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Experimentally Investigation of Exergy Analysis of Photovoltaic-Thermal (PVT) Water Cooling

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ABSTRACT

This study presents an experimental investigation into the exergy performance of a photovoltaic-thermal (PVT) water cooling system equipped with copper fins in two distinct geometries—cylindrical and rectangular—under varying water flow rates (1, 3, and 5 L/min). Conducted under real environmental conditions, the research aimed to optimize heat dissipation and evaluate system efficiency enhancements resulting from different fin designs and cooling intensities. The results show that electrical efficiency improved significantly with increased water flow, reaching a peak of 64% electrical exergy efficiency using cylindrical fins at 5 L/min, compared to 60% for rectangular fins under the same conditions. Thermal efficiency also increased, with cylindrical fins achieving up to 80% at 5 L/min, outperforming rectangular fins which reached approximately 70%. However, thermal exergy efficiency exhibited a decline under higher surface heat flux due to increased irreversibilities, with rectangular fins slightly outperforming cylindrical fins by maintaining lower exergy losses (-13% vs. -15%). Overall exergy efficiency decreased with increasing surface heat flux but remained more stable at higher flow rates, with cylindrical fins maintaining 0.1–0.12 compared to rectangular fins' 0.09–0.11. These findings underscore the importance of optimized thermal management, demonstrating that combining higher water flow rates with advanced fin geometries—particularly cylindrical fins—can significantly enhance energy and exergy performance in PVT systems, thus supporting their application in sustainable energy technologies.

1. INTRODUCTION

The elevated cost of fossil fuels and environmental issues associated with nuclear energy are drawing more attention to the utilization of sources of clean energy. Solar energy is a primary source of renewable energy [1, 2]. Traditional technologies utilized for harnessing solar energy consist of solar collectors and photovoltaic (PV) systems [3-8]. The electrical output power of a photovoltaic system diminishes as the temperature (Temp) of the photovoltaic modules rises. Conversely, a solar water collector needs an external electrical source to provide the electrical power necessary for water pumping. The integration of a photovoltaic module with a solar water collector resulted in a solar photovoltaic thermal (PVT) water collector. A PVT collector supplies the necessary electrical energy to circulate water. Furthermore, it conveys the excess heat from the photovoltaic module to water. The rising demand for energy and the detrimental environmental impacts of conventional energy conversion systems have prompted researchers to investigate renewable energy systems, not only for electricity generation but also for the development of renewable-assisted energy systems including PVT [9]. Solar energy, a type of renewable energy, has garnered the attention of researchers due to its benefits, including versatile utilizes, little maintenance expenses, and lower emissions [10, 11].

Solar thermal collectors including parabolic troughs, solar stills, evacuated tubes, and flat plates convert solar radiation into heat or electricity [12, 13]. Most commercial solar cells convert 10–20% of sunshine into electricity at 25 degrees centigrade. However, the remaining radiation is transformed into heat, raising the PV panel Temp [14-16]. To maximize cell performance, the PV panel's operating cell Temp at rated power must be below 47 degree centigrade [17]. Each degree Celsius beyond this threshold reduces PV panel electrical efficiency by 0.45-0.65% [18]. Photovoltaic cell materials also expand somewhat at high Temps, lowering open-circuit voltage and fill factor. Air Temp and solar irradiation regulate short-circuit current and open-circuit voltage, affecting photovoltaic cell I-V curves. Module Temp increases short-circuit current linearly and inversely affects open-circuit voltage. A large photon energy portion, perhaps surpassing the semiconductor materials' bandgap, is wasted as waste heating [19]. Photovoltaic panels produced less power due to overheating [20].

Thermodynamics is used to optimize energy conversion and heat transport factors in photovoltaic-based energy conversion systems [21]. To improve PV module performance, air, water, refrigerant, and heat pipes have been used to dissipate the heat produced in the modules for thermal use (including domestic hot water and space heating) while keeping the PV panel Temp below 47 degrees Celsius [22]. A flat plate solar thermal collector may improve incident sunlight conversion in addition to employing more energy-efficient photovoltaic module components, which raised pricing [23]. The modified PVT solar collector provides both thermal (low-grade energy for water and hot air) and electrical (high-grade DC energy).

Prakash et al. [24] created a mathematical model to simulate hybrid PVT system performance. The PVT model energy efficiency was assessed utilizing energy balance methods for air and water cooling. Photovoltaic systems generate more power utilizing thermal collectors. Water cooling increases PVT system thermal efficiency by 50-67%, whereas air cooling improves it by 17-51%. Nižetić et al. [25] found that spraying water on both panel sides increased electrical efficiency to 16.3% and lowered PV cell Temp from 54 to 24 degree centigrade. Cooling just the back reduces efficacy to 14%. Aste et al. [26] used a mathematical model to evaluate the thermal and electrical efficiency of a glazed PVT water collector with a flat plate absorber, roller bonding, and a thin-layer PV cell. This research found that the PVT system's efficiency increased from 13.2% (for the PV panel alone) to over 42%. Saygin et al. [27] eliminated the absorber plate by integrating the PV panel and collector. The cover-panel gap and air mass rate of flow were evaluated to determine the PVT system's optimal performance. Saygin et al. [27] found that the PVT system performs best with a 3-5 mm panel-cover gap. Air mass rate of flow increases system thermal efficiency.

PV cell electricity production and cooling include irreversible energy conversion processes that limit the system's heat and power output. Energy/exergy analysis is increasingly used to understand energy system irreversibility and find ways to improve them [27-29]. This strategy is promising for improving PVT system performance [30-32]. Nguyen et al. [29] theoretically evaluated the exergy and energy performance of a glazed PVT collector, taking into account operational factors like cooling medium intake Temp and mass rate of flow. The research found that lowering input Temp increases energy efficiency but decreases exergy efficiency. For optimal collector exergy and energy efficiency, the cooling water input Temp should be 30-40 degrees Celsius. Kallio and Siroux used MATLAB to improve PT/V collector design by assessing electrical and thermal exergy efficiencies. The PVT collector's thermal energy efficiency may reach 80%, while its max thermal exergy is roughly 2%, based on solar irradiation. Recent experiments by Kim et al. [31] examined the exergy and energy efficiency of an air-based PVT collector. Depending on air rate of flow, the air-kind PVT collector's mean thermal exergy and energy efficiencies varied from 35 to 50% and 8.5% to 14%, respectively.

From the mid-1970s, PVT was studied theoretically and experimentally. Kern and Russell [33], and Hendrie [34] have provided the PVT/a and PVT/w systems' essential notion and data utilising water or air as the coolant. The technical validity was quickly proved. Later research concentrated on flat-plate collectors, notably by Raghuraman and Cox [35, 36], Braunstein and Kornfeld [37], and Lalović et al. [38] in the 1980s. O'Leary and Clements [39], Mbewe et al. [40], Al-Baali [41], and Hamdy [42] studied light-concentrating photovoltaic-thermal (PVT) system performance.

From late 1980s to nearly a decade, Garg et al. [43] studied hybrid PVT air and liquid heating systems analytically and experimentally [43-45]. They used a steady state PVT/a model to show that a second front cover does not reduce heat loss over the critical threshold, and the single-glass cover traps more heat than the double-glass cover [45].

Bhargava et al. found that mechanically driven PVT/a systems may be self-sustaining within specified design parameters like packing factor and airflow rate [46]. A PVT/a collector with integrated compound parabolic concentrator (CPC) troughs was tested using a steady-state model [43, 47]. According to parametric analysis, thermal and electrical outputs increase with absorber length, air mass flow rate, and packing factor but decrease with duct depth. Cost-performance testing is done on the final design. Sopian et al. [48] used a steady-state model to compare single- and double-pass PVT/a collectors. The double-pass arrangement performed better due to solar cell cooling and lower front cover temperature. Later, an experimental unit was added [49]. Prakash [24] studied a classic PVT collector for air and water heating transiently. Air-heating is less efficient than water heating owing to poor heat transmission between the absorber plate and the circulating air. Bergene and Lovvik [50] created a detailed flat-plate PVT/w collecting system physical model for performance evaluation. The fin-width-to-tube-diameter ratio showed 60%–80% efficiency. Agarwal and Garg showed that packing factor affects thermosyphon thermal efficiency but not cell efficiency, and storage tank water capacity affects performance. Their work evolved to include flat-plate PVT/w collector system experiments with simple parabolic reflectors [51].

de Vries [52] investigated the steady-state, long-term performance of numerous Dutch PVT collector systems using the modified Hottel–Whillier model. Single-covered design outperformed uncovered design, which has low thermal efficiency, and double-covered design, which has mediocre cell efficiency. However, Fujisawa and Tani [53] found that the uncovered design's exergy output density is somewhat higher than the single-covered design's because thermal energy represents a considerable proportion of unavailable energy. For low-temperature water heating systems like swimming pools, the cheap unglazed PVT/w system is recommended. Anti-freeze solutions may help in intense winter circumstances, but summer performance suffers [54]. In experimental PVT/w systems in Riyadh (at 24.6N), Saudi Arabia [55], increased summer ambient temperatures may reduce photovoltaic efficiency by 30%, while thermal efficiency remains good. Winter photovoltaic modules perform better, but thermal performance decreases.

Rockendorf et al. [56] developed prototypes of a thermoelectric collector (which initially produces heat and then electricity) and a PVT/w collector (which uses solar cells on an aluminium absorber and copper tubing). TRNSYS simulations showed that the PVT/w collector produced much more electricity than the thermoelectric collector.

Despite advancements in PVT systems to improve solar energy utilization, significant gaps remain in optimizing their performance, particularly in addressing exergy losses. Conventional PV modules convert less than 15% of solar energy into electricity, with over 80% dissipated as heat, leading to efficiency reductions due to elevated operating Temps. While cooling techniques like air and water cooling have demonstrated promise, existing studies predominantly focus on energy performance, overlooking exergy analyses that reveal irreversibilities and opportunities for system improvement. Furthermore, limited research investigates the impact of advanced design modifications, including optimized fin geometries and varied cooling rates, on PVT efficiency. Although water cooling has been demonstrated to enhance thermal efficiency by 50-67%, the influence of high-water rate of flows on exergy efficiency remains insufficiently explored. Most studies have centered on flat-plate absorbers, leaving the performance of alternative designs, including cylindrical and rectangular fins, underexplored. Additionally, the integration of copper fins, known for superior thermal conductivity, into PVT systems has not been extensively examined. This study aims to address these gaps by experimentally analyzing exergy losses in PVT systems utilizing two innovative copper fin shapes—cylindrical and rectangular—under varying water mass rate of flows (1, 3, and 5 L/min), providing critical insights for the development of efficient and sustainable solar energy solutions.

2. EXPERIMENTAL WORK

This PVT water cooling system was tested outdoors under real environmental conditions to evaluate its performance in practical applications. The PV panel, rated by the manufacturer to achieve a maximum power of 80 W under a radiation intensity of 1000 W/m² and a Temp of 25 degree centigrade, was subjected to natural sunlight with solar radiation recorded between 10 a.m. and 4 p.m. An Eppley pyranometer was used to measure solar radiation, offering reliable detection of over 90% of all solar radiation without requiring sun-tracking equipment. The pyranometer's calibration constant of 11.99×10^{-6} V/Wm^{-2} ensured accurate data collection.

The experimental setup involved water rate of flows of 1, 3, and 5 L/min, with J-type thermocouples used to measure water Temp changes within a range of 0 to 760 degree centigrade, ensuring compatibility with the multimeter for precise readings as shown in Figures 1 and 2. The system components included a PVT module, a heat exchanger, a water pump, a flow meter, and a storage tank. Data were recorded to calculate the thermal and electrical efficiencies of the PVT water cooling system under real environmental conditions, providing valuable insights into its operational performance and potential for practical implementation.

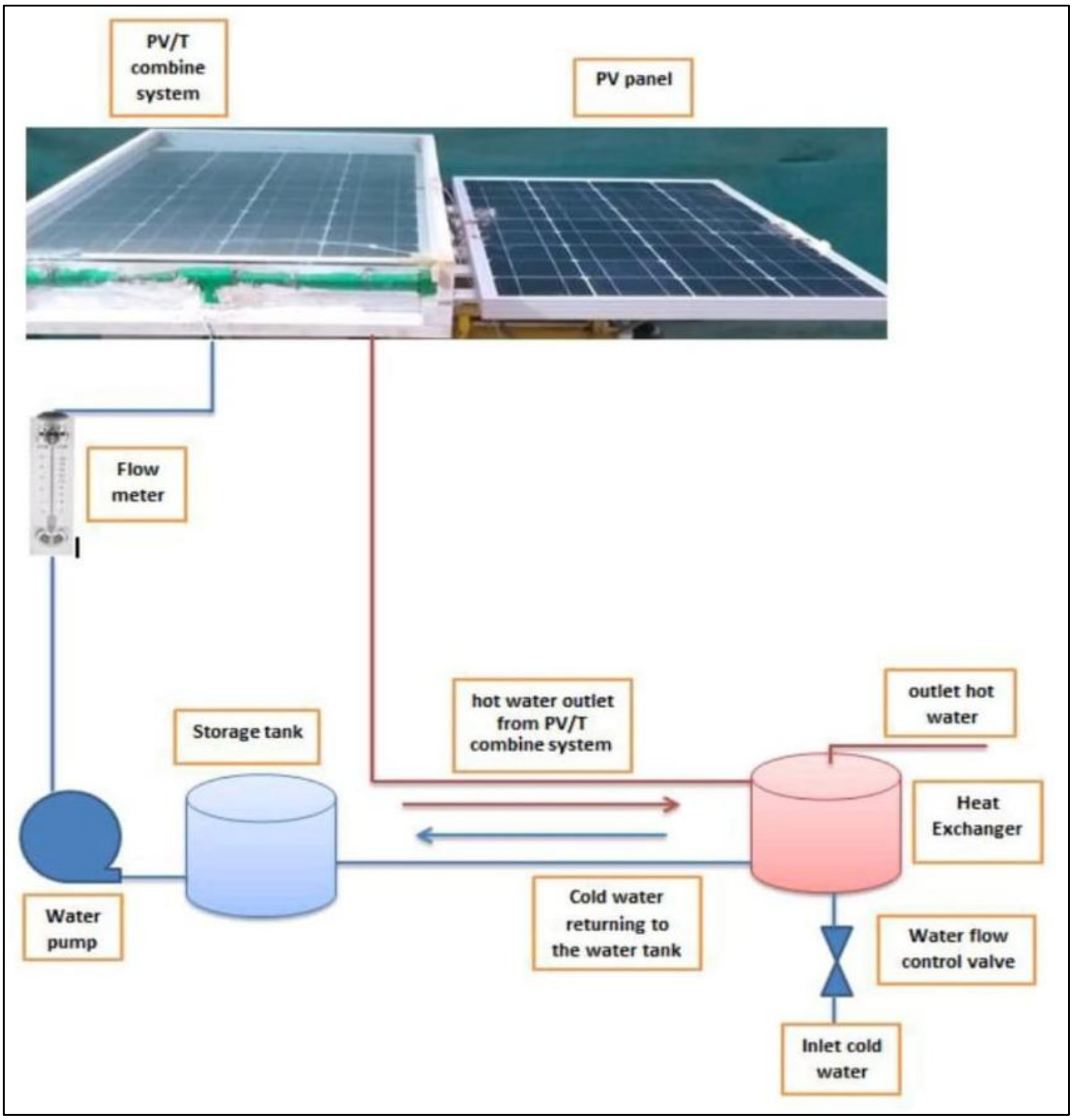
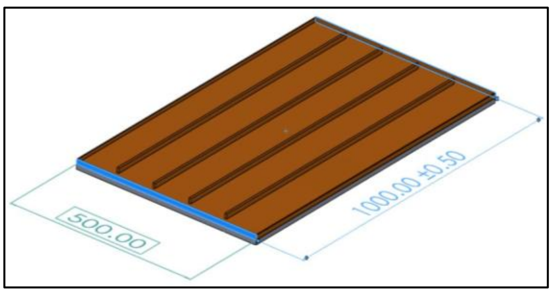


Figure 1. Schematic diagram of the PVT water cooling system

Figure 2. The utilized PVT in this experimental work with the applied copper collectors

3. FABRICATION OF COOLING FINS

Using high-conductivity copper to enhance thermal performance for the PVT water-cooling system, the manufacturing procedure of the cooling fins included creating two separate shapes, cylindrical and rectangular. Constructed utilizing a homogeneous circular cross-section, the cylindrical fins Precision machining equipment helped to cut copper rods with a 10 mm diameter and 500 mm length to size. The dimensions were selected to maximize heat surface area transmission while preserving structural efficiency. To guarantee best thermal contact and eliminate surface contaminants, the rods were polished and cleaned. Made from copper sheets of 500 mm in length, 50 mm in breadth, and 5 mm in thickness, the rectangular fins were Perfect, and uniform dimensions were guaranteed utilizing laser cutting technique as shown in Figure 3. To remove imperfections and enhance heat conductivity, the edges were deburred and polished. Both fin designs found use in the water-cooling mechanism of the PVT system. Utilizing soldering to provide strong thermal and mechanical connections, the fins were firmly fixed to the 1000 mm × 500 mm copper base plate of the PVT system. The dimensions were precisely adjusted for efficient heat dissipation, hence improving the thermal and exergy performance of the system.



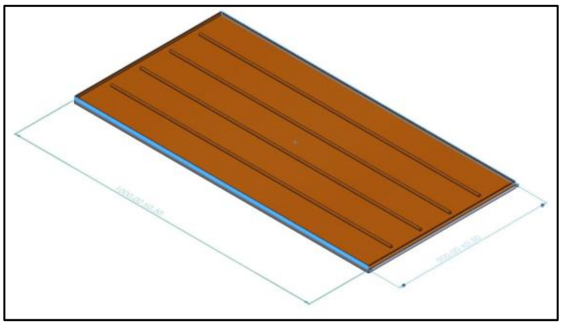


Figure 3. Sheet and tube water thermal collector dimensions and geometry

4. PERFORMANCE EVALUATION

The amalgamation of efficiency parameters delineates the performance of the PV-T collector. Thermal and electrical efficiencies were the fundamental types. Thermal efficiency represents the proportion of the system's thermal output to the incident solar irradiation, while electrical efficiency was the proportion of the system's electrical output to the incident solar radiation that falls on the collector's surface area during a certain duration. Overall efficiency is the aggregate of thermal and electrical efficiencies, utilized to assess overall performance.

$$\text{Photo Electric conversion efficiency, } \eta e = \frac{I_m V_m}{GA} \quad (1)$$

$$\text{Thermal Efficiency, } \eta \text{ th} = \frac{mc_p(T_f - T_i)}{GA} \quad (2)$$

Whereas, m refers to the water mass rate of flow kg/sec, c_p refers to specifical water heat (4186 J/KgK).

G denotes the daily world sunlight reaching on the collector surface, T_i represents the intake fluid Temp and T_f signifies the outlet fluid Temp.

$$\text{Overall Efficiency, } \eta_o = \eta_{th} + \eta_e \quad (3)$$

The energy saving efficiency η_f is also used: it is defined as:

$$\text{Energy saving efficiency, } \eta_f = \eta_e/\eta_{power} + \eta_{th} \quad (4)$$

Whereas:

η_{power} denotes the electrical power generating efficiency of conventional power plants, with a value of 38%.

5. EXERGY ANALYSIS MODEL

The exergy of the PVT water cooling system is demonstrated graphically to enhance understanding of the system's energy performance. The performance of the PVT water cooling system is analyzed from an exergy perspective by considering the system as a control volume. The system is presumed to function in semi-steady-state circumstances to facilitate the study. The exergy balance for the PVT system, accounting for both thermal and electrical outputs, may be articulated utilizing the following equation:

$$\sum \xi in = \sum \xi lost + \sum \xi out \quad (5)$$

In Formula (5), ξin denotes exergy intake, ξout signifies exergy output, and ξlost indicates exergy loss or destruction resulting from the irreversible process. The quantity ξin in Formula (6) denotes the net input exergy rate. In solar systems, like a PVT system, the input energy consists of the solar radiation incident on the system's surface area; hence, the input exergy is equivalent to the exergy of the incoming solar irradiation (ξsun). Consequently, Formula (5) may be represented as demonstrated in Formula (6):

$$\xi in = \xi sun \qquad (6)$$

The overall output exergy (ξout) produced by PVT systems represents the total of the thermal and electrical exergy (ξel and ξth), and it may be written as:

$$\sum \xi out = \sum \xi th + \sum \xi el \qquad (7)$$

When the thermal exergy equals the variance between the flow exergy at the collector output and intake, the exergy balance is established.

$$\xi th = \xi mass,out - \xi mass,in \qquad (8)$$

$$\xi sun = \sum \xi th + \sum \xi el + \sum \xi lost \qquad (9)$$

$$\xi sun = (\xi mass,out - \xi mass,in) + \sum \xi el + \sum \xi lost \qquad (10)$$

A multitude of methods has been developed for determining the exergy of solar irradiation. Many researches including [57-59] advocated for the use of Eq. (11) in the exergy study of solar irradiation received by the PVT system.

$$\xi sun=Esun[1-4Tamb3Tsun+13(TambTsun)4] \qquad (11)$$

Tsun denotes the solar surface Temp (about 5777 K), whereas Tamb represents the ambient air Temp around the panel. Eqs. (12) and (13) delineate the decomposition of thermal and electrical (ξel and ξth) exergy of the system [60, 61].

$$\xi th=\xi th\xi sun=mCp[(Tout-Tin) -Tamb\ ln(ToutTin)]G(1-TambTcol) \qquad (12)$$

$$\xi el=\xi el\xi sun=\xi elG(1-TambTcol) =Isc\times Voc\times FFG(1-TambTcol) \qquad (13)$$

Whereas,
T_{col} denotes the collector's surface Temp, and T_{amb} represents the general Temp of the panel.

6. RESULTS AND DISCUSSION

Figure 4 presents a detailed comparative analysis of the electrical efficiency (η) of photovoltaic (PV) panels subjected to varying surface heat flux levels under different water flow rates (1, 3, and 5 L/min), with the integration of cylindrical (Eta E1) and rectangular (Eta E2) fin geometries. The data clearly indicates a strong correlation between thermal management strategies and PV performance, emphasizing the critical role of convective heat dissipation in mitigating temperature-induced efficiency losses. At the lowest flow rate of 1 L/min, a pronounced decline in electrical efficiency is observed with increasing heat flux, particularly beyond 300 W/m², where thermal accumulation surpasses the system's cooling capacity. Under these conditions, cylindrical fins exhibit superior performance, especially at lower heat flux intensities, due to their enhanced surface area-to-volume ratio and improved convective heat transfer coefficients. Notably, as surface heat flux exceeds a critical threshold (~600 W/m²), the efficiencies of both fin configurations converge, indicating a thermal saturation point where the influence of geometry diminishes, and the limited flow rate fails to offset the thermal load effectively.

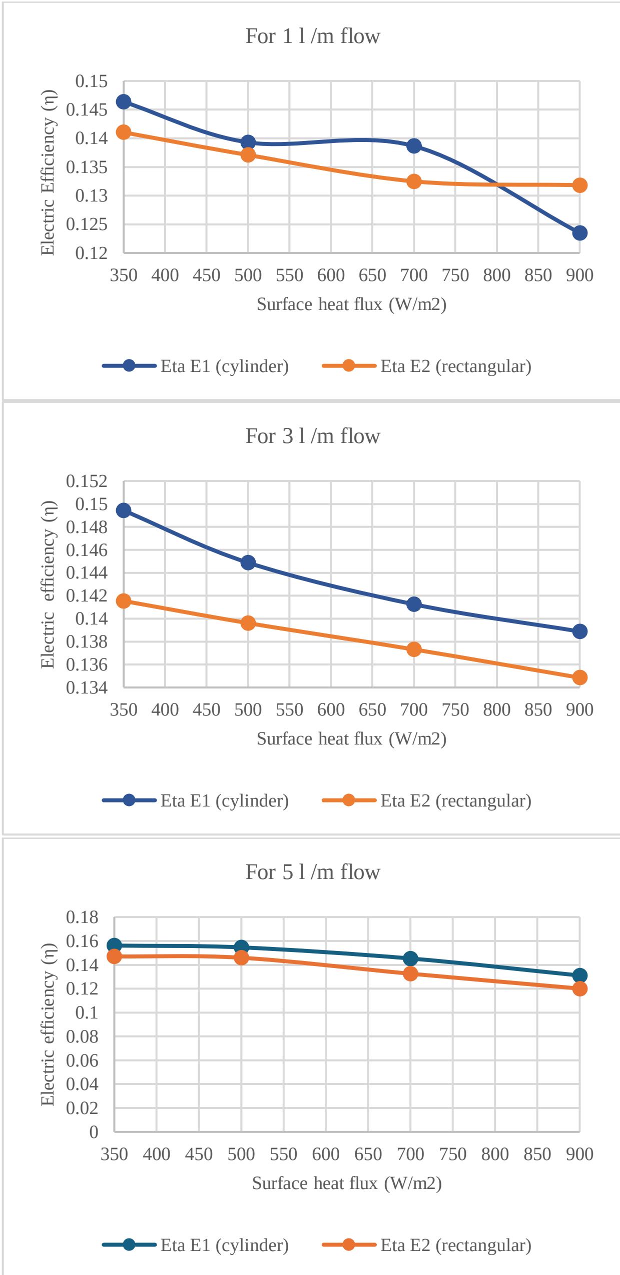


Figure 4. The difference in the electrical efficiency of the panel for various water flow mass rate

When the flow rate is increased to 3 L/min, the variation in efficiency becomes less volatile across the heat flux spectrum, and cylindrical fins consistently maintain higher efficiency values compared to rectangular fins. This suggests that the enhanced flow improves the Reynolds number, facilitating turbulent boundary layer development and more effective heat removal from the absorber surface. At the highest flow rate of 5 L/min, the performance gap between the two fin types narrows, and the efficiency curve stabilizes across the tested heat flux range, indicating that the system has reached a near-optimal convective cooling regime [62, 63]. This trend implies a diminishing return effect, where further increases in flow rate yield marginal gains in efficiency due to the asymptotic behavior of thermal resistance reduction.

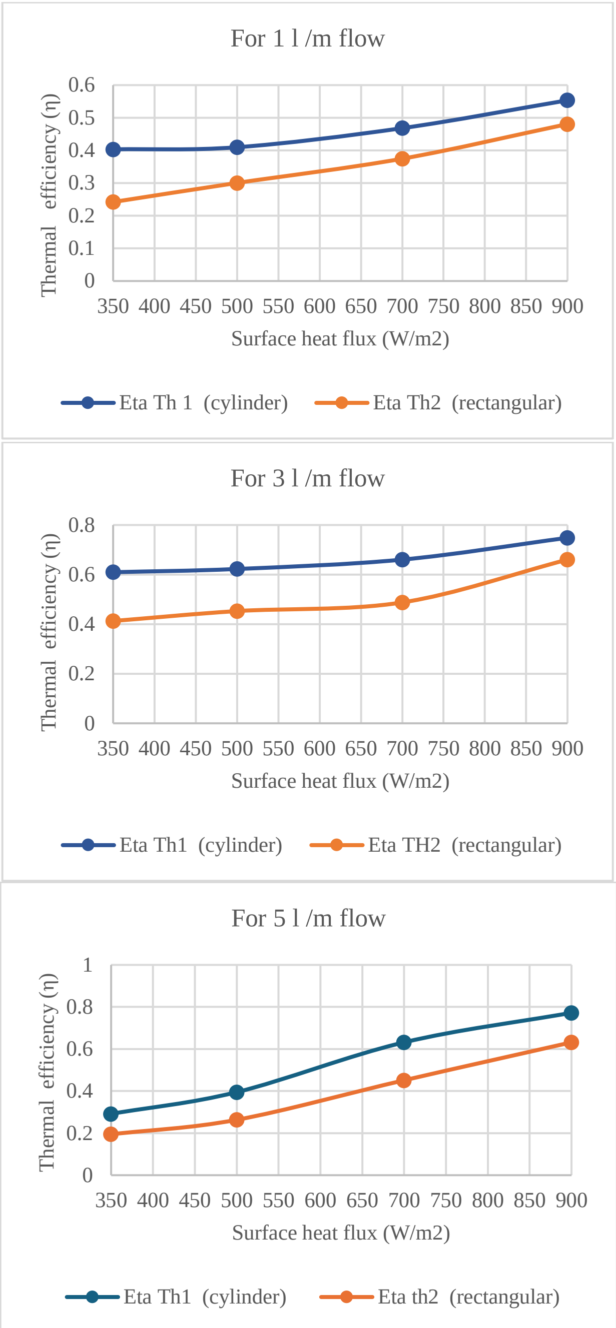


Figure 5. The difference in the thermal efficiency of the panel for various water flow mass rate

Figure 5 illustrates the variation in thermal efficiency (η_th) of the PVT (Photovoltaic Thermal) water cooling system under different surface heat flux levels (ranging up to 1000 W/m²) and water flow rates (1, 3, and 5 L/min), revealing distinct trends that underscore the critical role of flow rate and fin geometry in thermal performance. At a low flow rate of 1 L/min, thermal efficiency increases gradually with rising heat flux, yet cylindrical fins (η_th1) consistently outperform rectangular fins (η_th2), achieving thermal efficiencies of approximately 0.6 and 0.4, respectively, at 1000 W/m². This difference is attributable to the cylindrical fins' greater effective surface area and improved convective heat transfer characteristics, which facilitate more efficient thermal dissipation despite the limited flow-induced turbulence at low Reynolds numbers.

As the flow rate increases to 3 L/min, a significant improvement in heat extraction is observed across both fin configurations. The cylindrical fins reach an efficiency of 0.75, while rectangular fins achieve 0.6, indicating that the elevated flow enhances convective cooling by increasing the heat transfer coefficient and reducing the thermal boundary layer thickness. At the highest flow rate of 5 L/min, thermal efficiency approaches its peak values, with cylindrical fins attaining up to 0.8 and rectangular fins nearing 0.7. The reduced disparity between fin geometries at this stage suggests that the dominant cooling mechanism transitions from geometry-dependent conduction to bulk convective removal, where the effect of flow rate outweighs geometrical influence.

The data trends reveal that the impact of surface heat flux becomes more pronounced at lower flow rates, where inadequate cooling leads to a steeper temperature gradient across the absorber surface, resulting in higher thermal losses. Conversely, higher flow rates suppress these gradients by facilitating uniform temperature distribution and improved fluid mixing. Moreover, cylindrical fins consistently demonstrate superior thermal performance due to their circular cross-section, which enhances surface wettability and allows more effective heat transfer from the absorber to the fluid medium [64, 65]. The smoother increase in thermal efficiency across all heat flux levels with cylindrical fins also suggests greater thermal stability and more effective energy utilization under dynamic thermal loads [66, 67].

Figure 6 presents the electrical exergy efficiency (η_ele) of the PVT (Photovoltaic Thermal) system as a function of surface heat flux under three distinct water flow rates (1, 3, and 5 L/min), revealing a generally increasing trend across all configurations. This upward trajectory in exergy efficiency with rising surface heat flux signifies improved thermodynamic performance and energy utilization, driven by higher thermal gradients that enhance the overall energy conversion potential of the system. At the lowest flow rate of 1 L/min, both cylindrical (Ex_ele1) and rectangular fins (Ex_ele2) demonstrate nearly equivalent performance, converging at approximately 60% exergy efficiency at 1000 W/m². The negligible difference at this stage can be attributed to the limited heat extraction capacity of the system, where low fluid velocity constrains convective heat transfer, minimizing the geometric advantage of cylindrical fins.

However, as the water flow rate increases to 3 L/min, cylindrical fins begin to demonstrate a marginal yet consistent improvement in exergy efficiency—achieving around 62% compared to 60% for rectangular fins. This enhancement reflects improved heat dissipation due to increased flow-induced turbulence and a higher Reynolds number, which reduces the PV module temperature and minimizes entropy generation. The thermal benefit of cylindrical fins becomes more pronounced at 5 L/min, where their efficiency peaks at 64%, outperforming rectangular fins (61%) under the same thermal load [68]. This divergence highlights the role of fin geometry in optimizing thermal conductivity pathways and facilitating enhanced heat transfer coefficients at elevated flow regimes.

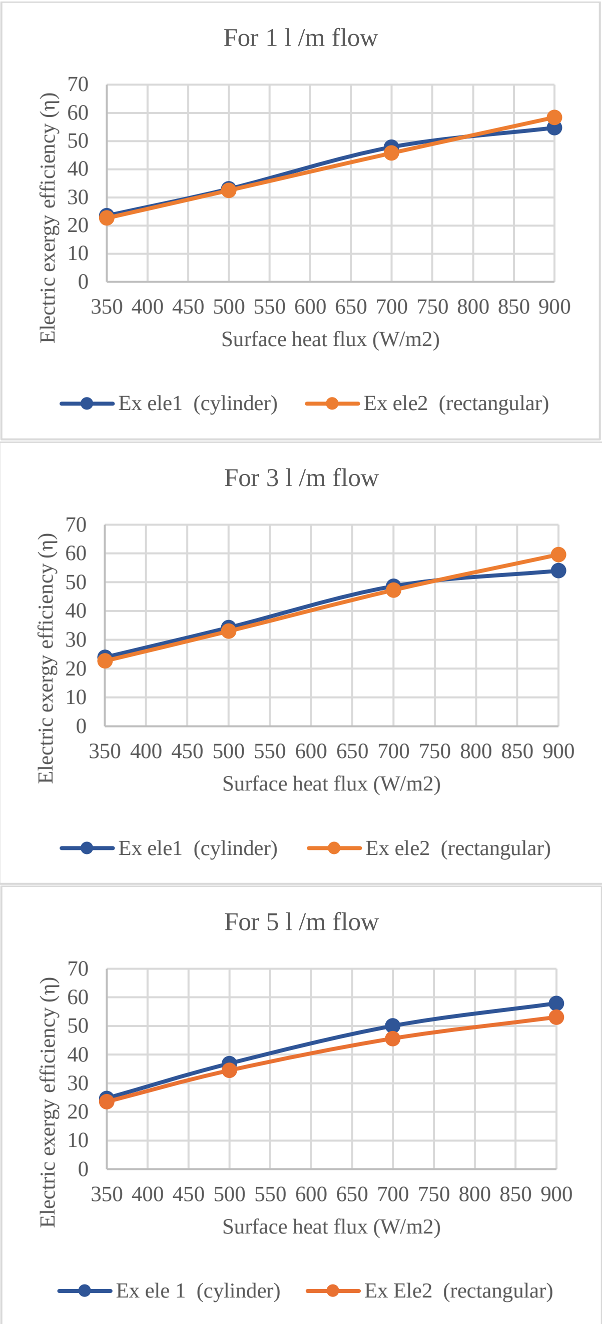


Figure 6. The difference in the electrical exergy efficiency of the panel for various water flow mass rate

Figure 7 presents a detailed evaluation of the thermal exergy efficiency (η_{th}) of the PVT system as a function of varying surface heat flux and coolant mass flow rates (1, 3, and 5 L/min), demonstrating a consistent degradation in exergy performance with increased thermal loading, primarily due to intensified thermal irreversibilities and entropy generation within the system. At a minimal flow rate of 1 L/min, η_{th} assumes slightly negative values, decreasing to approximately -11% and -9% for cylindrical (Ex Th1) and rectangular fins (Ex Th2), respectively, at 1000 W/m², highlighting significant exergy destruction caused by elevated absorber temperatures and insufficient convective heat transfer. Although increased coolant flow rates at 3 and 5 L/min improve the Reynolds number and enhance forced convection, the thermal exergy efficiency continues to decline—reaching -14% for cylindrical fins and -12% for rectangular fins at 3 L/min, and further deteriorating to -15% and -13%, respectively, at 5 L/min - indicating that the rate of exergy destruction exceeds the compensatory capacity of convective enhancement. The marginally superior performance of rectangular fins across all conditions may be attributed to their planar geometry, which enables more uniform coolant coverage and mitigates thermal gradients, whereas cylindrical fins, despite their beneficial impact on electrical efficiency, may induce localized hot spots and elevated thermal resistance under high heat flux conditions. The sustained decline in η_{th} with increasing surface heat flux, even under elevated flow rates, emphasizes a critical constraint in thermal management strategies for PVT systems: namely, that enhanced fluid flow and fin geometry alone are insufficient to counteract the fundamental second-law limitations imposed by irreversible heat transfer processes under extreme thermal loading [69, 70].

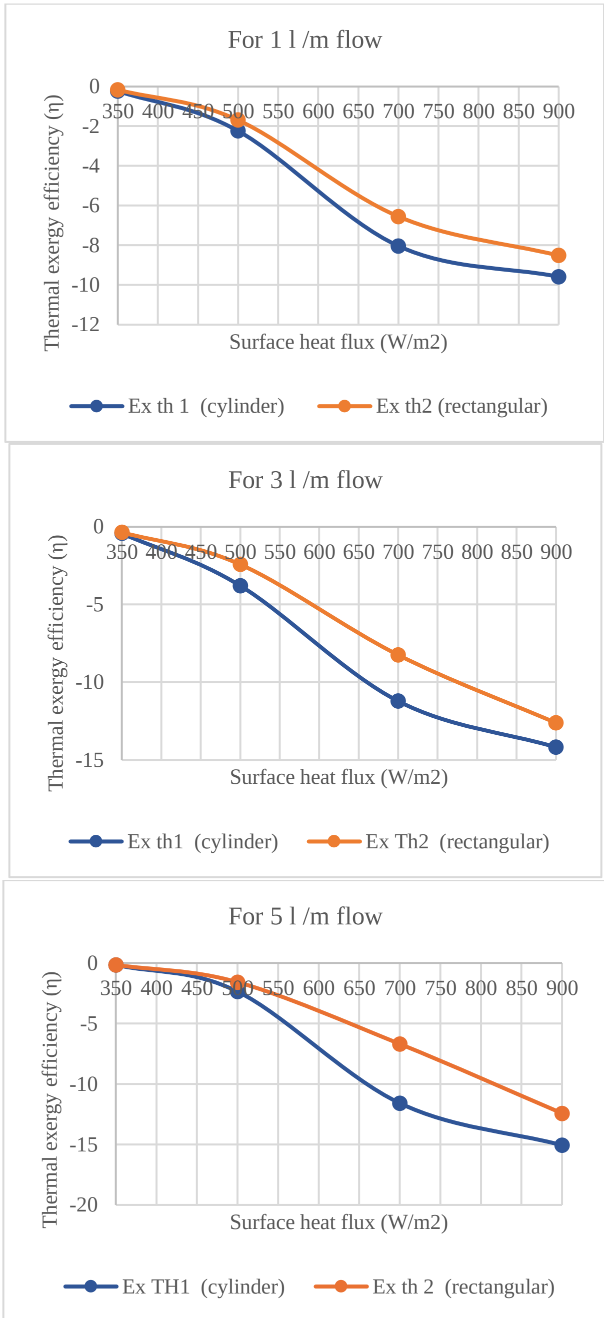


Figure 7. The difference in the thermal exergy efficiency of the panel for various water flow mass rate

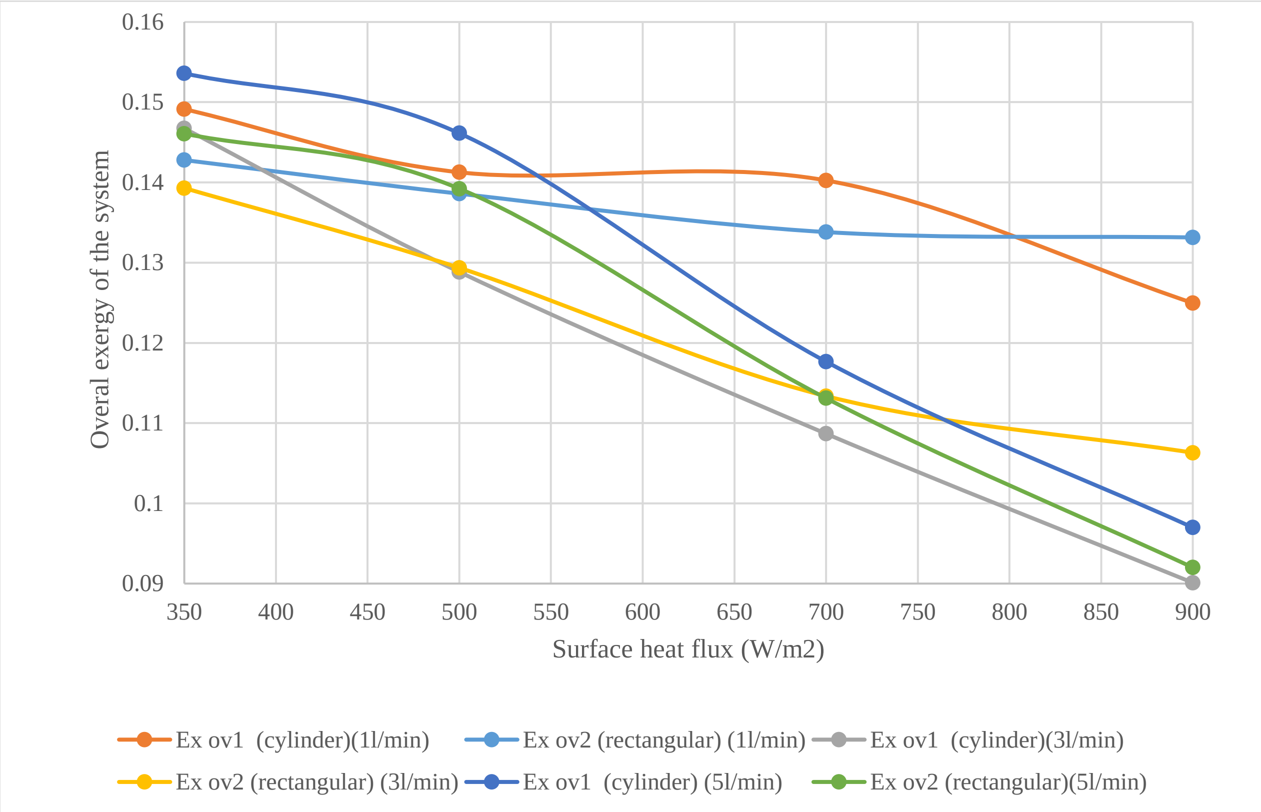


Figure 8. The difference in the overall exergy efficiency of the panel for various water flow mass rate

Figure 8 illustrates the variation in overall exergy efficiency (η_{ov}) of the PVT system as a function of increasing surface heat flux under different water flow rates (1, 3, and 5 L/min) and fin configurations, revealing a general downward trend in efficiency attributable to heightened thermal irreversibilities and entropy generation at elevated heat inputs. At the lowest flow rate of 1 L/min, the system initially achieves the highest exergy efficiency due to minimal thermal inertia and rapid thermal response, with cylindrical fins marginally outperforming rectangular ones; however, this advantage diminishes rapidly as surface heat flux increases, and efficiency drops sharply to approximately 0.12 at 1000 W/m². This decline reflects insufficient heat removal capacity and excessive exergy destruction under limited coolant flow. At 3 L/min, the initial exergy efficiency is comparatively lower, but the reduction with heat flux is more gradual, suggesting improved thermal stabilization and a more balanced heat extraction-to-generation ratio. Cylindrical fins continue to exhibit a consistent performance edge due to their geometry promoting turbulent flow and enhanced convective heat transfer. At the highest flow rate of 5 L/min, the system demonstrates the most stable exergy response across the heat flux spectrum, albeit with the lowest starting efficiency; cylindrical fins maintain approximately 0.1 efficiency at 1000 W/m², underscoring their effectiveness in sustaining thermal equilibrium. This behavior highlights a trade-off between initial thermal responsiveness and sustained exergy performance. The superior behavior of cylindrical fins can be attributed to their increased surface area-to-volume ratio, which facilitates improved convective heat dissipation and lowers localized temperature gradients, thereby reducing thermal resistance and enhancing overall system exergy performance. These observations reinforce the necessity for integrated thermal-hydraulic design optimization, including fin geometry and flow rate tuning, to minimize exergy losses and sustain high-efficiency operation under dynamic environmental and thermal loading conditions.

7. CONCLUSION

This study presents a comprehensive thermodynamic and performance evaluation of a photovoltaic-thermal (PVT) water cooling system equipped with two distinct copper fin geometries—cylindrical and rectangular—under three different water flow rates (1, 3, and 5 L/min). The core innovation of this work lies in its detailed analysis of thermal exergy efficiency across varying operating conditions, providing a nuanced understanding of how geometry and cooling rate affect energy utilization and entropy generation.

The findings reveal that cylindrical fins consistently enhance electrical efficiency, achieving up to 64% electrical exergy efficiency and 80% thermal efficiency at a flow rate of 5 L/min and 1000 W/m² heat flux, primarily due to increased surface area and turbulence-induced convective heat transfer. However, rectangular fins exhibit a notable performance advantage in terms of thermal exergy efficiency, particularly at lower to intermediate flow rates (1–3 L/min) and moderate heat flux levels, where thermal irreversibilities are less dominant. For example, at 3 L/min and 800 W/m², rectangular fins surpassed cylindrical fins by up to 2% in thermal exergy efficiency, suggesting better thermal uniformity and reduced entropy generation.

Despite these insights, the study also acknowledges that an optimized design configuration combining flow rate, fin geometry, and operating heat flux has not yet been fully identified. Future work should incorporate a parametric optimization approach, possibly leveraging multi-objective algorithms, to determine the optimal fin geometry and flow rate combination that maximizes overall exergy efficiency while maintaining structural and economic feasibility.

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