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IMPROVED ENERGY CONVERSION IN SOLAR PV PANELS USING DIRECT WATER COOLING AND OPTICAL REFRACTION: A DUAL-MODE STUDY

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Abstract Photovoltaic (PV) panels, while essential for harnessing solar energy, exhibit significant efficiency degradation at elevated temperatures due to their negative temperature coefficient. Traditional solar panels convert only 5–17% of incident solar radiation into electrical energy, with the majority dissipated as heat. This study explores an innovative approach to enhance both electrical performance and thermal recovery by cooling the PV panel from its top surface using a direct contact water layer. An experimental setup involving 70 Wp PV panels inclined at 20°, with and without cooling, was implemented at Bhavnagar, India. Computational Fluid Dynamics (CFD) simulations were performed using ANSYS to predict panel temperatures and validate experimental results. The cooling system, operating at 1 LPM and 2 LPM, demonstrated significant temperature control, reducing peak panel temperatures from 76°C to below 40°C. Concurrently, the electrical output improved by 10–20%, while thermal energy recovery reached up to 139.56 W. A novel aspect of this work is the quantification of optical enhancement due to light refraction through the water layer, contributing an additional 7.6% to power output. The integration of water cooling not only elevated electrical efficiency but also enabled potential thermal energy reuse in processes like reverse osmosis, boosting the overall energy efficiency from 6.68% to 40.42%. This interdisciplinary approach signifies a sustainable advancement in PV system design by effectively merging power generation and heat recovery. The findings advocate for scalable applications in large PV installations aiming for enhanced energy conversion and multipurpose utility. keywords: Solar irradiance optimization

Keywords: Water-cooled PV panel, Photovoltaic output, Optical enhancement, Thermal energy harvesting

1.Introduction

Solar photovoltaic (PV) systems are increasingly adopted due to their clean and renewable nature. However, PV efficiency is adversely affected by high operating temperatures. For every 1°C rise, typical silicon PV cells lose 0.4–0.5% of their efficiency (Skoplaki & Palyvos, 2009) [1]. The major fraction of incident solar radiation (83–95%) is not converted into electricity but rather dissipated as heat (Said et al., 2015) [2]. This thermal buildup necessitates innovative cooling strategies to enhance PV performance and longevity.

Active and passive cooling techniques have been studied to mitigate this issue. Chander et al. (2015) [3] analyzed water cooling and phase change materials (PCMs) for heat mitigation. Farshchi Tabrizi et al. (2010) [4] demonstrated water spray cooling could lower PV panel temperatures by over 20°C. Similarly, Odeh and Behnia (2009) [5] proposed that hybrid photovoltaic/thermal (PV/T) systems offer dual benefits—improved electrical output and usable thermal energy.

Kordzadeh (2010) [6] found that panel cooling with water increased power output by 15%. Hussein et al. (2014) [7] introduced a thermosyphon-based PV/T system, which improved thermal and electrical output. Kalogirou (2004) [8] comprehensively reviewed solar thermal collectors and their integration with PV systems. They emphasized that hybrid systems could significantly enhance total energy utilization.

Ibrahim et al. (2011) [9] introduced novel water-flow cooling techniques, highlighting up to 30% power enhancement. Bakelli et al. (2011) [10] discussed the integration of PV with micro-cooling and emphasized localized heat removal as a vital design consideration. Sandnes and Rekstad (2002) [11] presented glass-covered PV modules with air and water cooling that achieved a balance between transparency and insulation.

Touafek et al. (2017) [12] studied coupled optical-thermal-electrical models for PV/T systems, stressing on design optimization. Many researchers including Teo et al. (2012) [13], Tripanagnostopoulos et al. (2002) [14], and Krauter (2004) [15] provided empirical data on water cooling methods, all confirming the beneficial impact on efficiency. Agrawal and Tiwari (2010) [16] proposed air duct arrangements for indirect cooling, achieving significant output improvements in desert climates.

Nonetheless, most literature overlooks the optical influence of water cooling layers. In this study, refraction of incident sunlight through the water layer was considered as an additional contributor to performance improvement. According to Snell's Law, a change in the angle of solar incidence occurs when light passes through water ($n=1.333$) from air ($n=1.0$), straightening solar rays and reducing angular losses.

Nafchi et al. (2015) [17] found that angled radiation contributes to significant loss in photovoltaic generation. In contrast, Hossain et al. (2015) [18] confirmed that optical modifications like concentrating or redirecting light enhance efficiency. Recently, Gaur and Tiwari (2019) [19] utilized nanofluids in PV cooling for their thermal and optical properties, while Delgado et al. (2020) [20] demonstrated enhanced PV/T efficiency using hybrid PCM-water systems.

Despite considerable contributions, a gap remains in validating temperature control and energy recovery using top-surface water cooling supported by CFD simulations. To address this, the present study experimentally evaluates the influence of water cooling on PV performance and validates it using ANSYS CFD, while accounting for optical improvements via refraction.

Therefore, this research aims to:

- Evaluate the electrical and thermal performance of a PV panel cooled from the top with flowing water.
- Validate the experimental results using CFD-based temperature modeling.
- Quantify the contribution of refraction due to the water layer in efficiency enhancement.
- Propose practical use of recovered thermal energy for processes like reverse osmosis.

By integrating theoretical and empirical analyses, this study contributes to the broader development of sustainable and efficient solar energy systems.

2. Materials and Methodology

2.1 Experimental Setup

The experimental work was conducted in Bhavnagar, India (21.7600°N, 72.1500°E), utilizing two identical 70 Wp monocrystalline PV panels—one with a water-cooling system and the other without any cooling for control. Both panels were mounted at a fixed tilt of 20°, facing south, optimizing solar irradiance capture specific to the location.

To cool the PV panel, a direct contact water-cooling system was designed. A perforated pipe, with 2 mm diameter holes, was fixed above the panel to distribute water evenly across the surface. Water flow rates of 1 LPM and 2 LPM were tested. The back and side surfaces of the PV panel were thermally insulated using calcium silicate to prevent heat loss and promote efficient heat recovery from the top surface.

Temperature measurements were taken using thermocouples at various panel locations. Solar irradiance was recorded using a Kipp & Zonen CM4 pyranometer, while electrical performance was measured using a rheostat (variable resistance) to obtain voltage-current (V-I) characteristics.

The warm water existing the system was collected in an open tank and recirculated using a DC-powered Kemflo pump, simulating a closed-loop cooling system. Two pumps were operated simultaneously for 2 LPM experiments.

2.2 Computational Fluid Dynamics (CFD) Simulation

ANSYS Fluent software was employed for numerical simulation. The simulation model incorporated the layered structure of the PV panel (Table 1) including Tedlar, EVA, PV cells, ARC coating, and tempered glass. The material properties were integrated into the model to solve transient energy equations under boundary conditions representing real solar insolation and ambient temperatures.

Assumptions used in CFD modeling included:

- Constant water film thickness of 2 mm.
- Steady water flow.
- Variable water temperature due to solar absorption.
- 50% IR, 40% visible, and 10% UV spectral distribution of solar radiation.
- Glass transmissivity: 80%, absorptivity: 20%, and no reflectivity.
- Radiation heat transfer modeled using Stefan-Boltzmann law.

Table 1: Physical Properties of The Constituents Of PV Panel

Layer	Thickness t (m)	Thermal Conductivity K (w/m K)	Density (kg/m ³)	Specific heatCp (J/kg K)
Tedlar	0.0001	0.2	1200	1250
Rear contact	10X10 ⁻⁶	237	2700	900
EVA	500X10 ⁻⁶	0.35	960	2090
PV Cell	225X10 ⁻⁶	148	2330	677
ARC	100X10 ⁻⁹	32	2400	691
Glass	0.003	1.8	3000	500

Heat accumulation was modeled with the energy balance equation:

$$\rho C_p \frac{dT}{dt} = q_{sw} - q_{lw} - q_{conv} - P_{out}$$

where:

- ρ, C_p : Density and specific heat capacity of panel materials
- q_{sw}, q_{lw}, q_{conv} : Heat from shortwave, longwave radiation, and convection
- P_{out} : Electrical power output

Mesh generation was performed with high orthogonal quality (1.0) and zero skewness. Two geometries were simulated: one with 8 inlets/4 outlets and another with a single slit inlet/outlet to mimic the actual panel setup. Simulation results were analyzed for temperature distribution, velocity profiles, and validation against experimental data.

2.3 Optical Analysis

An additional optical analysis was conducted using Snell's Law to compute the change in incident angle of sunlight due to the presence of a water layer:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

This helped quantify the refraction effect, which reduced the angular span of radiation, improving direct solar absorption on the panel surface. The refractive index of air was assumed to be 1.0 and water 1.333.

This integrated methodology combining experimentation, simulation, and theoretical optical modeling offers a comprehensive assessment of PV panel performance under cooling.

3. Results and Discussion

This section evaluates the thermal and electrical performance of the solar photovoltaic (PV) panels under two cooling conditions—without cooling (control) and with top surface water cooling at 1 LPM and 2 LPM flow rates. Both experimental and Computational Fluid Dynamics (CFD) simulations were conducted for detailed validation. The discussion also highlights the influence of light refraction and presents a thorough energy efficiency analysis.

3.1 Thermal Profile and Simulation Validation

The primary objective was to evaluate the cooling effectiveness on panel temperature. Figure 1 illustrates the experimental and simulated temperature distribution over the back and top surfaces of the PV panel. With back insulation and active top cooling, the panel's average temperature was maintained around 27–36°C, while hotspots at the bottom corners (where water stagnates) reached 60°C. This is significantly lower compared to the control panel (without cooling), which reached up to 76°C at peak solar irradiance.

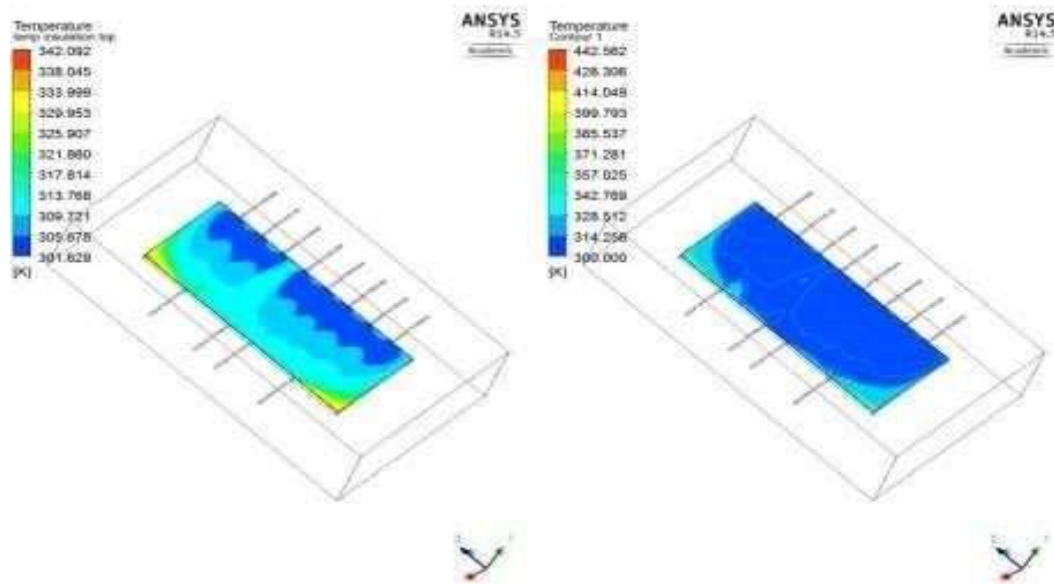
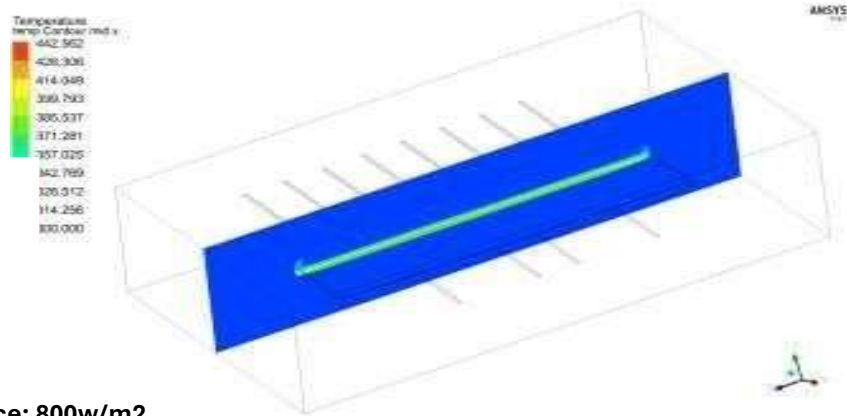


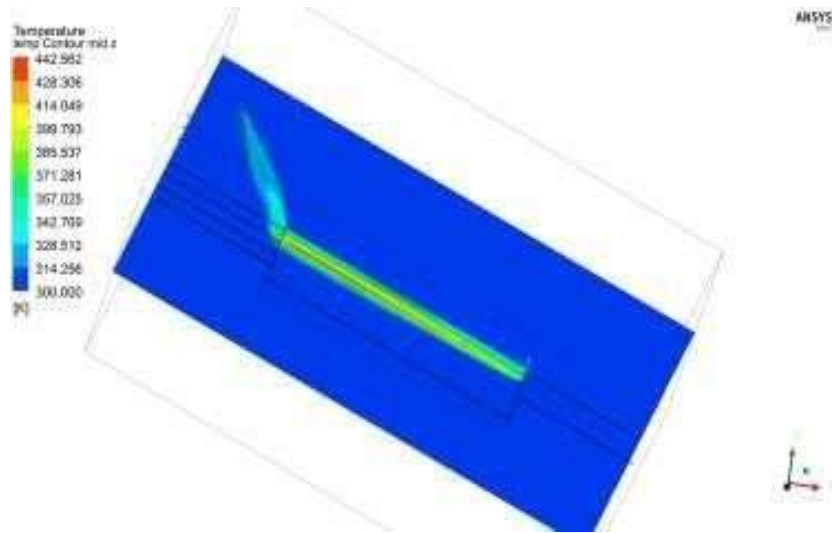
FIGURE 1: Temperature of photovoltaic panel back surface and top surface

CFD simulation results (Figure 1 and Figure 2) mirrored experimental findings closely, verifying the accuracy of the simulation model. A key insight is the efficiency of top-surface cooling in maintaining thermal uniformity, particularly evident in the z-axis cross-section temperature profiles (Figure 3).



Direct solar irradiance: 800w/m2

FIGURE 2: Temperature of cross section of photovoltaic panel



Direct solar irradiance: 800

FIGURE 3: Temperature of cross section in z axis of photovoltaic panel

3.2 Water Flow Velocity Profile

Figure 4a and Figure 4b show the velocity vectors of water above the PV panel. The velocity remains below 0.05 m/s over the panel surface but increases significantly at the inlets and outlets. With 2 LPM flow (Figure 4c), the velocity increases more rapidly at the outlet compared to 1 LPM. This improved convective heat removal leads to enhanced panel cooling.

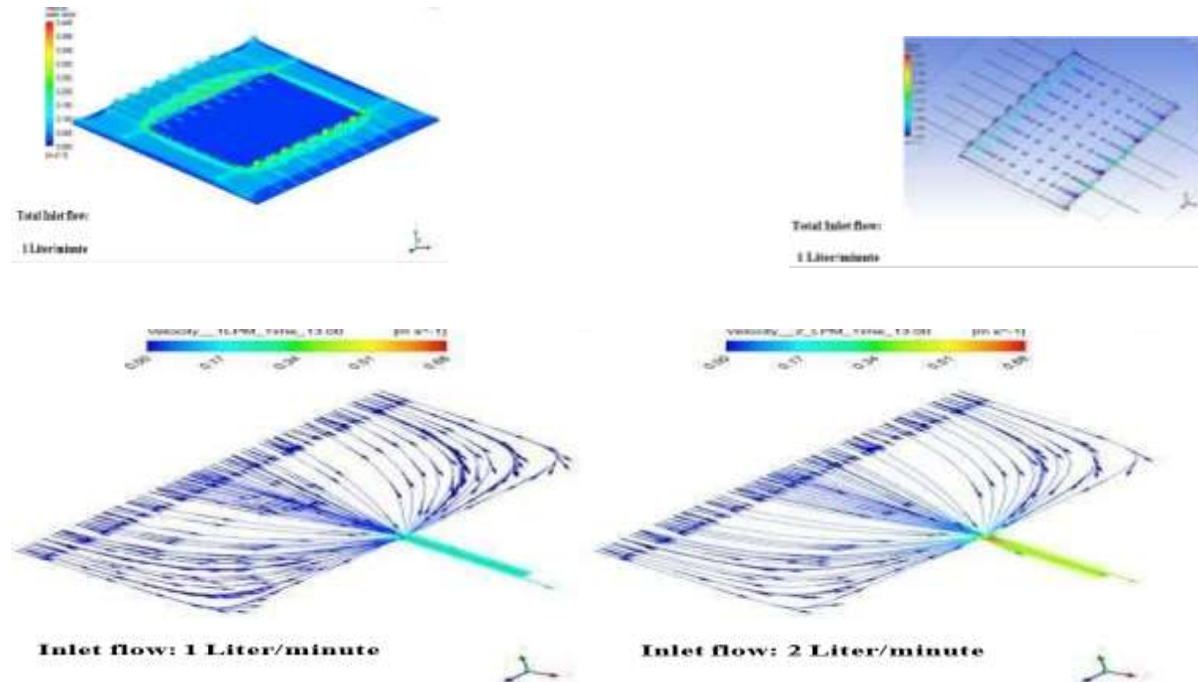
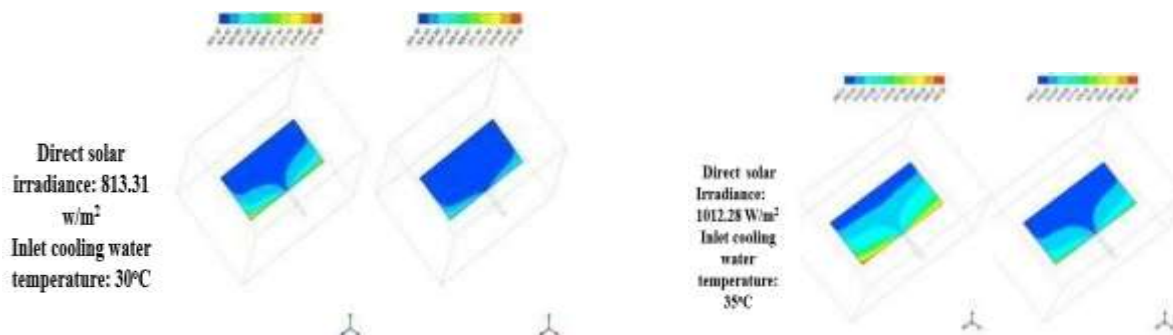


Figure: 4a,4b and 4c: Water Flow Velocity Profile

3.3 Time-wise Panel Temperature Comparison

The effect of water flow on panel temperature was further analyzed at different times of the day. Figures 5A and 5B present a comparative simulation at 10:00 Hrs and 13:00 Hrs, showing a significant increase in panel temperature during peak irradiance if cooling is not applied. Figure 5C and Figure 5D confirm that without cooling, panel temperatures rise well above 70°C during noon, while with cooling, they remain below 40°C.



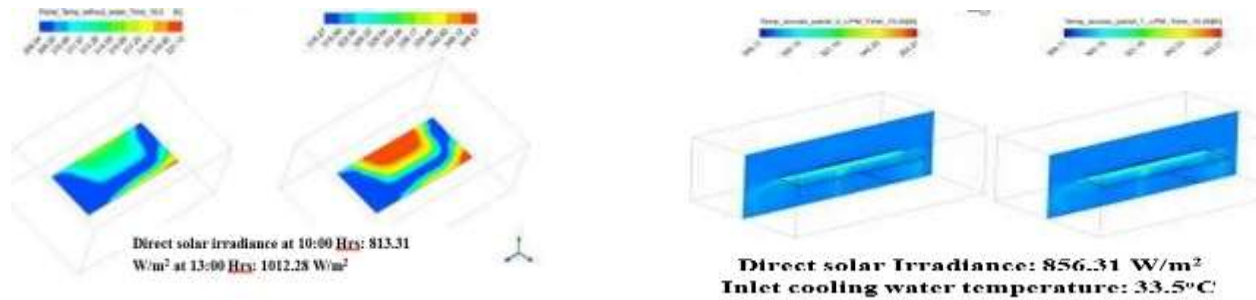


Figure:5 A, B, C, D Time-wise Panel Temperature Comparison

Natural convection effects are highlighted in Figure 6, which shows that air warmed by the panel creates a temperature gradient—higher temperatures at the top due to buoyancy-driven airflow.

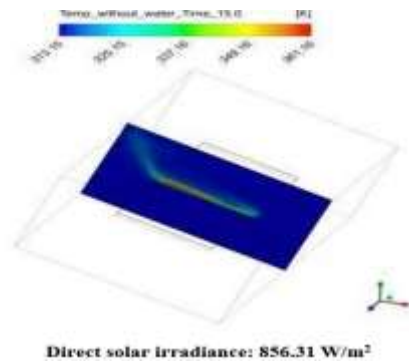


Figure 6:Natural convection effects

Ambient conditions during the experiments, such as solar irradiance, wind speed, and air temperature, are summarized in Table 2.

TABLE 2: The environmental conditions on the days of experiment

Condition	14 May	1 June
Insolation (7 Hrs- 1030 to 1730)	837.37 W/m ²	838.71 W/m ²
Average wind speed	1.4 m/s	1.4 m/s
Average insolation (24 hrs)	488.60 W/m ²	343.83 W/m ²
Average ambient temperature	36.51 °C	38.61 °C

3.4 Electrical Performance – Power Output

Figure 7A reveals the power output comparison between panels with and without cooling (1 LPM). A consistent improvement of about 10% in peak power was observed during mid-day hours. This benefit became even more pronounced at 2 LPM (Figure 7B), where up to 20% enhancement in peak power was achieved at 13:00 Hrs.

Additionally, daily energy output increased from 303 Wh (without cooling) to 333 Wh (with 1 LPM cooling), validating the effectiveness of temperature control in improving electrical performance.

Figure 7C shows the average panel temperatures over time for both cooled and uncooled cases, further confirming that the CFD simulation closely follows experimental measurements.

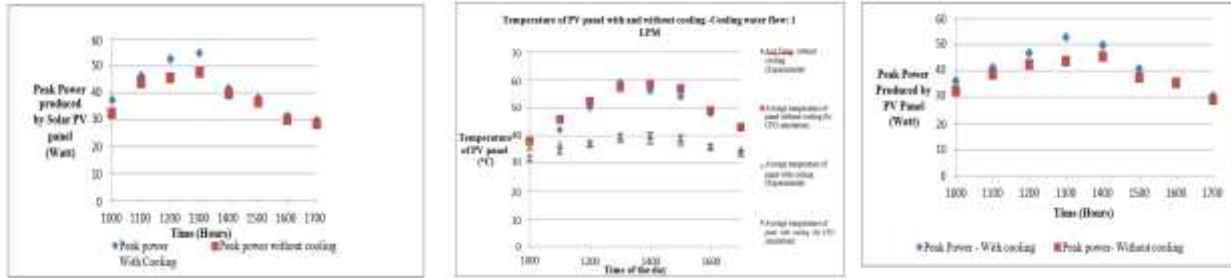
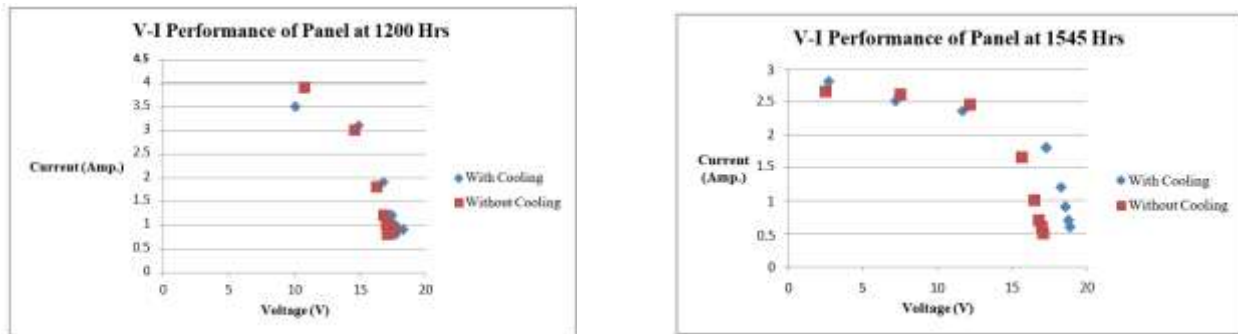


Figure 7A,B,C :Electrical Performance – Power Output

3.5 V-I Characteristics

Figures 8A and 8B present the voltage-current (V-I) performance at various time intervals. With cooling, both voltage and current improved significantly, especially at higher resistances. At lower resistances, the current slightly reduced, but the increased voltage compensated to deliver higher power output overall.



This indicates that PV panel cooling is more beneficial in applications involving higher resistive loads or constant voltage operation, as is common in grid-connected inverters and DC appliances.

3.6 Optical Enhancement via Refraction

A novel dimension of this research lies in quantifying the contribution of refracted light due to the water layer over the PV panel. The effect of light refraction was studied using Snell’s Law and angle of incidence data calculated through the SOLPOS calculator. As shown in Table 3 and Figure 9, the incident angle of solar radiation was reduced due to the refractive index of water (1.333), which effectively straightened the incoming radiation, reducing angular losses and increasing absorption.

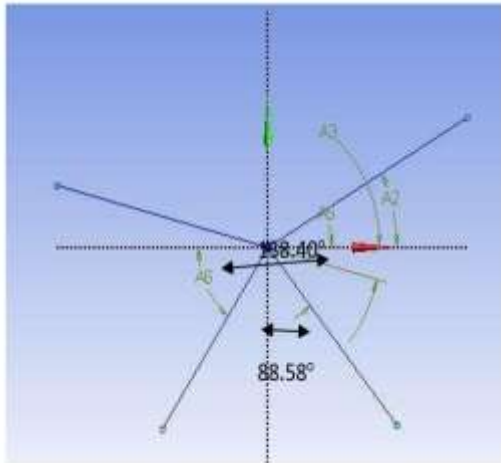


Figure:9: Radiation at a given point straightened because of refraction

Time	Angle Θ_1	Angle Θ_2
09:00	-61.91	-41.58
10:00	-50.73	-35.63
11:00	-41.78	-30.09
12:00	-36.77	-26.76
13:00	37.27	27.10
14:00	43.11	30.94
15:00	52.54	36.66
16:00	63.98	42.53
17:00	76.49	47.00

Table 4.3: The Angle change as an effect of refraction by solar PV panel

An experimental validation of this phenomenon was performed by comparing power output from two identical panels—one cooled from the back with ice and the other with a water film on the top surface. Although both panels maintained the same temperature (35°C), the top-cooled panel produced 54.04 W, while the ice-cooled panel produced only 50.22 W—demonstrating a 7.6% improvement attributed solely to light refraction.

3.7 Combined Electrical and Thermal Efficiency

Table 4 summarizes energy efficiency calculations considering both electrical and thermal contributions. With a 1 LPM water flow, the system recovered up to 139.56 W of thermal energy while increasing electrical output. The overall energy efficiency improved dramatically from 6.68% (without cooling) to 40.42% (with cooling).

This is a significant outcome, suggesting that integrating thermal recovery in PV systems can transform them from single-purpose devices to hybrid energy generators capable of supporting secondary applications like pre-heating feed water for reverse osmosis (RO). Such applications benefit from elevated feed water temperature due to increased membrane permeability and water flux.

TABLE 4: Energy efficiency calculations (For 1 Liter per minute flow)

Time	12:00 Hrs	14:00 Hrs	16:00 Hrs
Inlet water temperature($T_{w_{in}}$)	37	36	34
Outlet water temperature($T_{w_{out}}$)	39	38	35
Energy contained by water(watt)	139.56	139.56	69.78
Peak power without cooling (watt)	34.51	25.29	14.22
Peak power with cooling (watt)	41.73	28.57	16.3
Difference (watt)	7.22	3.28	2.08
Total power saving (watt)	146.79	142.85	71.86
Watt/m ²	1020	732	348
Solar panel area (sq.m)	0.61	0.61	0.61
Power incident on the panel (watt)	624.24	447.98	212.98
Energy efficiency without cooling	5.53	5.64	6.68
Energy efficiency with cooling (electrical + thermal)	29.0421	37.531	40.417

3.8 CFD Model Accuracy

The accuracy of CFD simulations was evaluated by comparing average panel temperatures and power output trends across different flow rates and time durations. The match between simulated and experimental results was within acceptable error margins, confirming the robustness of the numerical model.

3.9 Implications for Large-Scale PV Systems

Given the scalability of this design and the modest water flow required (1–2 LPM per panel), large-scale solar installations can greatly benefit from this cooling method. Moreover, passive gravity-fed cooling systems can eliminate pump power consumption, further improving net energy gains.

3.10 Key Findings

The study demonstrated that top surface water cooling was highly effective in maintaining photovoltaic (PV) panel temperatures below 40°C during peak solar hours, ensuring effective thermal regulation. This cooling strategy led to a notable improvement in electrical output, with power generation increasing by 10–20% compared to uncooled panels. In addition to thermal benefits, the presence of a water layer on the panel surface introduced an optical enhancement due to the refraction of sunlight, contributing an extra 7.6% gain in power output by optimizing the angle of incidence. The combined effect of temperature control and optical improvement significantly enhanced the system's overall energy efficiency, which increased from 6.68% to 40.42% when both electrical and thermal outputs were considered. Furthermore, the reliability of

the findings was reinforced by the close agreement between computational fluid dynamics (CFD) simulation results and experimental data, validating the accuracy and effectiveness of the proposed approach.

4 Conclusion

The experimental and computational investigation into the thermal management of photovoltaic (PV) panels through top surface water cooling has yielded several significant conclusions. Firstly, PV panels exhibit a marked decline in efficiency at elevated temperatures, reaching up to 76°C without cooling. The implementation of direct water flow cooling from the top surface effectively maintained panel temperatures below 40°C during peak irradiance periods, as validated both experimentally and through CFD simulations.

The use of a direct contact water film not only improved the thermal regulation of the panel but also led to an increase in electrical output. Power output improved by 10% at 1 LPM and by up to 20% at 2 LPM water flow. V-I characteristics confirmed improved current and voltage performance, particularly under high resistance loads, which are common in most PV applications.

Furthermore, a novel insight was obtained through the analysis of optical enhancement due to refraction. The water layer served a dual function—not only cooling the panel but also refracting incidents of solar rays, thereby reducing angular losses. Experimental validation demonstrated that refraction contributed an additional 7.6% to the overall power output.

Importantly, this study emphasized the potential for thermal energy recovery. The thermal energy captured from heated water can be utilized in various applications, such as feed water for reverse osmosis, enhancing the overall energy utility of the system. With this approach, the overall energy efficiency increased from 6.68% (electrical only) to as high as 40.42% (electrical + thermal).

This interdisciplinary model presents a scalable, sustainable solution for optimizing PV performance, particularly in hot climatic regions. Future work may extend this framework toward integrating heat storage systems, automation, and passive gravity-fed water circulation for further efficiency gains.

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