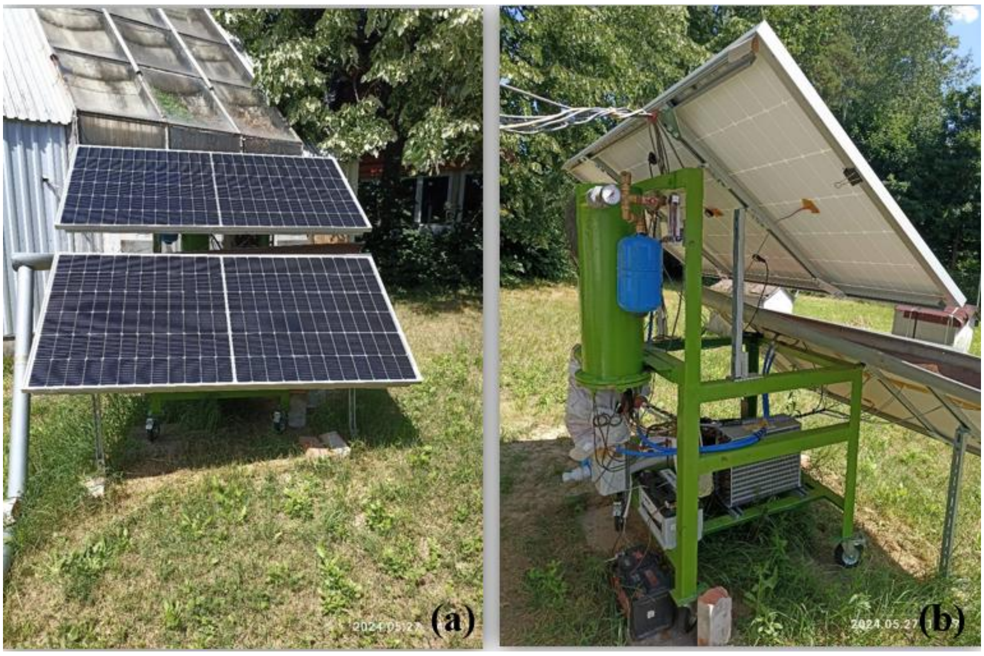

Figure 1. Experimental Setup, a: PV and PVT, b: back side of both panels
Source: prepared by authors

Material

The experimental setup was designed to evaluate the impact of varying water flow rates, employed as a cooling medium, on the performance of photovoltaic (PV) systems. It included both a standard PV panel and a modified version (see Figure 1). The modified panel featured copper pipes attached to its back with a synthetic resin adhesive that contains 75% aluminium, applied in layers ranging from 3 to 5 mm thick. This design allows for adjustments in flow rate to optimize heat dissipation. Additionally, the system is equipped with 20 mm of XPS insulation to minimize thermal losses and maintain stable temperatures. An Arduino-based control unit is central to the setup, overseeing real-time data collection and monitoring through a network of strategically placed sensors.

Methods

As part of our experimental framework, a carefully selected set of sensors was used to monitor and improve the performance of both standard and modified PV systems. These sensors played a vital role in collecting real-time data and evaluating system efficiency and behaviour. For temperature monitoring, the LM335 sensor was employed, offering high accuracy with a precision margin of ±1°C across a broad temperature range. To measure solar irradiance, the TF 6003.0000 BG sensor was used; this device detects global radiation through a silicon diode beneath a PMMA dome, making it well-suited for photovoltaic studies, climate monitoring, and agricultural applications. The experimental trials were conducted between 11:00 AM and 02:00 PM, during which both PV systems were assessed. The analysis focuses on comparing two cooling flow rates, 4 *l*/min and 7 *l*/min, while examining how solar irradiance and ambient temperature influence the working temperature of the modified PV panel.

Results

This study investigates the thermal response of a modified photovoltaic (PV) system under two different coolant flow rates: 4*l*/min and 7 *l*/min. Our primary goal is to understand how ambient temperature and solar irradiance individually affect the working temperature of the PV panel, as well as how these factors interact in a combined model.

Initially, we conduct two-dimensional comparisons to evaluate the separate impacts of ambient temperature and solar irradiance on the surface temperature of the PV panel (PVT-T) for each flow rate. We apply linear regression models and report the coefficients of determination (R^2) to measure the strength of these relationships. To investigate the combined effects of both environmental factors, we use three-dimensional (3D) visualisations. We then develop multiple linear regression models that incorporate both ambient temperature and solar irradiance to assess their combined influence on PV temperature, as evaluated through R^2 values.

Additionally, we perform an Analysis of Covariance (ANCOVA) to examine how the three factors (flow rate, ambient temperature, and solar irradiance) affect the PV working temperature. This analysis also checks for potential interaction effects, specifically whether the impact of flow rate depends on the levels of solar irradiance or ambient temperature.

Solar Irradiation

Figure 2 illustrates the relationship between solar irradiance (measured in W/m²) and the working temperature (PVT-T) of the modified PV panel at two different flow rates: 4 *l*/min on the left and 7 *l*/min on the right. Each plot features a linear regression model, complete with its equation and R^2 value. At the 4 *l*/min flow rate, we see a strong correlation (R^2 = 0.925), meaning that 92.5% of the changes in the PV temperature can be attributed to solar irradiance.

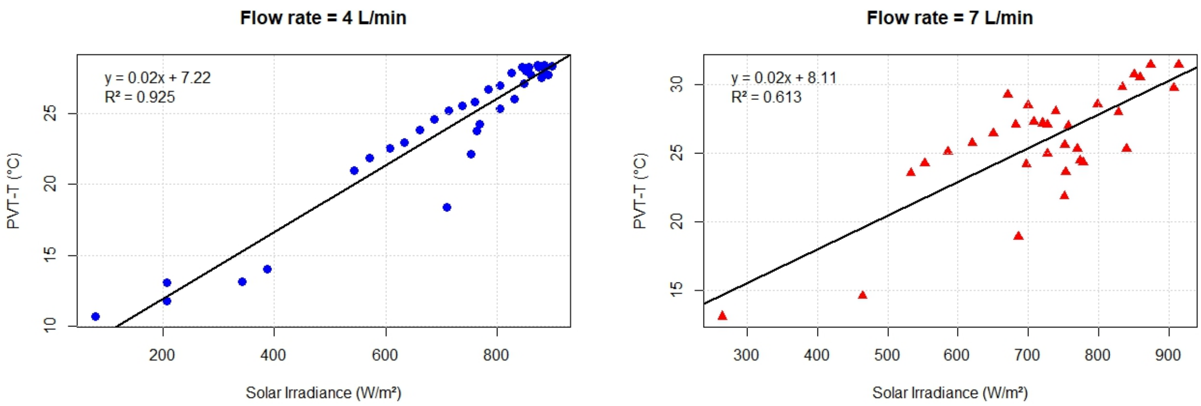

Figure 2. PVT-T vs Solar Irradiation for both flow rates

Source: prepared by authors using R

The slope of 0.02 indicates that for every 100 W/m² increase in irradiance, the temperature rises by 2°C. This reflects a high sensitivity to temperature changes due to limited cooling.

In contrast, at the 7 *l*/min flow rate, the correlation is weaker (R^2 = 0.613), and the data shows more scatter. This suggests that the higher flow rate improves cooling, making the temperature less dependent on solar irradiance. Overall, these findings emphasise that the thermal response of the PV panel to solar irradiance is significantly affected by the cooling flow rate, highlighting the critical role of flow rate optimisation for effective temperature management.

While the linear models show a strong correlation, there is noticeable scatter around the regression line, especially at certain irradiance levels, where similar solar radiation results in different PVT-T values. This inconsistency suggests that other factors, such as fluctuations in ambient temperature, may have influenced the panel's temperature, as these weren't controlled in real-time. Additionally, the cooling system's intermittent operation at this lower flow rate could have caused short-term variations in heat removal efficiency, affecting the temperature. Instrumentation errors, such as delays in sensor response, might also contribute to these discrepancies, particularly in changing weather conditions. While these variations are evident, they don't significantly weaken the model's reliability, as shown by the high R^2 value. This highlights the need for synchronised environmental monitoring and consistent system operation for accurate thermal performance analysis of PV systems.

Ambient Temperature

Figure 3 illustrates how the ambient temperature (°C) affects the working temperature of the modified PV panel (PVT-T) under two different cooling flow rates: 4 *l*/min (left) and 7 *l*/min (right). Each graph includes a linear trend line along with its equation and R^2 value, showing how closely the data fits the model. At the lower flow rate of 4 *l*/min, there's a strong link between ambient temperature and PV temperature, with an R^2 of 0.802. The steep slope of the line (1.98) means that for every 1°C rise in ambient temperature, the panel's temperature increases by nearly 2°C, highlighting its sensitivity when cooling is limited. In comparison, the 7 *l*/min flow rate shows a weaker correlation (R^2 = 0.672) and a gentler slope (1.07), suggesting that the panel temperature still rises with ambient temperature, but the effect is less pronounced. This suggests improved thermal control at higher flow rates. Overall, the flow rate plays a crucial role in determining how ambient temperature affects PV heating. Higher flow rates help moderate the panel temperature, making the system less reactive to changes in environmental conditions.

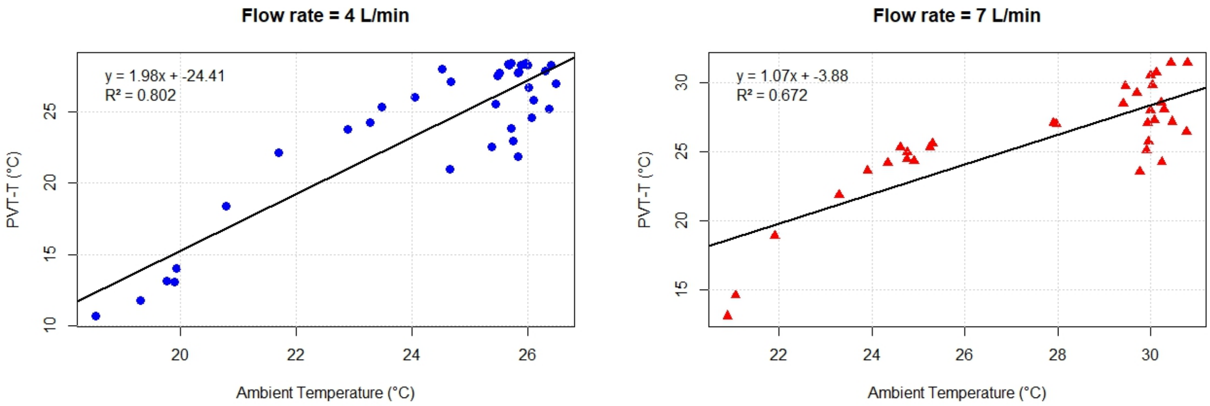

Figure 3. PVT-T vs Ambient Temperature for both flow rates
Source: prepared by authors using R

The linear relationship between ambient temperature and the PV panel's working temperature is fairly strong, especially at 4 *l*/min (R^2 = 0.802). However, there is some variability in the data, particularly at higher ambient temperatures, indicating that ambient temperature alone may not fully account for the differences in PVT-T. Other factors could be influencing the results. One possible reason is the combined or delayed effect of solar irradiance, which significantly impacts panel heating but isn't included in this model. High sunlight periods at moderate ambient temperatures might lead to unexpectedly high PVT-T values, and the opposite could also occur. Additionally, the thermal inertia of the PV system can result in delayed temperature changes. This effect may be more noticeable at lower flow rates, like 4 L/min, where cooling capacity is limited, making the system more sensitive to environmental fluctuations. Other factors, such as inconsistent cooling system operation, sensor noise, calibration drift, and timing mismatches in measurements, may also contribute to the observed variability.

The Combined Effect of Solar Irradiation and Ambient Temperature

After examining the individual effects of ambient temperature and solar irradiance on the PV panel's working temperature, both variables are now combined into a single 3D linear model to assess their joint predictive power. Figure 4 combines the two factors into a 3D model to predict the temperature of the modified PV panel (PVT-T) at two cooling flow rates: 4 *l*/min (left) and 7 *l*/min (right). Each plot displays the regression plane and the R^2 value, indicating the degree to which these factors explain temperature changes.

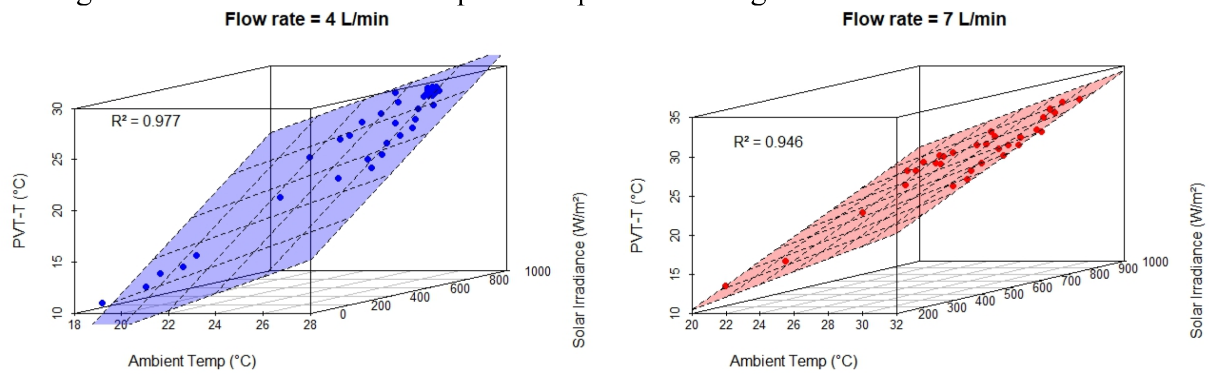

Figure 4. PVT-T vs Ambient Temperature for both flow rates
Source: prepared by authors using R

At 4 *l*/min, the model achieves an impressive R^2 of 0.977, meaning nearly 98% of the temperature variation is explained by the combined effects of temperature and solar exposure. The data points cluster tightly around the regression plane, showcasing strong predictive accuracy in these lower cooling conditions. For the 7 *l*/min flow rate, the model still performs well with an R^2 of 0.946. While this is slightly lower than at 4 *l*/min, it indicates that even with increased cooling, the panel's temperature remains significantly influenced by ambient and solar factors. These findings highlight that both ambient temperature and solar irradiance are crucial for understanding PV heating, particularly at lower flow rates, where cooling has a lesser impact. The slight drop in R^2 at 7 L/min suggests that the cooling system plays a more significant role in regulating the panel temperature, thereby balancing out the effects of the environment.

ANCOVA Analysis

To statistically assess the influence of flow rate, solar irradiance, and ambient temperature on the PV panel's temperature rise, the difference between the working temperature of the modified PV panel and the conventional PV panel (ΔT), an Analysis of Covariance (ANCOVA) was performed. The goal was first to determine whether the flow rate has a significant effect on ΔT after controlling for irradiance and ambient temperature, and especially to test whether the effect of flow rate interacts with either irradiance or ambient temperature, whether its influence depends on those environmental conditions.

Table 1. ANCOVA Summary: Main Effects Model

Factor	Df	Sum of Squares	Mean Square	F-value	p-value
Flow rate	1	30.73	30.733	50.35	1.17E-09
Solar irradiance	1	16.45	16.447	26.95	2.24E-06
Ambient temperature	1	4.66	4.665	7.64	0.00741
Residuals	65	39.67	0.61		

Source: prepared by authors using R

Table 1 presents the ANCOVA model results, which evaluate the independent effects of flow rate, solar irradiance, and ambient temperature on the temperature increase (ΔT) of the modified PV panel. Each factor significantly influences ΔT, but to different extents. Flow rate had the most pronounced impact, with an F-value of 50.35 and a p-value of less than 0.001, indicating a clear difference in PV temperature between the low (4 *l*/min) and high (7 *l*/min) cooling rates, which emphasizes its critical role in temperature regulation. Solar irradiance also significantly affected ΔT, with an F-value of 26.95 and $p < 0.001$, confirming that greater sunlight intensity raises panel temperature. Ambient temperature had a minor but still significant effect ($F=7.64$, $p =0.007$), demonstrating its contribution to heat gain, albeit less than the other two factors. Overall, these results indicate that all three variables significantly impact the working temperature of the PV panel, with flow rate being the most influential. This provides a strong statistical foundation for exploring interaction effects in future analyses.

Table 2 presents the ANCOVA results with interaction terms, allowing us to examine how the effect of flow rate changes with solar irradiance and ambient temperature. As in the earlier model, flow rate, solar irradiance, and ambient temperature all significantly influence the temperature increase (ΔT), with flow rate having the most substantial impact ($p < 0.001$). Notably, the interaction between flow rate and solar irradiance was significant ($p < 0.001$). This means that the effect of flow rate on panel temperature varies depending on the amount of sunlight available, suggesting that the cooling system operates differently under varying sunlight conditions. On the other hand, the interaction between flow rate and ambient temperature was not significant ($p = 0.20$). This indicates that the effect of flow rate remains relatively stable regardless of changes in air temperature. These results support the interpretation that both flow rate and irradiance are individually essential and interdependent in determining PV thermal performance. The non-significant interaction with ambient temperature suggests that the effect of flow rate remains relatively consistent across different ambient temperature levels.

Table 2. ANCOVA Summary: Interaction Effects Model

Factor	Df	Sum of Squares	Mean Square	F-value	p-value
Flow rate	1	30.73	30.733	67.45	1.52E-11
Solar irradiance	1	16.45	16.447	36.1	1.03E-07
Ambient temperature	1	4.67	4.665	10.24	0.00216
Flow rate × Irradiance	1	10.21	10.209	22.41	0.0000129
Flow rate × Temperature	1	0.76	0.758	1.66	0.20187
Residuals	63	28.71	0.456		

Source: prepared by authors using R

Conclusions

This study investigated the thermal behaviour of a modified photovoltaic (PV) panel equipped with an active water-cooling system comprising copper pipes and aluminium adhesive, and compared it to a conventional PV panel. We assessed how two different cooling flow rates (4 *l*/min and 7 *l*/min) affected the panel's working temperature in relation to solar irradiance and ambient temperature, using ANCOVA statistical analysis to understand the impact of these factors on flow rate.

The findings reveal that flow rate is crucial for regulating PV temperature. At lower flow rates, the panel temperature is very sensitive to changes in solar irradiance and environmental conditions. However, increasing the flow rate leads to a more stable thermal performance, reducing this sensitivity. Linear regression analyses revealed strong correlations between environmental factors and PV temperature, particularly at a flow rate of 4 *l*/min. Additionally, 3D modelling indicated that the combined effects of solar irradiance and ambient temperature account for most of the temperature variations.

ANCOVA results further confirmed that flow rate, irradiance, and ambient temperature all significantly influence PV heating. Notably, the interaction between flow rate and irradiance was significant, indicating that cooling performance changes with sunlight intensity. In contrast, no significant interaction was observed between flow rate and ambient temperature, suggesting that flow rate effects are consistent across different air temperatures.

Optimizing the cooling flow rate is essential for ensuring efficient PV operation in varying environmental conditions. These insights help design more effective cooling strategies for PV systems, particularly in high-radiation climates, and support future modelling efforts that integrate environmental data with system configuration.

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