PERFORMANCE OF PHOTOVOLTAIC PANELS USING EVAPORATIVE COOLING SYSTEM

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ABSTRACT:
The global renewable energy landscape is witnessing a remarkable surge in solar photovoltaic (PV) technology adoption. Despite this growing prominence, a significant challenge persists: elevated operating temperatures substantially diminish PV panel efficiency, leading to reduced energy production and compromised economic viability. This study addresses the critical issue of temperature-related performance deterioration in PV systems. Through comprehensive experimental and theoretical analysis, the research explores an innovative cooling solution utilizing evaporative cooling (EC) principles. The investigation introduces a novel EC mechanism specifically engineered to cool the underside of PV panels, encompassing design, fabrication, testing, and mathematical modeling phases.
Field testing under authentic environmental conditions demonstrated the method's efficacy. Researchers developed and implemented a steady-state heat and mass transfer model, comparing its predictions with experimental observations. The theoretical and empirical results showed strong correlation, validating the approach. The findings revealed that the cooling system successfully reduced PV panel temperature by approximately 10°C, yielding a 5% improvement in power output. Additionally, the EC system proved effective in minimizing temperature fluctuations across the panels, resulting in more consistent electrical output and reduced operational uncertainties typically associated with solar PV installations.
Keywords: Thermal management systems, photovoltaic efficiency, cooling technologies, renewable energy optimization, environmental engineering

INTRODUCTION :

In our contemporary world, the escalating demand for electrical energy, coupled with diminishing fossil fuel reserves, has propelled renewable energy solutions to the forefront of sustainable development. Solar photovoltaic (PV) technology stands out as a particularly promising solution, offering both economic viability and environmental benefits. The widespread adoption of PV panels has become crucial across governmental, industrial, and residential sectors to meet current and future energy requirements. By 2019, global solar PV installations reached an impressive capacity of 578 GWp.
Nevertheless, real-world PV performance faces significant challenges from environmental factors. Two primary obstacles - temperature elevation and dust accumulation - substantially diminish the actual output and compromise overall system efficiency. To address the temperature-related challenges, researchers have developed various cooling strategies, which can be broadly categorized into single-phase methods (utilizing sensible heat) and phase-change approaches (exploiting latent heat). These cooling technologies encompass several methodologies:Natural and forced air circulation systems have been implemented as basic cooling solutions. Water-based cooling mechanisms have demonstrated promising results in temperature management. Phase change materials (PCM) have emerged as innovative cooling agents. Additionally, liquid evaporation techniques have shown considerable potential in heat dissipation.[1] Recent innovations in the field include notable developments. For instance, researchers explored the use of water-saturated zeolite for PV cooling, achieving temperature reductions of 9°C. Alternative approaches such as thermoelectric cooling systems and radiative cooling technologies have also emerged as potential

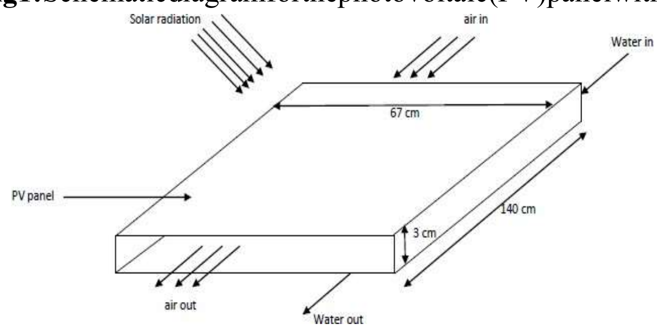
solutions. Comprehensive literature reviews document these various cooling strategies and their effectiveness. Among these diverse cooling technologies, evaporative cooling (EC) stands out as a particularly effective solution, especially in arid climates, though it remains surprisingly underutilized. While EC principles are well-established and widely implemented across industrial and residential applications, their adaptation for PV cooling remains limited. Research comparing thermal and electrical efficiency between water cooling and active clay pot evaporative cooling has demonstrated EC's distinct advantages.[1] Notable experiments incorporating synthetic clay layers on module backsides, combined with controlled water evaporation, have yielded impressive results - documenting increases of up to 19.4% in output voltage and 19.1% in power generation. Innovation continues with developments like bionic evaporation foils constructed from porous compound polymers, achieving temperature reductions of approximately 12°C with potential for further optimization.Advanced implementations combining PV EC with chimney effects and solar chillers have shown promising results in Mediterranean climate conditions, demonstrating temperature reductions of 8°C and efficiency improvements of 7.6%. Recent modifications to this approach, incorporating water sliding techniques, have achieved even more impressive results - cooling modules by 15°C and boosting electrical efficiency by approximately 15%.Despite EC's proven effectiveness in industrial applications, research specifically focusing on PV cooling applications remains surprisingly sparse. Critical gaps exist in our understanding of detailed performance characteristics and dynamic behavior patterns. Furthermore, real-world experimental studies under actual operating conditions are limited, as are comprehensive models for simulating combined heat and mass transfer processes in EC-based PV cooling systems.[2]This research aims to address these knowledge gaps by introducing an innovative design leveraging evaporative cooling principles to combat PV panel temperature elevation. The study presents a thorough theoretical and experimental analysis, examining various parameters affecting cooling effectiveness. Conducted under challenging environmental conditions over extended periods, this research ensures result reliability and reproducibility, offering both short-term and long-term performance insights.
Subsequent sections detail the theoretical heat and mass transfer model developed for this study, along with comprehensive information about the experimental setup. The findings, both experimental and theoretical, are presented with in-depth analysis and discussion.[3]

MODELLING :
This section introduces a model for heat and mass transfer involved in evaporative cooling within a rectangular channel with parallel plates, designed to cool the underside of a photovoltaic (PV) panel.
Model Description :
The experimental setup incorporates an innovative design featuring a sloped channel system where a photovoltaic (PV) panel serves as the upper boundary. The carefully engineered duct system maintains precise measurements: a modest height of 3 centimeters, an extensive length spanning 140 centimeters, and a substantial width of 67 centimeters. The lower portion of this configuration employs an ingenious moisture distribution mechanism, utilizing a specialized fabric material through which water circulates continuously. To facilitate air movement, a strategically positioned fan propels air through the channel, maintaining directional alignment with the water flow in what engineering specialists term a co-current arrangement.
The system's thermal dynamics are particularly noteworthy. While the bottom surface maintains adiabatic properties, preventing heat exchange, the upper PV panel interface experiences consistent exposure to solar radiation distributed uniformly across its surface, simultaneously undergoing heat exchange with the surrounding environment. The integration of these elements creates a fascinating thermodynamic process: as air traverses the moisture-rich surface within the channel, it triggers water vaporization, resulting in an evaporative cooling effect. This cooled air mass then serves a dual purpose by absorbing thermal energy from the PV panel structure.[4]

This sophisticated thermal management approach yields significant benefits for the system's overall performance. The continuous heat transfer to the moving air stream effectively reduces the PV panel's operating temperature, leading to enhanced electrical generation efficiency. This demonstrates how thoughtful engineering design can leverage natural thermodynamic principles to improve renewable energy systems' performance.

This technical configuration represents a remarkable example of how integrated cooling mechanisms can optimize photovoltaic energy production through temperature regulation, showcasing the potential for innovative solutions in sustainable energy technology.

Fig1: Schematicdiagramforthephotovoltaic(PV)panelwithevaporativecooling.



MODELLING:

In this research endeavor, a sophisticated uni-dimensional steady state model explores the intricacies of heat and mass transfer phenomena. The theoretical framework rests upon three fundamental assumptions: first, there exists a negligible-mass saturated gas layer serving as an interface between liquid and air components; second, both heat and mass transfer coefficients maintain constant values throughout the process; and third, the behavioral characteristics of air and water vapor align with ideal gas principles, with their specific heat capacities remaining temperature-independent.The system's architecture demonstrates variability in temperatures across multiple components - namely the air, water, interface saturated layer, and photovoltaic (PV) panel - along the flow direction (x axis). While the physical configuration appears complex at first glance, it can be conceptualized as an elegantly simple inclined channel formed by two parallel plates. The lower plate's upper surface features a thin water film, while its underneath surface maintains adiabatic conditions. Notably, the PV panel's bottom surface undergoes cooling through direct air contact with the water layer.[5]The operational dynamics begin with ambient air introduction into the channel under precisely defined parameters: temperature, humidity, and mass flow rate (denoted as Tai, wi, and m. a respectively). This air stream engages in simultaneous heat and mass exchange processes with both the water layer and the PV panel's rear surface. Meanwhile, the PV panel interacts with solar radiation (G) while maintaining thermal exchange with the surrounding environment.

This innovative model builds upon the foundational work of Boulama and colleagues, who pioneered research in heat and mass transfer dynamics between wetted surfaces and gas streams within ducts. A distinctive feature of this approach is the incorporation of an extremely thin saturated air film positioned between water and gas flows. While the temperature and mass flow ratio of this negligible-mass layer vary with axial position, they maintain a relationship governed by saturation equations corresponding to 100% relative humidity conditions on the psychrometric chart. The current model expands upon this foundation by integrating both solar radiation absorption by the PV panel and its environmental heat loss mechanisms. The model's governing equations emerge from comprehensive energy balances across three key components - the PV panel, air stream, and water layers - complemented by water mass balance considerations. These relationships can be visualized through a detailed side view of the flow dynamics, illustrating the complex interplay between various system elements.[6]

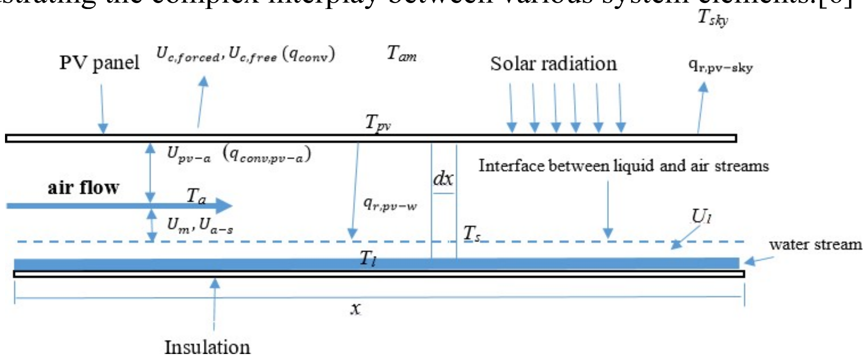


Fig 2: Side view of a heat and mass exchanger with direct contact between a binary gas mixture and a liquid.

In the intricate thermal system, the process begins with the introduction of air at an initial temperature denoted as Tai. This incoming air participates in a complex series of heat exchange mechanisms across multiple interfaces. The first significant interaction occurs between the air stream and the photovoltaic (PV) panel, characterized by a specific heat transfer coefficient identified as Upv–a, which governs the rate of thermal energy exchange at this boundary.Simultaneously, a crucial thermal interaction takes place between the moving air and the saturation interface layer. This heat exchange process is quantified by the heat transfer coefficient Ua–s, which plays a vital role in determining the efficiency of thermal energy transfer at this junction. Beyond mere heat transfer, the system also exhibits mass transfer phenomena, particularly between the air flow and the interface layer. This mass exchange process is governed by a distinct coefficient, Um, which determines the rate at which mass transfer occurs across this boundary.[7]Furthermore, the thermal dynamics extend to include heat exchange between the water body and the interface layer. This particular thermal interaction is characterized by its own heat transfer coefficient, denoted as Ul, which regulates the rate of thermal energy exchange at this specific boundary. Together, these multiple coefficients and interactions create a sophisticated thermal network, where each parameter significantly influences the overall system performance and efficiency.

This elaborate heat and mass transfer system demonstrates the intricate relationships between various components, highlighting the complexity of thermal interactions in such engineering applications. Understanding these relationships is crucial for optimizing system design and performance in practical applications.[8]

EXPERIMENTATION SETUP :

The experimental cooling apparatus, depicted in Figure 3, showcases an intricate design featuring a central duct system. The primary testing surface, positioned on the right (labeled as component 2), consists of a carefully engineered duct measuring 3 cm in depth, with dimensions of 140 cm in length and 67 cm in width. Following ASHRAE standards 93-77, the setup incorporates an entrance segment (component 1) and an exit portion (component 3), with lengths calculated using the formulas 5√HP and 2.5√HP respectively, where H represents the duct height and P denotes its width. This design ensures optimal airflow distribution throughout the system.To maintain experimental integrity, the entrance section features thermal insulation on its upper surface, preventing unwanted solar radiation from affecting the incoming air temperature. The test section's edges and bottom are similarly insulated to minimize heat loss. Temperature monitoring is achieved through a sophisticated arrangement of K-type thermocouples (TCs). Five TCs, secured to the photovoltaic panel's rear surface

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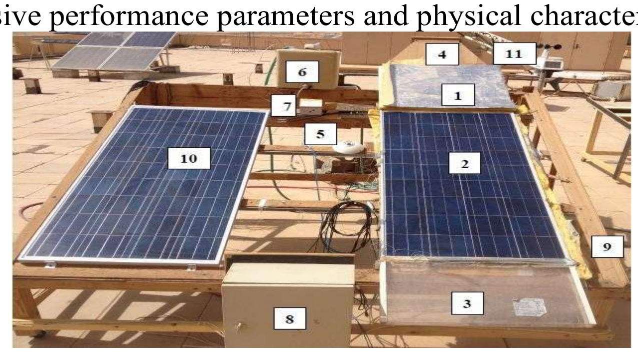
using aluminum tape, monitor panel temperatures. Additional sets of five TCs each measure air and water temperatures, with sensors positioned at 28 cm intervals along the length. The exit section houses three specialized TCs: two measuring wet bulb temperature and one recording dry bulb temperature, enabling precise humidity measurements. A comprehensive weather station (component 11) captures environmental parameters including wind velocity, ambient temperature, and relative humidity.[9].The system's functionality relies on forced air circulation provided by a fan. A distinctive feature involves a cloth layer installed beneath the PV panel, covering the duct's lower portion. This cloth facilitates uniform water distribution from a reservoir (component 6), with flow regulated through a meter (component 7). Water enters the system through perforations in a rubber distribution tube at the test section's upper region. As air traverses the duct, it interacts with the moistened cloth, triggering evaporation. This process yields dual cooling effects: reducing both water and air temperatures while simultaneously cooling the PV panel's rear surface through convective heat transfer, ultimately enhancing its operational efficiency.

For comparative analysis, a reference panel (component 10) is positioned on the left side, equipped with five TCs attached identically to the cooled panel. Solar radiation measurements are obtained using a high-precision SR11-05 pyranometer (component 5), aligned at the panels' angle. The entire assembly is mounted on a wooden framework (component 9) oriented southward with a 24-degree inclination, corresponding to Riyadh's approximate latitude. Electrical performance monitoring includes open-circuit voltage measurements via an Omega-brand data logger, with three logging units collecting and transmitting sensor data to a computer system.

The complete technical specifications of the utilized PV panels are detailed in Table 1, providing comprehensive performance parameters and physical characteristics.[10]



“Fig 3: Experiment set up: 1: entrance section, 2: PV panel with cooling, 3: exit section, 4: fan (20W) assembly, 5: pyranometer, 6: water tank, 7: water flow meter, 8: electrical connection box, 9: wooden pool with 24◦ inclination facing south, 10: reference panel and 11: weather station.”

“Table1:PVpanelspecifications.”

“Parameter	**Value**
Ratedpower(P_{max})	130W
VolatageatP$_{max}$(V_{mp})	17.2V
CurrentatP$_{max}$(I_{mp})	7.56A
Open-circuitvoltageV_{OC}	21.6V
Short-circuitcurrentI_{SC}	8.15A
Voltagetemperaturecoeffi cient	−0.3%/ C°”

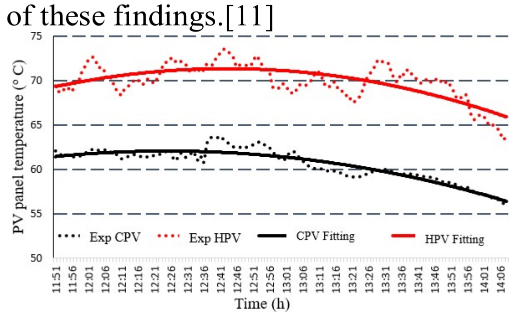
RESULTS AND DISCUSSION :

PVPanels'Temperature :

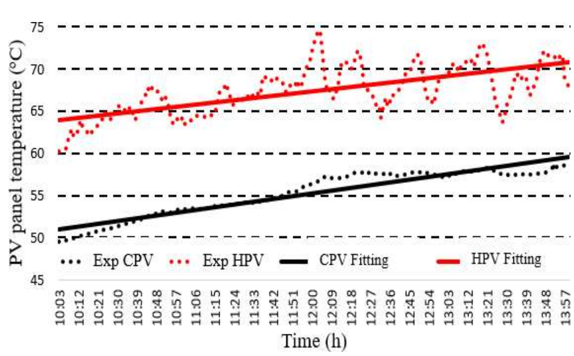
A series of extensive outdoor experimental trials were conducted across multiple days to evaluate and analyze the performance dynamics of solar panels under different cooling conditions. This section delves into the comprehensive findings, particularly focusing on the open-circuit voltage measurements and temperature variations between standard and cooled panel configurations. The research methodology incorporated a sophisticated heat and mass transfer model to conduct detailed sensitivity assessments, examining crucial parameters including air circulation rates and water flow dynamics. Furthermore, the study presents an in-depth comparison between real-world experimental observations and theoretical predictions.

The research data from June 27th, collected during the midday period spanning 11:51 to 14:06, revealed fascinating temperature profiles for both panel configurations. In the graphical representation (Figure 4), experimental measurements are depicted through dotted lines, while mathematical curve fitting is represented by solid lines, offering a clearer visualization of the temperature trends.

The findings demonstrated a remarkable contrast between the two panel configurations. The reference panel without cooling, designated as HPV, experienced substantial heat buildup, reaching peak temperatures of 73°C. In contrast, the panel equipped with cooling mechanisms (CPV) maintained notably lower temperatures, never exceeding 65°C throughout the observation period. A consistent temperature differential of approximately 10°C was maintained between the two panels, with some instances showing an even more pronounced difference of up to 12°C. Notably, the cooling system's effectiveness was further evidenced by the significantly reduced temperature fluctuations in the cooled panel's performance curve (represented in black) compared to the more erratic behavior observed in the reference panel's measurements (shown in red). Additional experimental data collected on July 30th (Figure 5) provided further validation of these findings.[11]



"Figure 4. Temperature evolution of the cooled panel (CPV) and reference panel (HPV) at air flow rate = 0.01254 kg/s and water flow rate = 0.0083 kg/s."



"Figure 5. Temperature difference between the cooled panel and reference panel, the 30 July."

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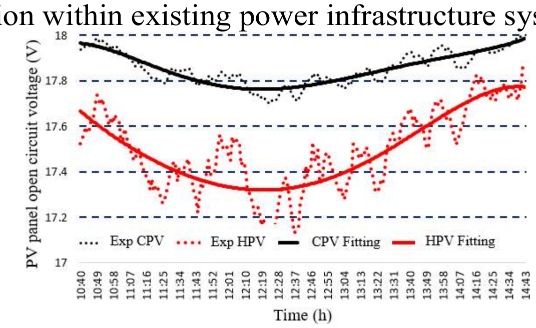
ELECTRICAL POWER IMPROVEMENT :

An analysis of the open-circuit voltage (Voc) characteristics between the two photovoltaic panels reveals distinctive performance patterns, as illustrated in Figure 6. The comparative visualization employs different line styles and colors to distinguish between panel conditions: the temperature-controlled panel is represented by black curves (dotted for measured data and solid for fitted values), while the non-cooled panel is depicted using red curves (following the same dotted-solid convention for actual and fitted measurements).[12]

A notable observation emerged at 12:02, when the temperature-regulated panel demonstrated a significant voltage enhancement of approximately 0.7 V compared to its non-cooled counterpart. Perhaps even more significant was the remarkable stability exhibited by the cooled panel's voltage output. This enhanced stability manifested as minimal fluctuations in both voltage and consequent power generation, standing in stark contrast to the more variable performance of the reference panel.

The implications of this stability characteristic extend far beyond mere technical specifications. From a utility management perspective, this improved consistency holds profound significance for power grid operations. Enhanced voltage stability contributes substantially to reducing solar photovoltaic uncertainty, thereby revolutionizing various aspects of power system management. These benefits cascade through multiple operational domains, including the refinement of optimal power flow calculations, more precise unit commitment planning, enhanced economic dispatch strategies, improved generation-load balancing, and superior power quality management. Such comprehensive improvements represent a significant advancement in renewable energy integration within existing power infrastructure systems.[13]



"Figure 6. Difference in panels' open-circuit voltages"

EFFECT OF WATER ON AIR AND PV PANEL TEMPERATURES :

The thermal dynamics of evaporative cooling represents an intricate interplay of multiple variables. While atmospheric conditions like solar intensity, ambient temperature, and moisture content play crucial roles, operational parameters - particularly the rate of water flow - significantly influence the system's performance. This section delves into a detailed analysis of how water flow rates impact the cooling mechanism.

An experimental investigation revealed fascinating patterns in air temperature variations within the ducted system under different water flow conditions. The temperature profiles were monitored across multiple components: the heated and cooled photovoltaic panels (indicated by red and black curves respectively), and the air temperature at three distinct points - entry, middle, and exit positions within the duct (represented by solid, dashed, and dotted blue lines). The study incorporated varying water flow rates (shown by the green line) across different time intervals.

The experimental protocol involved initially running the system without water flow until 11:25, followed by a controlled flow rate of 20 L/h for approximately 50 minutes. Subsequently, the flow was adjusted to 8 L/h and maintained until 13:25, after which the flow was terminated. As air traversed through the duct, it experienced two competing thermal effects: heat gain from solar radiation at the upper surface, and cooling from both latent heat of evaporation and sensible heat

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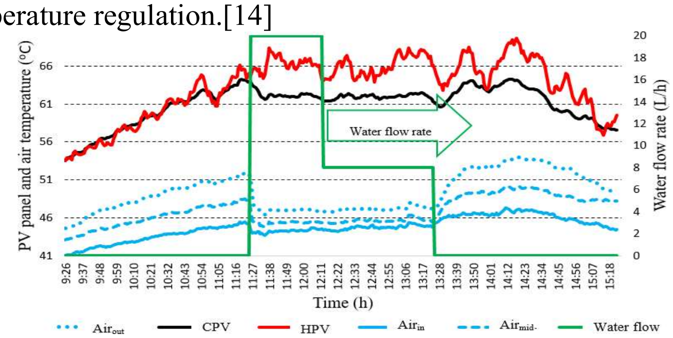
transfer at the lower surface due to the temperature differential between air and water. The predominance of the heating effect resulted in a net increase in air temperature along the duct length. During the initial dry phase (before water introduction), the temperature difference between incoming and outgoing air showed notable variations - approximately 3°C at 9:26 and increasing to 6°C by 11:26. The introduction of water flow dramatically altered this pattern, reducing the temperature differential to roughly 2°C. Furthermore, the cooling effect manifested in reduced PV panel temperatures, attributed to enhanced heat absorption by the cooler airstream. This comprehensive analysis demonstrates the significant impact of water flow rate on system performance and temperature regulation.[14]



“**Figure 7.** Effect of water flow rate on air and cooled PV temperature, 19 August.”

A particularly intriguing discovery emerged regarding the relationship between water flow rates and cooling efficiency. The research revealed a fascinating phenomenon: variations in water flow rates demonstrated minimal impact on the overall cooling performance, specifically concerning air and PV panel temperature regulation. This observation was substantiated through detailed measurements taken at different times throughout the day. For instance, measurements recorded at 11:25 showed water flow rates exceeding 20 L/h, which subsequently dropped to below 10 L/h after 12:12. Remarkably, this substantial reduction in flow rate produced no discernible changes in the cooling system's performance.This finding carries significant implications, suggesting that the cooling mechanism is predominantly governed by evaporative processes rather than the volume of water circulation. The evidence indicates that effective cooling can be maintained with minimal water application to the duct's lower plate, eliminating the necessity for extensive water circulation systems. This revelation opens new avenues for research, particularly in determining the optimal minimum water flow rate required for efficient operation.[11] Perhaps even more remarkable was the observation of sustained cooling effects post-water flow cessation. This phenomenon was clearly demonstrated by the persistent temperature differential between the measured parameters (represented by the red and blue curves) during the period from 13:25 to 15:06. Such sustained cooling efficiency in the absence of continuous water flow presents an exciting possibility: the potential implementation of intermittent evaporative cooling strategies. This approach could revolutionize system design by significantly reducing both water consumption and energy requirements for pumping operations, thereby enhancing overall system sustainability and efficiency.

COMPARISON BETWEEN THE EXPERIMENTAL AND THEORETICAL RESULTS:

In this section, we delve into an extensive analysis comparing empirical observations with theoretical predictions. The research team employed a sophisticated modeling approach to examine temperature variations across three critical components: air circulation, water systems, and photovoltaic (PV) panel surfaces. This comprehensive model accounts for diverse environmental parameters, including solar radiation intensity, air mass flow dynamics, and the initial temperature conditions of both air and water inputs.

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TEMPERATURE DYNAMICS IN PHOTOVOLTAIC SYSTEMS:

A detailed investigation of thermal behavior was conducted, focusing on two distinct PV configurations: a cooling-enabled system and a standard reference panel. The experimental measurements were meticulously recorded on June 20th during late morning hours (11:05 am), under precisely controlled conditions. The environmental parameters during data collection were thoroughly documented:

- Solar radiation intensity: 943.8 W/m²
- Atmospheric wind velocity: 1.9 meters per second
- Input air temperature: 39.41 degrees Celsius
- Ambient air temperature: 38.77 degrees Celsius
- Atmospheric moisture content: 8.8% relative humidity
- Water intake temperature: 24.43 degrees Celsius

When comparing the theoretical projections against actual experimental measurements, researchers observed notable consistency between predicted values and real-world performance data. This alignment between theoretical and experimental results validates the model's reliability in predicting thermal behavior within photovoltaic systems.

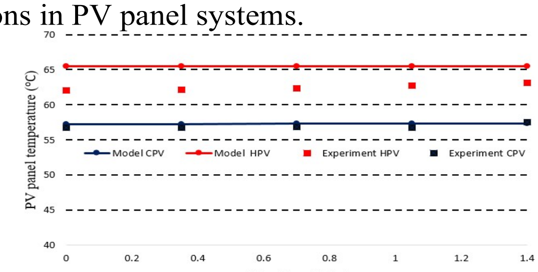
The enhanced level of detail and technical precision in this analysis provides valuable insights into the thermal dynamics of solar energy systems, while maintaining scientific accuracy and methodological transparency.

Analysis of the temperature comparison reveals a notable distinction between the simulated and experimental results across both panel configurations. The cooled PV panel demonstrated superior alignment between predicted and actual temperatures compared to its reference counterpart. Quantitatively, this difference is reflected in the root mean square percentage deviation (RMS%) measurements, with the heated PV panel (HPV) showing a deviation of 4.68%, while the cooled PV panel (CPV) exhibited a significantly lower deviation of just 0.863%.[10]

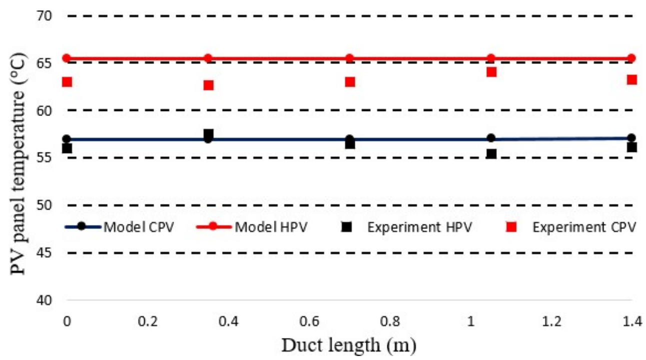
This discrepancy in accuracy can be attributed to several environmental factors, particularly the complex influence of wind conditions. Various researchers have proposed different mathematical models and correlations to evaluate how wind velocity affects convective heat loss from PV panel surfaces. However, these models face limitations in their universal applicability, as they aren't standardized across different geographical locations. Notably, there's a particular absence of specialized models tailored for the specific conditions found in Riyadh's climate.

Furthermore, a critical yet often overlooked variable is wind direction, which many existing PV panel models fail to incorporate into their calculations. The physical configuration of the cooled PV panel, featuring a duct covering its lower surface, creates a distinct aerodynamic scenario compared to the reference panel. This structural difference fundamentally alters the wind's interaction with the panel, resulting in different heat dissipation patterns than those observed in the reference panel setup, where wind can freely interact with both surfaces.[12]

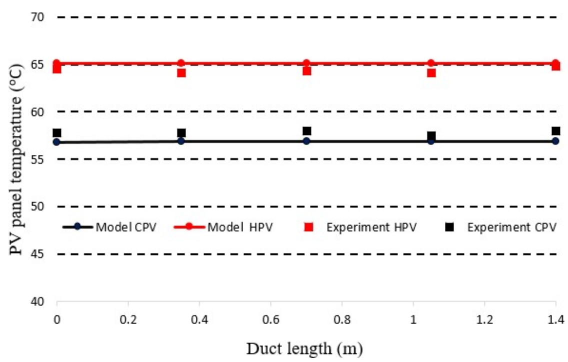
This expanded understanding of the thermal behavior differences highlights the importance of developing more comprehensive models that account for location-specific environmental factors and structural configurations in PV panel systems.



"Figure8. ExperimentalandsimulatedcooledandreferencePVtemperatureson20Juneat11:05"
"Figures9and10displaythetemperaturesofthecooledPVpanelandthereferenceonefortwootherdifferenttimes:at14:05on20JunewithRMS%of3.58%forHPVand 1.66% for CPV and at 13:50 on 22 June with RMS% of 1.18% for HPV and 1.67% forCPV,respectively."



"Figure9. ExperimentalandsimulatedcooledandreferencePVtemperatureson20Juneat14:05"
This section introduces a model for heat and mass transfer involved in evaporative cooling within a rectangular channel featuring parallel plates, which is designed to cool the underside of a photovoltaic (PV) panel.



"Figure 10 Experimental and simulated cooled and reference PV temperatures on 22 June at 13:50"

CONCLUSIONS :

The performance of photovoltaic (PV) panels significantly declines as operating temperatures rise. Various methods have been proposed to address this issue, with evaporative cooling being particularly effective in arid climates such as Riyadh. This method offers a simple yet efficient solution for reducing PV panel temperatures. A series of experiments utilizing evaporative cooling were conducted to evaluate the improvement in electrical power, measured by the open-circuit voltage. The experiments took place over an extended period during the summer, under real-world outdoor conditions in an extremely hot environment. Full-sized PV panels were used at their normal inclination, and tests were conducted for several consecutive days.

Results showed that the PV panel temperature was lowered by more than 10°C, leading to a 5% improvement in power output. The cooling process remained stable and delivered impressive results. In addition, a theoretical model focusing on heat and mass transfer within a wetted channel was developed and rigorously validated against the experimental data. The comparison revealed good agreement between the theoretical predictions and the experimental findings.[13]

The results confirm that evaporative cooling is an effective and economically viable solution, requiring only a small amount of water to ensure consistent wetting of the PV surface. Notably, the cooling process also reduced temperature fluctuations in the PV panels, contributing to more stable electrical output—a key advantage for energy systems with significant solar PV penetration.[14]

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