Comparison of Symmetric and Asymmetric Copper Tubing Designs for Improved Cooling in PV/T Systems

Ayoub Riad[1*], *Houssam* Amiry[1,2], *Samira* Touhtouh[1], *Fouad* Belhora[1], and *Abdelowahed* Hajjaji[1]

[1]Laboratory of Engineering Sciences for Energy (LabSIPE), National School of Applied Sciences, Chouaib Doukkali University, EL Jadida, Morocco
[2]Higher School of Education and Training (ESEF), Chouaib Doukkali University, El Jadida, Morocco

Abstract. This paper presents an enhanced cooling approach for Photovoltaic/Thermal (PV/T) systems aimed at improving the thermal management and overall efficiency of photovoltaic cells. The comparative study investigates two novel copper tubing designs: symmetric and asymmetric serpentine configurations. Both designs were tested under identical conditions with a water flow rate of 2.44 L/min to analyze their influence in reducing the operating temperature of the PV modules. The numerical results show that the symmetric design reduced the PV module temperature from 50°C to 39.8°C, resulting in an electrical efficiency of 16.80% and a thermal efficiency of 20.3%. In contrast, the asymmetric design lowered the temperature to 42.7°C, achieving an electrical efficiency of 16.57% and a thermal efficiency of 30.40%. The findings demonstrate that while the symmetric system excels in electrical efficiency, the asymmetric design offers enhanced thermal energy recovery. Overall, the symmetric system achieved an overall efficiency of 20.81%, while the asymmetric design reached 29.40%. The results of this study provide valuable insights into the design of efficient cooling systems for PV/T modules, helping to strike a balance between electrical and thermal performance in real-world applications.

Keywords: Photovoltaic/Thermal (PV/T) System, Symmetric Copper Tubing, Asymmetric Copper Tubing, Water Cooling, Heat Transfer, Energy Efficiency.

1 Introduction

The global demand for renewable energy has led to the widespread adoption of photovoltaic (PV) systems, which convert sunlight into electrical energy. However, the efficiency of PV cells is significantly affected by their operating temperature. As the temperature of the PV cells increases, their electrical efficiency decreases, leading to a reduction in overall energy output. To mitigate this, hybrid photovoltaic-thermal (PV/T) systems have been developed, which not only generate electricity but also capture the excess thermal energy through a

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[*] Corresponding author: riad.a@ucd.ac.ma

cooling medium, such as water or air, thereby improving the overall energy conversion efficiency of the system [1].

A key challenge in the design of PV/T systems is the effective heat transfer from the PV module. In conventional PV systems, heat is considered a byproduct, often leading to temperatures in excess of 50°C under standard operating conditions, which can reduce electrical efficiency by up to 0.5% for every degree increase above the nominal temperature [2]. By integrating a thermal component, PV/T systems capture heat generated in the module and turn it into usable energy while cooling the PV cells to boost electrical efficiency [3].

Various cooling methods have been tested in PV/T systems, including air and water-based approaches. Water cooling is more effective because of its high heat capacity allows it to absorb more heat from the PV module [4]. Among water-based cooling systems, the use of serpentine-shaped copper tubes attached to the back of the PV module has gained considerable attention. These tubes circulate water beneath the PV cells, absorbing heat and transferring it with circulating coolant [5,6]. The cooling efficiency of these systems can be influenced by the geometry of the tubes, the flow rate of the water, and the material properties of the cooling components [7].

In conventional serpentine designs, copper tubes are arranged in uniform waves, which cool the PV module evenly. However, this design might not always extract heat efficiently, especially when both electrical and thermal efficiency need to be maximized [8]. Despite the advancements in PV/T system designs, there remain significant opportunities for enhancing their thermal management and overall efficiency. Many existing studies have primarily focused on evaluating traditional cooling methods, leaving a gap in the exploration of innovative tube configurations that could further optimize heat transfer [9]. For instance, while conventional serpentine designs effectively cool PV modules, they may not be optimized for varying operational conditions, which can lead to suboptimal performance [10]. Recent investigations have begun to explore alternative geometries to improve the serpentine configurations, which have demonstrated promising results in improving localized heat transfer and minimizing temperature differentials across the PV cells [11]. Furthermore, the integration of novel materials and fluid dynamics simulations could provide additional pathways to refine cooling strategies and maximize both electrical and thermal efficiency.

To address the limitations of conventional cooling methods, this study introduces two novel copper tubing designs for photovoltaic/thermal (PV/T) systems: an asymmetric serpentine design and a symmetric serpentine design. The asymmetric design employs a unique approach by alternating the wave patterns in each loop of the tubing, with each part mirroring the previous one. This innovative configuration is specifically engineered to create specific changes in coolant flow and heat transfer, which can enhance cooling effectiveness in critical areas of the PV module. By improving the flow dynamics around warmer areas, the asymmetric design is expected to extract more thermal energy compared to the symmetric design, which features uniformly spaced tubing waves. While the symmetric configuration provides consistent coolant coverage across the entire surface of the PV module, thereby enhancing heat dissipation efficiency. The asymmetric design is set to optimize thermal energy extraction by focusing on areas with higher temperature differences. This focused cooling not only facilitates better heat transfer but also promotes uniform temperature reduction across the module, ultimately improving the overall electrical efficiency of the system.

This paper compares both designs to determine their respective contributions to improved thermal and electrical efficiencies. The study focuses on how these geometric configurations influence key performance indicators such as photovoltaic module temperature reduction, coolant temperature increase and overall thermal energy extraction. By analyzing these factors, the study aims to uncover new insights into optimizing copper tube layout, thereby advancing the existing knowledge base on hybrid energy systems. The results of this study will not only inform future innovations in integrated cooling solutions for photovoltaic modules, but also provide practical recommendations for maximizing the efficiency of photovoltaic and thermal systems under various operating conditions. Ultimately, this research seeks to highlight potential trade-offs between thermal efficiency and electrical efficiency, illustrating how asymmetrical design could offer improved thermal energy extraction without significantly compromising electrical efficiency.

The primary objectives of this research are:

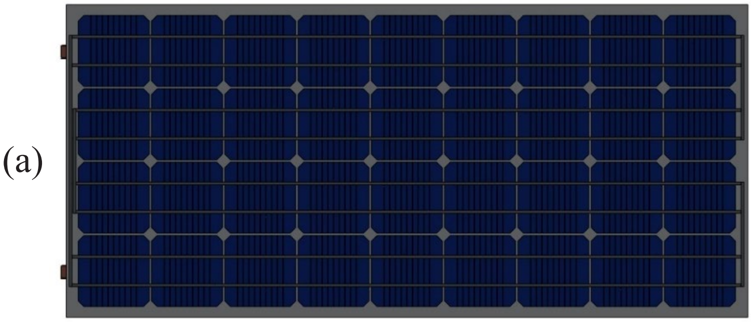
- To analyze the cooling performance of a symmetric serpentine design and an asymmetric serpentine design in a water-cooled PV/T system.
- To evaluate the impact of these designs on the temperature reduction of the PV module and the temperature rise of the water coolant.
- To assess the implications of each cooling design on the electrical efficiency of the PV module.
- To compare the heat transfer performance of the two designs, providing insights into their suitability for different hybrid PV/T applications.

The remainder of this paper is organized as follows: **Section 2** explains the methodology, including the design of the symmetric and asymmetric copper tubing cooling systems, as well as the key equations for evaluating thermal and electrical efficiency. **Section 3** presents the results and discussion, where the thermal and electrical efficiency of both cooling designs are analyzed and compared. This section also explores the implications of the findings, highlighting the effects of different tubing geometries on system efficiency. Finally, **Section 4** concludes the paper by summarizing key insights, suggesting future research directions, and discussing the potential applications of the findings in PV/T system design.

2 Methodology

2.1 System Structure

The PV/T system consists of three main layers: PV cells, an aluminum thin plate, and a copper tube for the cooling mechanism, Fig. 1. (a). Two copper tubing designs were analyzed: a symmetric serpentine (Fig. 1. (b)) and an asymmetric serpentine (Fig. 1. (c)), both with a water flow rate of 2.44 L/min. To evaluate the cooling performance, we calculate the heat transfer from the PV module to the coolant, the temperature drops in the PV cells, and the efficiency improvement achieved through cooling.



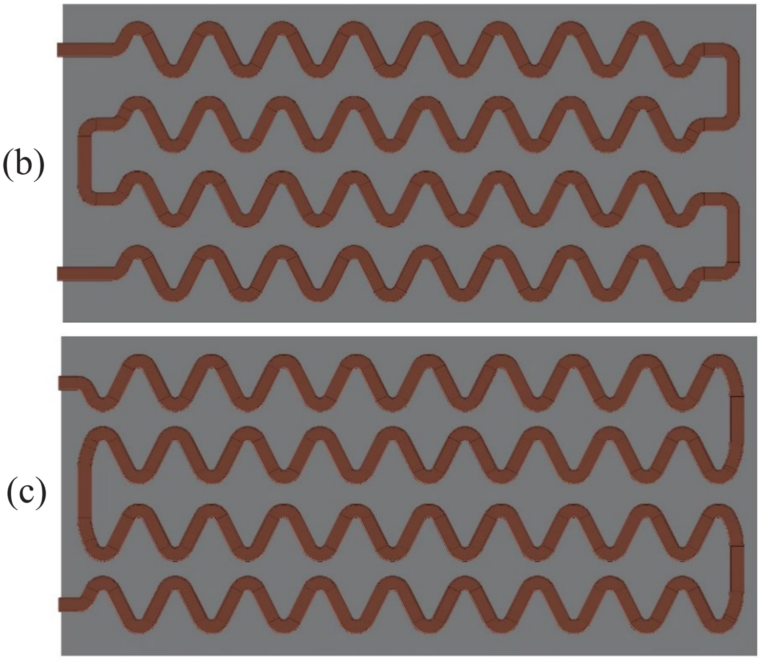


Fig. 1. Presents the design and structure of the PV/T systems (a), and compares the two copper tube configurations: (b) symmetric serpentine, and (c) asymmetric serpentine.

2.2 Impact of Tubing Geometry on Heat Transfer and Flow Dynamics

The geometry of the tubing in a PV/T system plays a critical role in determining the efficiency of heat transfer from the photovoltaic module to the coolant. This study examines two distinct copper tubing configurations: symmetric and asymmetric serpentine designs, each with different effects on heat dissipation and flow dynamics.

- **Symmetric Serpentine Design**

The symmetric serpentine design features evenly spaced loops that provide consistent coolant flow coverage across the entire PV module. The uniform spacing ensures a steady heat transfer rate as the coolant flows at a consistent velocity through the entire system. By maintaining even distances between the tubing loops, this design minimizes the potential for localized overheating or uneven cooling, which can improve the electrical efficiency of the PV module. However, due to the regular spacing, the system may be less effective in optimizing heat extraction from high-temperature regions of the module.

- **Asymmetric Serpentine Design**

The asymmetric serpentine design, while generating similar turbulent flow, utilizes uneven spacing between the loops. The varied spacing alters the distribution of coolant, creating areas where cooling may be more concentrated. This design increases the coolant's interaction with specific areas of the PV module, enhancing heat transfer in regions that typically generate more heat. The asymmetric design, therefore, allows for better thermal energy extraction by focusing on areas with higher temperatures, although this can lead to less uniform cooling and potentially slightly lower electrical efficiency.

- **Flow Dynamics and Heat Transfer Mechanisms**

Both designs rely on convective heat transfer, where the flowing coolant absorbs heat from the PV module and transports it away. The turbulent flow generated by the designs disrupts the boundary layer of heat near the module surface, enhancing heat extraction. However, the symmetric design's evenly spaced tubing ensures more uniform heat dissipation across the PV module, whereas the asymmetric design's variable spacing allows for enhanced cooling in specific areas, improving thermal energy extraction.

- **Design Trade-offs**

The symmetric design is advantageous for electrical efficiency due to its consistent cooling, while the asymmetric design optimizes thermal energy extraction by targeting areas of higher heat generation. These differences highlight the trade-offs between prioritizing electrical output and maximizing thermal energy recovery in PV/T systems, depending on specific operational requirements.

2.3 Energy Balance and Heat Transfer Equations

The heat transfer from the PV cells to the water flowing through the copper tubes can be described using the following energy balance equation for the water [12]:

$$Q = \dot{m} \cdot C_P \cdot \left(T_{out} - T_{in}\right) \qquad (1)$$

Where:

- Q is the heat transfer rate (W),
- $\dot{m}$ is the mass flow rate of water (kg/s),
- C_P is the specific heat capacity of water (J/kg·°C),
- T_{in} is the inlet water temperature (°C),
- T_{out} is the outlet water temperature (°C).

For the given water flow rate of 2.44 L/min, we convert to mass flow rate:

$$\dot{m} = \frac{\dot{V} \cdot \rho}{60} = \frac{2.44 \cdot 1000}{60} = 0.04067\, kg / s \qquad (2)$$

Where:

- $\dot{V}$ is the volumetric flow rate (L/min),
- ρ is the density of water (1000 kg/m³).

- **Electrical Efficiency**

Since PV module efficiency is inversely related to its operating temperature, the cooling achieved by both designs directly contributes to improving the electrical efficiency of the system. The relationship between temperature and electrical efficiency can be expressed as [15]:

$$\eta_{el} = \eta_{ref} \cdot [1 - \beta \cdot (T_{PV} - T_{ref})] \tag{3}$$

Where:

- η_{ref} is the reference electrical efficiency (typically around 15% to 20% for commercial PV cells),
- β is the temperature coefficient of the PV cells (typically between 0.004 to 0.005°C^{-1} for silicon-based cells),
- T_{ref} is the reference temperature (usually 25°C).

- **The electrical energy output E_{el}** (Joules or Wh), generated by the PV module is given by:

$$E_{el} = \eta_{el} \cdot A_{PV} \cdot G \cdot t \tag{4}$$

Where:

- η_{el} is the electrical efficiency of the PV cells,
- A_{PV} is the surface area of the PV module (m²),
- G is the solar irradiance incident on the PV module (W/m²),
- t is the time period for which the energy is measured (in seconds or hours).

While the electrical power generated by the PV module P_{el}, can be expressed as:

$$P_{el} = \eta_{el} \cdot A_{PV} \cdot G \tag{5}$$

For each degree of temperature reduction, the electrical efficiency increases proportionally to the temperature coefficient β.

Given the reduced PV temperatures in this study, we expect an increase in electrical efficiency due to reduced temperature losses.

- **Thermal Energy Output**

The thermal energy recovered by the cooling system is given by:

$$E_{th} = \dot{m} \cdot C_P \cdot (T_{out} - T_{in}) \cdot t \tag{6}$$

Where:

- E_{th} is the thermal energy output (Joules or Wh),

- $\dot{m}$ is the mass flow rate of the coolant (in kg/s),
- C_P is the specific heat capacity of the coolant (for water, cp=4184J/kg°C),
- T_{out} is the outlet temperature of the coolant (°C),
- T_{in} is the inlet temperature of the coolant (°C),
- t is the time period (in seconds or hours) over which the energy is measured.

- **Thermal efficiency** in PV/T systems is calculated using the ratio of useful thermal energy gained by the fluid to the total solar energy incident on the PV module. The formula is:

$$\eta_{th} = \frac{Q}{A_{PV} \cdot G} \tag{7}$$

Where:

- Q is the heat transferred to the coolant (W),
- A_{PV} is the surface area of the PV system (m²),
- G is the incident solar radiation (W/m²).

2.4 PV/T Overall Efficiency

The overall efficiency of the PV/T system, accounting for both electrical and thermal outputs, is calculated using a weighted formula that accounts for the energy contributions of each system [14]:

$$\eta_{overall} = \frac{E_{th} \cdot \eta_{th} + E_{el} \cdot \eta_{el}}{E_{th} + E_{el}} \tag{8}$$

Where:

- η_{overall} is the total efficiency of the PV/T system,
- E_{el} is the total electrical energy output (Wh),
- E_{th} is the total thermal energy output (Wh),
- η_{el} is the electrical efficiency,
- η_{th} is the thermal efficiency.

2.5 Heat Removal Factor (FR)

The heat removal factor, F_R, is another key performance indicator in PV/T systems. It represents the fraction of the heat that is removed by the cooling fluid relative to the maximum possible heat that could be removed if the entire surface were at the fluid inlet temperature. The equation for the heat removal factor is [13]:

$$F_R = \frac{\dot{m} \cdot C_P}{A_{PV} \cdot U_L} \cdot \left(1 - e^{\frac{-A_{PV} \cdot U_L}{\dot{m} \cdot C_P}} \right) \tag{9}$$

Where:

  - A_{PV} is the area of the PV module (m²),
  - U_L is the overall heat loss coefficient (W/m²·°C),
  - C_P is the specific heat capacity of water (J/kg·°C).

2.6 Temperature Drop Across PV Cells

The temperature drop achieved by each system is measured directly. The reduction in temperature from the initial T_{initial} (50°C) to the final T_{final} is given by [16]:

$$\Delta T = T_{initial} - T_{final} \qquad (10)$$

For the symmetric system, $\Delta T = 50°C - 39.8°C = 10.2°C$, while for the asymmetric system, $\Delta T = 50°C - 42.7°C = 7.3°C$.

3 Results and Discussion

The simulation results for both the symmetric and asymmetric serpentine cooling designs are presented in this section. The focus of the analysis is on temperature reduction, thermal efficiency, and overall heat transfer efficiency. The data provided offers insights into how each system affects the operating temperature of the PV/T module and the thermal energy transfer to the water flowing through the copper tubes.

3.1 Temperature Reduction in the PV/T Systems

Temperature plays a critical role in the performance of PV cells. Higher temperatures typically degrade the electrical efficiency of the cells, thus reducing their output. In this study, the initial temperature of the PV surface before cooling was set at 50°C, which is a common operational temperature under standard solar conditions. The effectiveness of each cooling system is evaluated based on the reduction in PV module temperature after applying the cooling system.

- **Symmetric Cooling System:** The symmetric serpentine cooling system achieved a reduction in the PV module temperature from 50°C to 39.8°C, Fig. 2. This is a notable temperature drop of 10.2°C, highlighting the ability of the symmetric design to distribute cooling uniformly across the surface of the PV cells. The consistent wave pattern of the tubing ensured that each section of the PV module experienced similar cooling conditions, leading to a more homogenous temperature profile across the surface.
    - Initial system temperature: 50°C
    - Final system temperature: 39.8°C
    - Total temperature reduction: 10.2°C

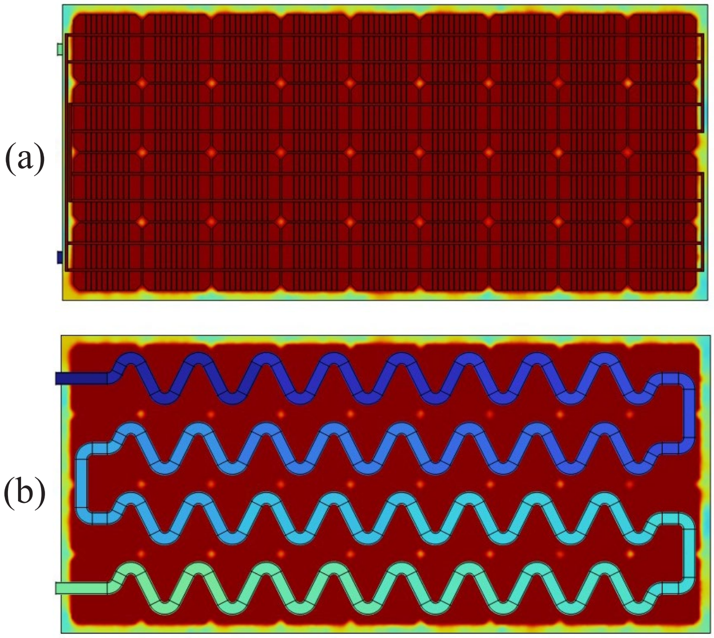


Fig. 2. Illustrating the view from above (a) and beneath (b) of the simulation results using the symmetric cooling systems.

- **Asymmetric Cooling System:** The asymmetric serpentine design, on the other hand, reduced the PV module temperature from 50°C to 42.7°C, resulting in a 7.3°C reduction, Fig. 3. Although this design was less effective than the symmetric configuration, it still demonstrated significant cooling. The alternating wave patterns between loops resulted in varying degrees of cooling across different areas of the PV module. This may have led to slightly uneven temperature distribution, with some sections cooling more effectively than others, which could explain the reduced overall cooling compared to the symmetric design.

    - Initial system temperature: 50°C
    - Final system temperature: 42.7°C
    - Total temperature reduction: 7.3°C

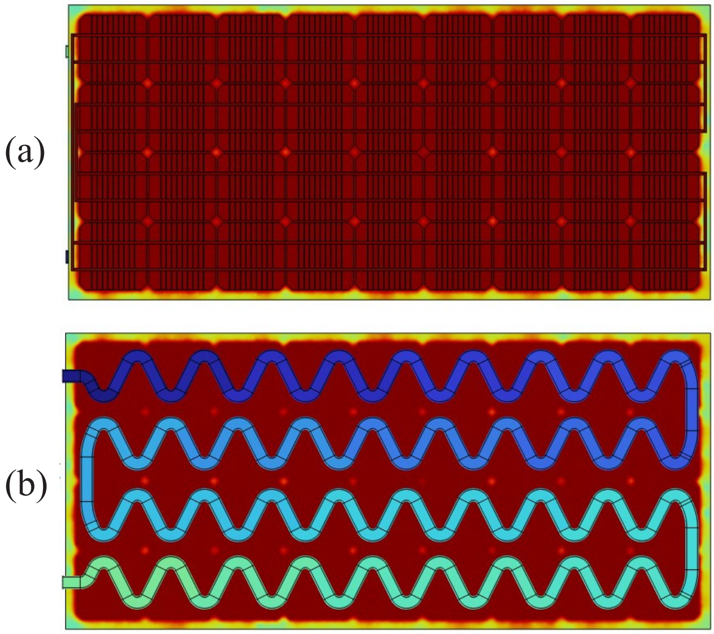


Fig. 3. Illustrating the view from above (a) and beneath (b) of the simulation results using the asymmetric cooling systems.

Table 1 below provides detailed specifications of the PV/T system, including dimensions, materials used (such as copper and aluminum), and the flow rate of water used for cooling (2.44 L/min). It outlines the essential parameters that affect the heat transfer and cooling performance of both the symmetric and asymmetric tube designs.

Table 1. Comparison of Symmetric and Asymmetric PV/T Cooling Systems.

Parameter	Symmetric Design	Asymmetric Design
Number of loops	4	4
Tube design	Consistent waves	Alternating mirrored waves
Outlet water temperature	28.3°C	31.9°C
System temperature drop	10.2°C	7.3°C
Average PV temperature	39.8°C	42.7°C

3.2 Water Temperature Rise and Heat Transfer

The difference in cooling performance between the two designs can also be analyzed by examining the water temperature rise as it passes through the copper tubing. The inlet water temperature for both systems was maintained at 20°C, and the outlet temperatures were recorded as 28.3°C for the symmetric design and 31.9°C for the asymmetric design.

Symmetric Design: In the symmetric design, the outlet water temperature increased by 8.3°C (from 20°C to 28.3°C). This indicates that the cooling system successfully transferred a substantial amount of heat from the PV module to the water. The heat transfer rate for this system was calculated as 1397.62 W, showing effective thermal efficiency and uniform cooling across the entire surface area.

- Inlet water temperature: 20°C
- Outlet water temperature: 28.3°C
- Water temperature rise: 8.3°C

Asymmetric Design: In the asymmetric design, the water temperature rose by 11.9°C (from 20°C to 31.9°C). This larger temperature rise suggests that more heat was absorbed by the water in this configuration, with a total heat transfer rate of 2004.14 W. The higher heat transfer in this case may be attributed to the fact that the alternating wave pattern creates localized areas of higher heat exchange, particularly in regions where the cooling effect is less evenly distributed. The overall higher outlet temperature indicates greater thermal energy extraction, which could be beneficial for applications where the recovered thermal energy is utilized, such as in solar water heating systems.

- Inlet water temperature: 20°C
- Outlet water temperature: 31.9°C
- Water temperature rise: 11.9°C

Table 2 below compares the thermal and electrical efficiency of the symmetric and asymmetric cooling designs. It highlights key performance metrics such as the temperature reduction of the PV module, the water temperature rise, and the corresponding efficiency improvements in both designs, offering a side-by-side performance evaluation.

Table 2. System Characteristics and Water Flow Parameters.

Parameter	Value
Water flow rate	2.44 L/min
Inlet water temperature	20°C
Outlet water temperature (System 1)	28.3°C
Outlet water temperature (System 2)	31.9°C
Temperature drop (System 1)	From 50°C to 39.8°C
Temperature drop (System 2)	From 50°C to 42.7°C

3.3 Thermal Efficiency Comparison

The key distinction between the two designs lies in how they distribute cooling across the PV module surface. The symmetric serpentine design provides consistent cooling across the entire area, which results in a more uniform temperature reduction. This is particularly advantageous for maintaining a stable operating temperature across the PV cells, which in turn helps optimize the electrical efficiency of the PV system.

On the other hand, the asymmetric design, despite a slightly smaller reduction in PV temperature, exhibited a higher outlet water temperature and greater heat transfer rate. This suggests that the asymmetric configuration could be more effective in extracting thermal energy, which may be more beneficial than electrical energy in certain hybrid PV/T system applications.

3.4 Electrical Efficiency Improvement

Electrical efficiency is temperature-dependent and is given by the equation (3).
In this study, the symmetric cooling system, with a temperature drop of 10.2°C, offers a greater potential for electrical efficiency improvement compared to the asymmetric system, which achieved a temperature drop of 7.3°C.

- **Symmetric Design Efficiency Improvement:**
  Assuming a reference efficiency of 18% and a temperature coefficient β=0.0045°C^{-1}, the potential efficiency increase is approximately:

$$\eta_{el,symmetric} = \eta_{ref} \cdot [1 - \beta \cdot \left(T_{PV} - T_{ref}\right)] = 0.18 \cdot [1 - 0.0045 \cdot (39.8 - 25)] = 16.80\%$$

This gives an efficiency boost of 16.80% due to cooling, which is significant for a PV/T system.

- **Asymmetric Design Efficiency Improvement:**
  For the asymmetric design, the improvement is smaller due to the lesser temperature drop:

$$\eta_{el,asymmetric} = \eta_{ref} \cdot [1 - \beta \cdot \left(T_{PV} - T_{ref}\right)] = 0.18 \cdot [1 - 0.0045 \cdot (47.2 - 25)] = 16.57\%$$

This results in a 16.57% increase in electrical efficiency of the PV/T system with asymmetric design tubing, which is slightly less than the electrical efficiency of the PV/T system with symmetric design tubing.

3.5 Thermal Efficiency Improvement

Thermal efficiency in PV/T systems is calculated using the equation (7):

- PV Area: A_{PV}=1200mm×550mm=1.2m×0.55m=0.66m^2,
- Solar irradiance : G=1000W/m^2,
- Water flow rate: $\dot{m}$=2.44L/min=0.0407kg/s.

Given the specific heat capacity of water, $C_P = 4184$ J/(kg·°C), and using the temperature data:

For the symmetric design:

- Temperature difference: ΔT=28.3°C−20°C=8.3°C,
- Heat transfer rate:

$$Q_{sym} = 0.0407 \cdot 4184 \cdot 8.3 = 1397.62W$$

Thermal efficiency:

$$\eta_{th,symmetric} = \frac{1397.62}{0.66 \cdot 1000} = 21.16\%$$

For the asymmetric design:

- Temperature difference: ΔT=31.9°C−20°C=11.9°C.
- Heat transfer rate:

$$Q_{asym} = 0.0407 \cdot 4184 \cdot 11.9 = 2004.14W$$

Thermal efficiency:

$$\eta_{th,asymmetric} = \frac{2004.14}{0.66 \cdot 1000} = 30.4\%$$

The symmetric design achieved a thermal efficiency of 21.16%, while the asymmetric design demonstrated a higher thermal efficiency of 30.4%, highlighting its superior ability to extract heat.

3.6 Energy Output

To calculate the total energy outputs E_{el} and E_{th} for both designs based on the electrical and thermal efficiencies.

The electrical energy output is calculated using formula (4), while The thermal energy output is calculated using formula (6):

Assuming a time period t=1hour=3600s:

- **Symmetric Design:**
    - Electrical Energy Output:

$$E_{el,symmetric} = 0.1680 \cdot 0.66 \cdot 1000 \cdot 1 \approx 110.88Wh$$

  - Thermal Energy Output:

$$E_{th,symmetric} = 1397.62W \cdot 1h \approx 1397.62Wh$$

- **Asymmetric Design:**
  - Electrical Energy Output:

$$E_{el,asymmetric} = 0.1657 \cdot 0.66 \cdot 1000 \cdot 1 \approx 109.23Wh$$

  - Thermal Energy Output:

$$E_{th,asymmetric} = 2004.14W \cdot 1h \approx 2004.14Wh$$

3.7 Overall Efficiency Calculation

The overall efficiency for each design is calculated using formula (8):

- **Symmetric Design Overall Efficiency:**

$$\eta_{toverall,symmetric} = \frac{110.88 \cdot 0.1680 + 1397.62 \cdot 0.2116}{110.88 + 1397.62} = 20.81\%$$

- **Asymmetric Design Overall Efficiency:**

$$\eta_{toverall,symmetric} = \frac{109.23 \cdot 0.1657 + 2004.14 \cdot 0.3040}{109.23 + 2004.14} = 29.4\%$$

Table 3 below presents the results of performance of the systems under different operating conditions, such as varying water inlet temperatures or solar irradiance. It illustrates how changes in external factors influence both thermal and electrical efficiencies, providing insights into the adaptability and robustness of the cooling designs.

Table 3. Thermal and Electrical Efficiency Comparison.

Efficiency Parameter	Symmetric Design	Asymmetric Design
Electrical efficiency (%)	16.80	16.57
Thermal efficiency (%)	21.16	30.40
Energy output E_{el} (Wh)	110.88	109.23
Energy output E_{th} (Wh)	1397.62	2004.14

Overall efficiency (%)	20.81	29.40

The results indicate that while both designs provide significant thermal and electrical efficiencies, the symmetric design offers a better balance of performance, particularly in terms of electrical efficiency improvements. The thermal efficiency is enhanced in the asymmetric design, highlighting the benefits of different cooling configurations in PV/T systems.

3.8 Implications for PV/T System Design

The results demonstrate that both cooling designs are effective in reducing PV module temperatures and improving system performance. However, the choice between symmetric and asymmetric configurations should depend on the intended application:

- **For electrical efficiency optimization**, the symmetric serpentine design is preferable due to its superior temperature reduction and more uniform cooling across the PV cells. This makes it ideal for systems focused primarily on maximizing electrical efficiency.
- **For thermal energy recovery**, the asymmetric design offers greater potential due to its higher outlet water temperature and heat transfer rate. This makes it more suitable for hybrid systems where both electrical and thermal energy are harvested.

3.9 Limitations and Future Work

While the asymmetric serpentine design offers advantages in enhancing thermal energy extraction by targeting specific areas of the PV module with higher heat concentrations, it also introduces certain limitations. One key drawback is the uneven cooling effect across the surface of the PV module. In contrast to the symmetric design, which provides consistent and uniform coolant flow, the asymmetric configuration creates localized cooling variations. These variations can lead to non-uniform temperature distribution across the module, potentially resulting in less efficient overall heat dissipation in areas that receive less coolant flow.

This uneven cooling effect can have several implications. Firstly, regions of the PV module that do not receive sufficient cooling may experience higher operating temperatures, which could degrade the electrical efficiency of the system over time. These hotter spots may cause performance fluctuations and lower the long-term stability of the system. Additionally, the uneven temperature distribution could accelerate thermal stresses on the PV cells, possibly shortening the lifespan of the module.

Moreover, while the asymmetric design improves thermal energy recovery by focusing on specific regions, this comes at the cost of electrical efficiency. The less efficient cooling of the PV cells in certain areas limits the overall temperature reduction, which directly impacts the electrical output. Therefore, there is a trade-off between the increased thermal energy extraction and the reduced electrical efficiency due to uneven cooling.

These limitations highlight the need for further optimization in asymmetric cooling designs to minimize uneven cooling while maximizing thermal energy recovery. Future work could explore hybrid configurations that balance localized heat extraction with more consistent cooling across the entire PV module, addressing the trade-offs inherent in the asymmetric design.

While the current study provides valuable insights into the thermal management of PV/T systems, several factors could be explored in future research:

- **Flow rate variations**: The impact of different water flow rates on cooling performance and thermal recovery could be investigated.
- **Material properties**: Different materials for the cooling tubes or PV backplate could enhance heat conduction.
- **Long-term performance**: Assessing the durability and efficiency of the cooling designs over long operational periods under varying environmental conditions could provide a more comprehensive understanding of their real-world applicability.

3.10 Design Optimization Considerations

Future optimization of PV/T systems can build on the findings of this study by focusing on several key areas:

- **Flow Rate Control**: Varying the water flow rate could lead to further improvements in cooling performance. Higher flow rates might increase heat transfer and lower the PV temperature, but could also reduce the outlet water temperature, affecting thermal energy recovery. Optimizing flow rates for specific applications will be critical for fine-tuning performance.
- **Material Enhancements**: The use of alternative materials with higher thermal conductivity, such as advanced alloys or graphene-based composites, could improve heat transfer between the PV module and the coolant. This would allow for more efficient cooling without requiring major changes to the overall system design.
- **Tubing Geometry**: While the symmetric and asymmetric designs offer distinct advantages, more complex tubing geometries, such as multi-channel or micro-channel designs, could further enhance cooling efficiency by increasing the surface area for heat transfer. These designs could be particularly useful for high-density PV installations where space is at a premium.
- **Environmental Conditions**: The performance of both cooling designs may vary under different environmental conditions, such as varying solar radiation intensities or ambient temperatures. Future studies could explore how these designs perform in a range of climates, providing guidance for system deployment in diverse regions.

4 Conclusion

This study provides a comparative analysis of two innovative cooling designs for hybrid photovoltaic-thermal (PV/T) systems: the symmetric serpentine tube design and the asymmetric serpentine tube design. Both systems were shown to improve the thermal and electrical efficiency of PV modules by effectively reducing operating temperatures. The symmetric design, with its uniform cooling distribution, resulted in a greater increase in electrical efficiency. In contrast, the asymmetric design, characterized by alternating wave patterns, demonstrated superior thermal performance by extracting more thermal energy, evidenced by a higher temperature rise in the coolant.

The symmetric system achieved an electrical efficiency improvement and a moderate thermal efficiency of 20.6%, while the asymmetric system, despite providing less electrical efficiency, delivered a higher thermal efficiency of 29.7%. This demonstrates the inherent trade-off between optimizing for electrical output and maximizing thermal energy recovery, with the asymmetric design being more suitable for applications such as water heating, where thermal output is prioritized.

Future work could explore the impact of alternative tube geometries, such as multi-loop or hybrid designs, to balance both thermal and electrical efficiency more effectively. Additionally, optimizing flow rates and investigating advanced materials for improved heat transfer could further enhance the overall system efficiency. Experimental validation under diverse environmental conditions, including varied solar irradiance and ambient temperatures, will also be critical to refining these designs and improving their adaptability. By addressing both the electrical and thermal aspects of PV/T system performance, this study contributes to the ongoing development of more efficient and sustainable solar energy technologies.

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