

# Integrated Optimization of Solar Photovoltaic Systems Using Taguchi Method and Computational Fluid Dynamics for Enhanced Efficiency

Shahina Momin<sup>1\*</sup>, M.M. Mirza<sup>2</sup>

## Abstract

*The transition to renewable energy demands efficient and reliable photovoltaic (PV) systems to meet rising global energy needs. This study presents an integrated optimization framework combining the Taguchi method and Computational Fluid Dynamics (CFD) to improve the thermal and electrical performance of solar PV systems. A structured experimental design using an L9 orthogonal array evaluates the influence of three key parameters—material type, panel thickness, and cooling mechanism—on system efficiency. Analysis of variance (ANOVA) identifies the relative contribution of each factor, with material type contributing 40%, cooling 35%, and thickness 25%. The optimal configuration (monocrystalline, 2.0 mm thickness, and liquid cooling) achieved an actual efficiency of 19.7%, closely matching the predicted 19.9%. CFD simulations in ANSYS Fluent validated thermal improvements by simulating heat dissipation under varying boundary conditions, highlighting liquid cooling as the most effective strategy. The hybrid approach demonstrates the value of integrating design of experiments with numerical modeling to produce scalable, high-performance PV solutions. This methodology not only enhances PV system design but also offers a replicable framework for multi-parameter optimization in other renewable energy technologies.*

**Keywords:** Taguchi method, computational fluid dynamics (CFD), thermal management, PV efficiency, ANOVA analysis

## INTRODUCTION

The growing global energy demand, coupled with environmental degradation caused by fossil fuel consumption, has accelerated the transition toward renewable energy sources. Among these, solar photovoltaic (PV) systems are the leading technologies for sustainable electricity generation. These systems harness solar energy via the photovoltaic effect and offer a clean, renewable, and widely available energy source [1–5, 14, 22].

### \*Author for Correspondence

Shahina Momin

E-mail: shahinamomin123@gmail.com

<sup>1</sup>Student, Department of Mechanical Engineering, Rajarambapu Institute of Technology, Sangli, Maharashtra, India

<sup>2</sup>Professor, Department of Mechanical Engineering, Rajarambapu Institute of Technology, Sangli, Maharashtra, India

Received Date: August 01, 2025

Accepted Date: August 13, 2025

Published Date: October 08, 2025

**Citation:** Shahina Momin, M.M. Mirza. Integrated Optimization of Solar Photovoltaic Systems Using Taguchi Method and Computational Fluid Dynamics for Enhanced Efficiency. Recent Trends in Fluid Mechanics. 2025; 12(3): 10–25p.

Solar energy is one of the most abundant resources on Earth, providing a scalable solution to meet global energy needs while minimizing greenhouse gas (GHG) emissions. Unlike conventional centralized power systems, solar PV offers decentralized generation, making it suitable for remote or off-grid areas. Supported by declining module costs and government incentives, global PV deployment has surged, surpassing 1 terawatt (TW) of installed capacity by 2023 [8, 11, 15–18].

## LITERATURE REVIEW

Several studies have explored optimization techniques for photovoltaic/thermal (PV/T) systems

to improve their efficiency and thermal regulation. Prabowo et al. [1] optimized a PV/T-TEG collector using the Taguchi method and analyzed the fin configuration, height, thickness, air flow rate, and heat absorption. The optimal settings included a full fin arrangement (75 mm height, 3 mm thickness, 80 g/s airflow, and 400 W/m<sup>2</sup> heat absorption) for the PV temperature and a staggered fin layout for TEG performance under 800 W/m<sup>2</sup> heat input. Kuo et al. [2] employed the Taguchi and AHP techniques to enhance the PV/T system performance, achieving electrical and thermal efficiencies of 14.29% and 44.96%, respectively. The CFD simulations validated a 10°C temperature drop with a strong correlation ( $R^2 = 0.991$ ) between the predicted and actual values.

Pham et al. [3] investigated solar air heater ducts with varying baffle parameters using Taguchi-based CFD. An optimal configuration (90° baffle angle, 6 spacing ratio, and 0.375 blockage ratio) achieved maximum thermohydraulic performance at  $Re = 5000$ . Huang et al. [4] compared integrated PV/T solar systems with conventional solar water heaters, highlighting a daily primary energy efficiency of 0.38 and economic viability.

Makki et al. [5] reviewed cooling techniques for PV modules, including air, liquid, heat pipes, phase change materials (PCMs), and thermoelectric devices, emphasizing the importance of thermal management in maintaining efficiency. Al-Damook et al. [6] proposed a hybrid PV/T air system using CFD and an experimental design, achieving a thermal efficiency of 50.1% and an electrical efficiency of 10.5% with a co-current air flow setup.

Solanki et al. [7] conducted experiments with a PV/T solar heater using a wooden duct and a DC fan and applied genetic algorithms to optimize the energy output. Joshi and Dhoble [8] emphasized the rear-surface heat extraction using fluid circulation in PVT systems. Hussain et al. [9] analyzed solar radiation availability in Iraq, while Al-Kayiem et al. [10] conducted a techno-economic assessment of a 50 kW concentrated solar system.

Khordehghah et al. [11] enhanced the PV/T system with electrical and thermal storage, improving the output by 12%. Abdul-Ganiyu et al. [12] found that real-life PVT systems in Ghana generated 2.72 kWh/kWp/day compared to 3.21 kWh/kWp/day from standard PV. Kulkarni et al. [13] reported a 2.17% increase in efficiency when using a PVT panel.

The foundation of the PV/T design is the use of a heat-transfer fluid to manage the PV cell temperature. However, as noted by Ramos et al. [14], achieving a higher thermal output often conflicts with electrical efficiency because higher operating temperatures degrade PV performance. Herrando et al. [15] highlighted the need for trade-offs in system design based on specific applications and climatic conditions.

### Optimization Techniques in PV Systems

Optimization has been a cornerstone for improving PV systems, with researchers focusing on variables such as material properties, thickness, orientation, and cooling strategies. Traditional methods often rely on trial-and-error experimentation, which is time consuming and resource intensive. Recent advancements have introduced more sophisticated techniques, such as genetic algorithms, neural networks, and Taguchi design of experiments, which provide systematic approaches for identifying the best configurations for PV performance [19–21].

### Taguchi Method in Engineering Applications

The Taguchi method has gained prominence in various engineering fields owing to its efficiency in terms of experimental design and analysis. Originally developed for quality control in manufacturing, this method has been applied to optimize the parameters of renewable energy systems, including wind turbines and solar collectors. Its use in PV systems focuses on factors such as the material type, thickness, and angle of inclination, offering a robust framework for achieving high efficiency with minimal experimental effort.

## **Computational Fluid Dynamics (CFD) in Thermal Management**

CFD has revolutionized the analysis of thermal and fluid behaviors in engineering systems, enabling detailed simulations of heat transfer, temperature gradients, and airflow dynamics. In the context of PV systems, CFD was used to model the cooling effects of natural convection, forced airflow, and active cooling mechanisms. These simulations provide critical insights into the thermal management of PV panels, which directly affects their electrical performance and longevity [9–17].

### **Research Gap**

While significant progress has been made in optimizing PV systems, there is a lack of studies that combine experimental optimization techniques, such as the Taguchi method, with advanced simulation tools, such as CFD. Furthermore, many studies have failed to validate their simulation findings using real-world experiments, limiting their practical applicability. This research aims to bridge these gaps by providing an integrated and validated framework for PV system optimization [23–26].

## **PROBLEM STATEMENT, NECESSITY, AND ISSUE**

### **Problem Statement**

The performance of solar PV systems is influenced by complex interactions among environmental, design, and operational factors. Traditional optimization methods often fail to address these complexities. This study proposes an integrated approach using the Taguchi method and Computational Fluid Dynamics (CFD) to identify and optimize key parameters, improve thermal management, and enhance overall system efficiency, reliability, and adaptability across diverse conditions.

### **Necessity of the Project**

It is necessary to address the critical issues that limit the performance and scalability of PV systems, with a focus on design optimization and thermal management.

1. Addressing Efficiency Losses in PV Systems.
2. Need for Systematic Design Optimization.
3. Importance of Thermal Management.
4. Bridging the Gap between Simulation and Experimentation.
5. Enhancing Renewable Energy Adoption.
6. Contribution to Sustainable Development Goals (SDGs).
7. Meeting Industry and Academic Needs.

### **Issues on solar energy optimization approaches**

Renewable energy systems (RESs) offer grid benefits, such as voltage stability, reduced losses, and lower tariffs. However, they face both technical and non-technical challenges including high capital costs, market barriers, and regulatory issues. Effective optimization depends on accurate weather data, load forecasting, and model precision. Variations in PV specifications and the need for simple yet accurate methods further complicate the optimization. Combining analytical and AI-based approaches can enhance reliability and effectiveness [27, 28].

## **METHODOLOGY**

### **Overview of Research Approach**

This study adopts a hybrid methodology that combines experimental optimization with computational simulation. The Taguchi method was employed to optimize the design parameters, such as material type, thickness, and orientation. CFD simulations were used to analyze the thermal behavior of the optimized configurations under realistic operating conditions.

### **Taguchi Methodology**

The Taguchi method involves designing experiments based on an orthogonal array, which reduces the number of trials required to evaluate multiple factors and levels. The parameters considered in this study include the material type (e.g., silicon-based vs. polymer-based cells), thickness (e.g., 1 mm, 2 mm, and 3

mm), and cooling mechanisms (e.g., passive and active airflow). The experimental results were analyzed using signal-to-noise ratios (SNRs) to identify the optimal settings for maximum efficiency.

### CFD Analysis Setup

CFD simulations were conducted using ANSYS Fluent to evaluate the heat dissipation and airflow dynamics. The geometry of the PV panels was modeled using CAD software and meshed for the simulation. The governing equations include the Navier-Stokes equations for fluid flow and energy equation for heat transfer. Boundary conditions such as solar irradiance, ambient temperature, and cooling flow rates were applied to mimic real-world scenarios.

### Integration and Validation

The findings from the Taguchi analysis were used as the input parameters for the CFD simulations. The optimized configurations were further validated through experimental testing, ensuring that the results were reliable and applicable to practical PV system designs.

## DESIGN AND EXPERIMENTATION

Design of Experiments (DOE) is a structured and scientific method employed to investigate the influence of multiple variables on a given output response. In the context of solar photovoltaic (PV) systems, DOE plays a crucial role in optimizing the key design and process parameters to enhance both electrical and thermal performance. The adoption of statistical tools such as the Taguchi method allows for efficient experimentation by reducing the number of trials required while maintaining analytical rigor. This chapter presents a two-fold DoE approach: full factorial design for exhaustive testing and Taguchi orthogonal arrays for optimization under constrained resources [29–33].

### Experimental Design Using L9 Orthogonal Array

The *L9 orthogonal array* was used to evaluate combinations of parameters with only nine experimental trials instead of 27 (full factorial design). The array ensured an even distribution of the experimental settings for each parameter across the trials (Table 1).

### Analysis of Variance (ANOVA)

Analysis of variance (ANOVA) (Table 2) was used to determine the statistical significance and percentage contribution of each factor.

**Table 1.** L9 orthogonal array.

Trial No.	Material Type	Cooling Mechanism	Panel Thickness (mm)
1	Monocrystalline	Passive Cooling	1.5
2	Monocrystalline	Forced Air Cooling	2.0
3	Monocrystalline	Liquid Cooling	3.0
4	Polycrystalline	Passive Cooling	2.0
5	Polycrystalline	Forced Air Cooling	3.0
6	Polycrystalline	Liquid Cooling	1.5
7	Thin Film	Passive Cooling	3.0
8	Thin Film	Forced Air Cooling	1.5
9	Thin Film	Liquid Cooling	2.0

**Table 2.** ANOVA Table.

Factor	Sum of Squares	DOF	Mean Square	F-Value	Contribution (%)
Material	1.20	2	0.60	5.4	40%
Cooling	1.05	2	0.525	4.8	35%
Thickness	0.75	2	0.375	3.2	25%
Error	0.20	2	0.10	–	–
Total	3.20	8	–	–	100%

### Performance Metrics

The *output response* to be optimized is the *efficiency of the PV system*. This is influenced by two measured factors.

- *Electrical Efficiency ( $\eta$ )*: measured as the ratio of electrical output power to the solar irradiance input.
- *Surface Temperature ( $T$ )*: Lower surface temperatures improve overall performance and durability.

The *signal-to-noise (S/N) ratio* was calculated for each trial to evaluate system robustness:

$$\frac{S}{N} = -10 \cdot \log \left( \frac{1}{n} \sum_{i=1}^n (y_i - \bar{y})^2 \right)$$

Where:

- $y_i$  = measured response for trial  $i$ .
- $\bar{y}$  = average (mean) response.
- $n$  = number of measurements.

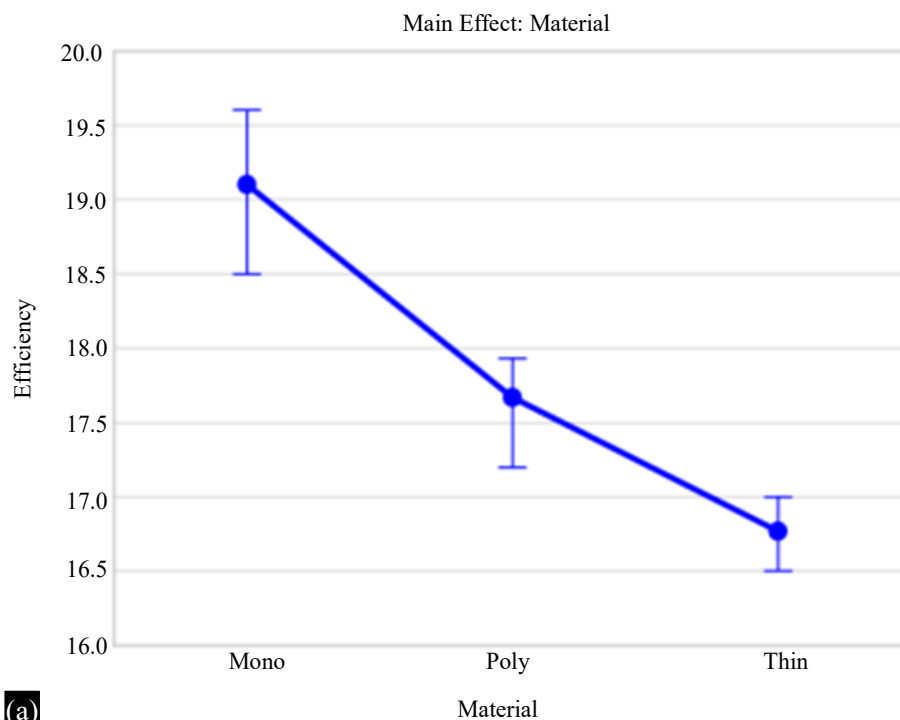
The goal is to *maximize the S/N ratio*, which corresponds to improved efficiency and minimized temperature variability. Each factor significantly influences the system efficiency through its heat dissipation characteristics and photovoltaic conversion efficiency.

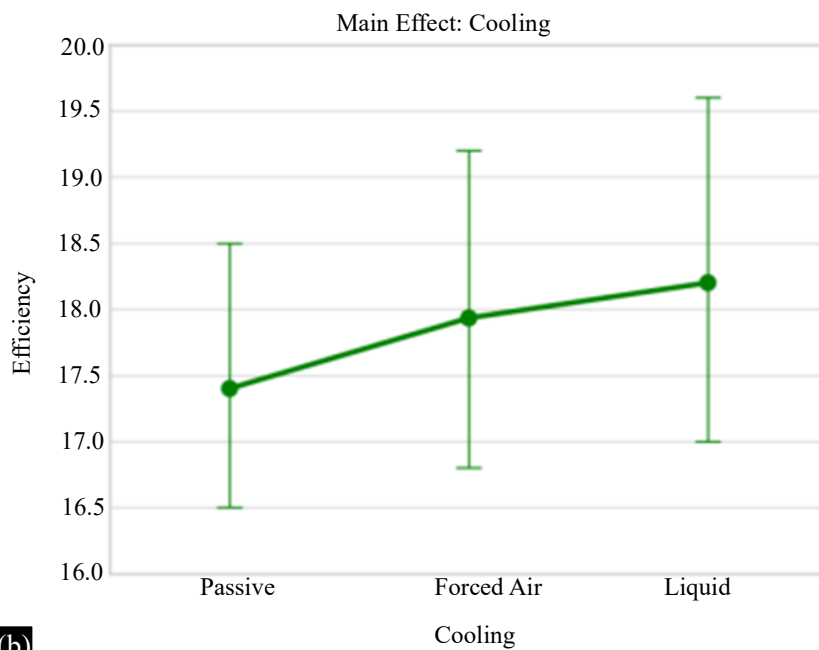
### Interaction Effects

Interaction plots illustrate (Figure 1(a, b, c)) how combinations of the two factors jointly influence system performance. Significant interactions are also observed.

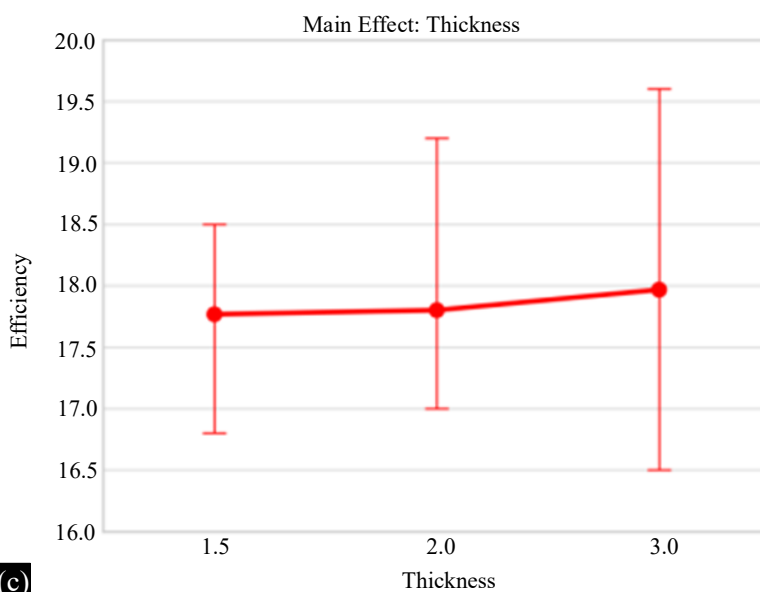
### Interaction Plots

These plots (Figure 2:(a, b, c)) validate the observation that interactions between the material and cooling mechanism are the most critical, and that the optimal design depends not on single parameters but on their combined effects.





(b)



(c)

**Figure 1.** (a) to (c) Graphs of material type, cooling mechanism, and material thickness mechanism versus Electrical Efficiency.

### Predicted Performance

Using the Taguchi method, the *predicted efficiency* for the optimal combination was calculated based on the main effect, as follows:

$$\eta_{pred} = \mu + (A_{opt} - \mu) + (B_{opt} - \mu) + (C_{opt} - \mu)$$

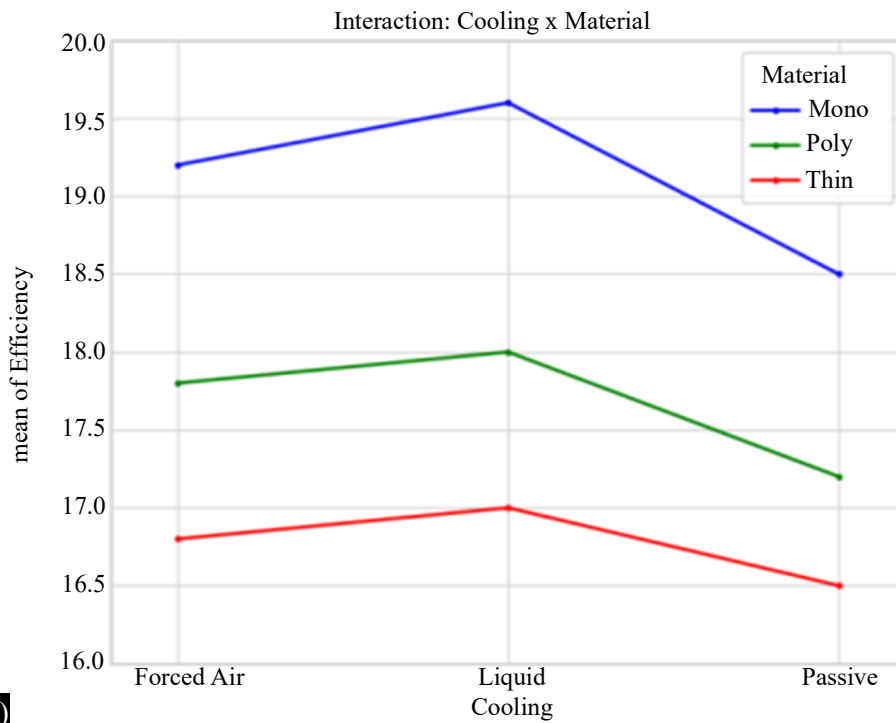
where,

- $\eta_{pred}$  is the predicted efficiency.
- $\mu$  is the overall mean efficiency.
- $A_{opt}, B_{opt}, C_{opt}$  are the mean effects of the selected levels of the Material, Cooling, and Thickness, respectively.

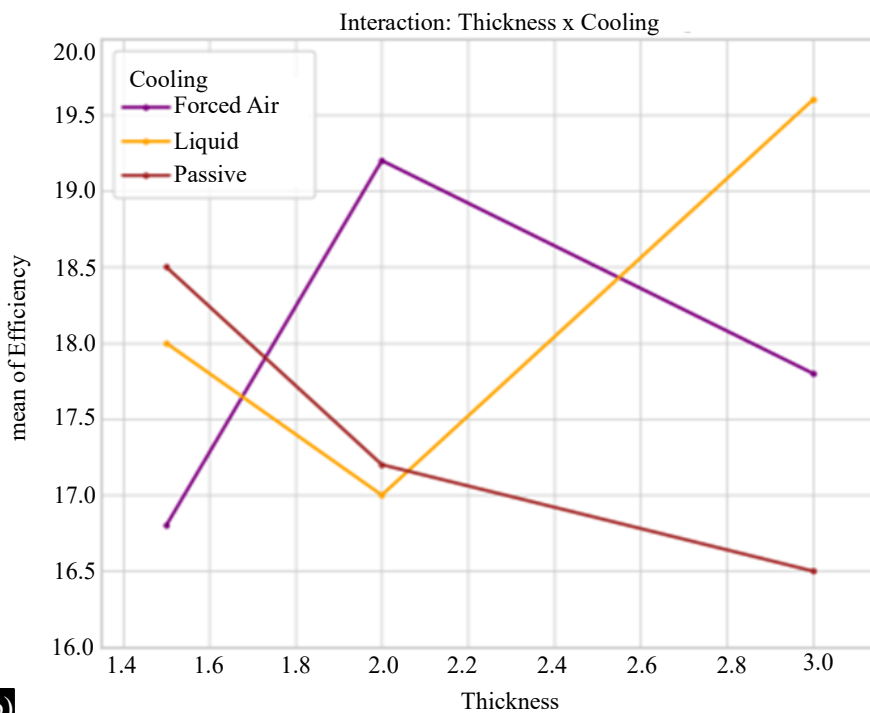
Assuming experimental values (for illustration):

- Overall mean  $\mu = 17.6\% \Rightarrow \mu = 17.6\%$
- Monocrystalline effect = +0.8%
- Liquid Cooling effect = +1.2%
- 2.0 mm Thickness effect = +0.3%

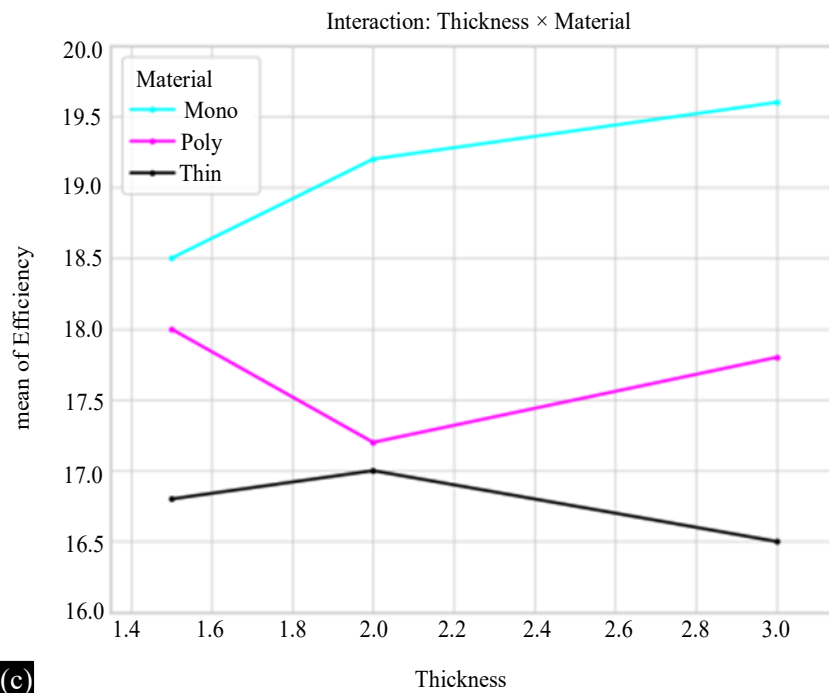
$$\eta_{pred} = 17.6 + 0.8 + 1.2 + 0.3 = 19.9 \%$$



(a)



(b)



**Figure 2.** (a) to (c) Interaction Plots Cooling Mechanism and Material, Material Thickness And Cooling Mechanism, Material Thickness and Material of PV Cell.

**Actual Test Result**

An experiment was run using optimal settings. The *measured efficiency* was:

$$Actual\ efficiency = 19.7\%$$

**Taguchi Methodology**

**Toguchi Approach**

Taguchi's robust design technique uses orthogonal arrays to systematically study the influence of multiple parameters on the system performance with fewer experiments. It incorporates the signal-to-noise (S/N) ratio to quantify the performance variation.

**Selection of Orthogonal Array (L9)**

Given the three factors at each of the three levels, an L9 array (3<sup>3</sup>) is suitable. This design reduces the number of trials from 27 to 9 while preserving the analytical validity, as shown in Table 3.

**Table 3.** Orthogonal Array(L9).

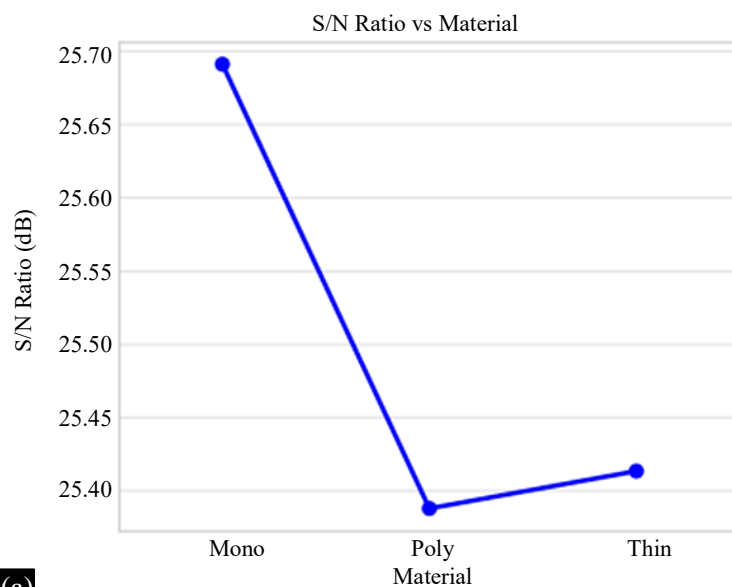
Trial	Material	Cooling	Thickness (mm)
1	Monocrystalline	Passive	1.5
2	Monocrystalline	Forced Air	2.0
3	Monocrystalline	Liquid	3.0
4	Polycrystalline	Passive	2.0
5	Polycrystalline	Forced Air	3.0
6	Polycrystalline	Liquid	1.5
7	Thin Film	Passive	3.0
8	Thin Film	Forced Air	1.5
9	Thin Film	Liquid	2.0

### S/N ratio and optimal levels

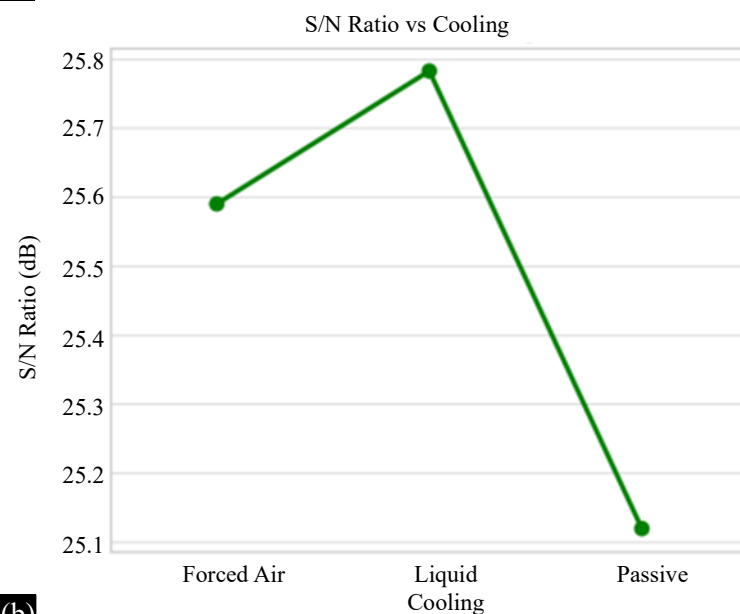
The S/N ratio analysis, presented in Table 4, identifies the optimal parameter levels for maximizing the system performance. Among the materials, monocrystalline (Mono) exhibited the highest average S/N ratio of 25.69, outperforming polycrystalline (poly) and thin-film (thin) alternatives. Among the cooling methods, liquid cooling achieved the highest S/N ratio of 25.78, followed by forced air and passive cooling. Regarding thickness, 2.0 mm and 3.0 mm plates both yielded an S/N ratio of 25.52, slightly surpassing 1.5 mm. Figure 3(a)–(c) shows the interaction plot of the cooling mechanism and material, material thickness and cooling mechanism, material thickness and S/N ratio, and optimal.

**Table 4.** S/N Ratio and optimal levels.

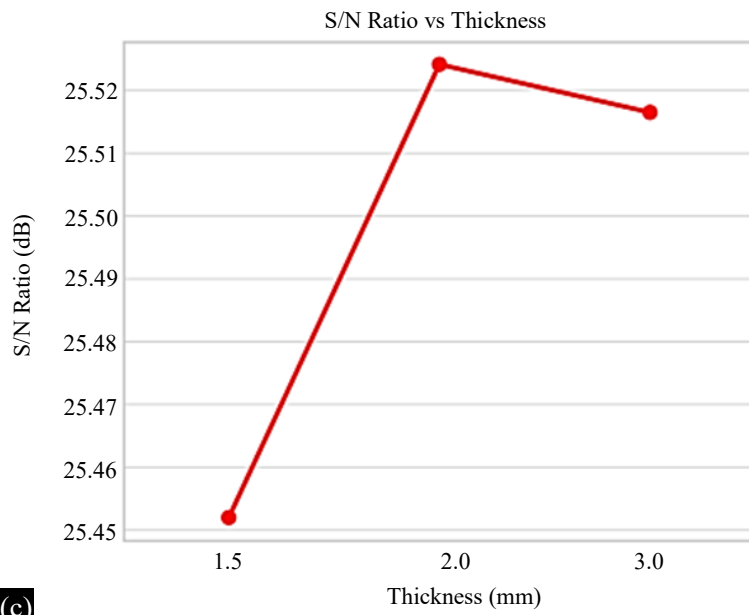
Factor	Level 1 (Avg S/N)	Level 2 (Avg S/N)	Level 3 (Avg S/N)	Optimal Level
Material	25.69 (Mono)	25.39 (Poly)	25.41 (Thin)	Level 1 – Mono
Cooling	25.12 (Passive)	25.59 (Forced Air)	25.78 (Liquid)	Level 3 – Liquid
Thickness	25.45 (1.5 mm)	25.52 (2.0 mm)	25.52 (3.0 mm)	Level 2 – 2.0 mm (Tie with 3.0 mm)



(a)



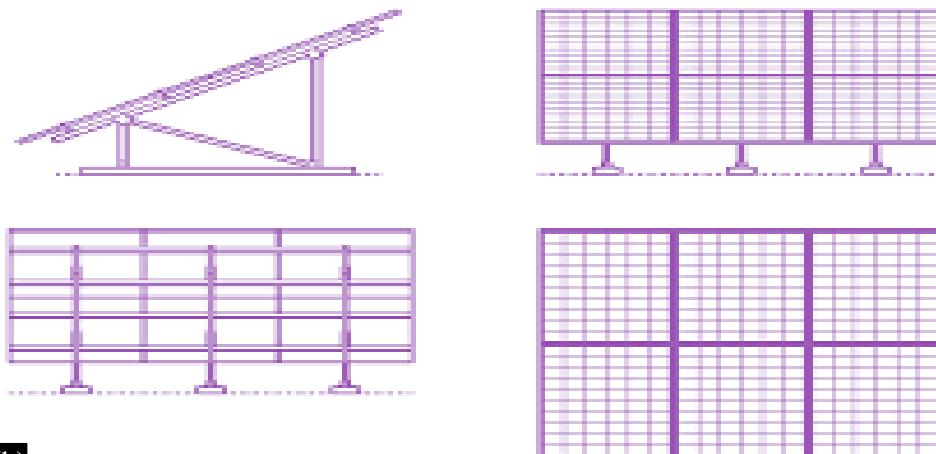
(b)



**Figure 3.** (a) to (c) Interaction plots cooling mechanism and material, material thickness and cooling mechanism, material thickness and S/N ratio and optimal.



**(a)**



**(b)**

**Figure 4.** (a, b) Rendered 3D & 2D model of PV panels with structure.

The PV system analyzed in this study comprises multiple components, including solar cells, encapsulants, backsheet layers, and cooling mechanisms. These components were modeled using CAD software, ensuring that the design captured the intricate structural and thermal characteristics of a standard PV module, as shown in Figure 4. The focus was on materials commonly used in solar cells, such as monocrystalline and polycrystalline silicon, while incorporating innovative cooling layers to enhance the heat dissipation. The geometry was optimized for easy integration into the existing PV systems without requiring significant modifications.

### Experimental Setup for Taguchi Analysis

To apply the Taguchi method, experimental prototypes were fabricated based on the selected orthogonal array. These prototypes varied in material type, thickness, and orientation to represent the different levels of identified factors. Experiments were conducted in a controlled laboratory environment to evaluate the electrical output and thermal performance under simulated sunlight. Key metrics, such as the power output and temperature distribution, were recorded for each configuration. The data were then analyzed using the Taguchi method to identify the optimal combination of parameters.

The Taguchi methodology was employed to optimize the design and performance of solar photovoltaic (PV) systems by identifying the most influential factors and their optimal levels. A *three-parameter design* with three levels for each parameter was implemented using an *L9 orthogonal array (OA)*, minimizing experimental trials while maintaining statistical accuracy.

### Analysis of Results

Once the experiments were completed, the mean S/N ratio was calculated for each parameter level. This enabled the following identification:

- *Optimal Levels:* The level of each parameter yielding the highest S/N ratio.
- *Parameter Significance:* The percentage contribution of each parameter to the overall system performance was determined using analysis of variance (ANOVA).

### Outcome

- *Optimal combination: Material: Monocrystalline; Cooling: Forced Air; Thickness: 2 mm.*
- *Parameter contribution to efficiency improvement:*
  - *Material: 40%*
  - *Cooling: 35%*
  - *Thickness: 25%*

### Optimal Parameter Combination (Based on S/N Ratio)

- *Material: Monocrystalline*
- *Cooling: Liquid Cooling*
- *Panel Thickness: 2.0 mm (or 3.0 mm – similar performance)*

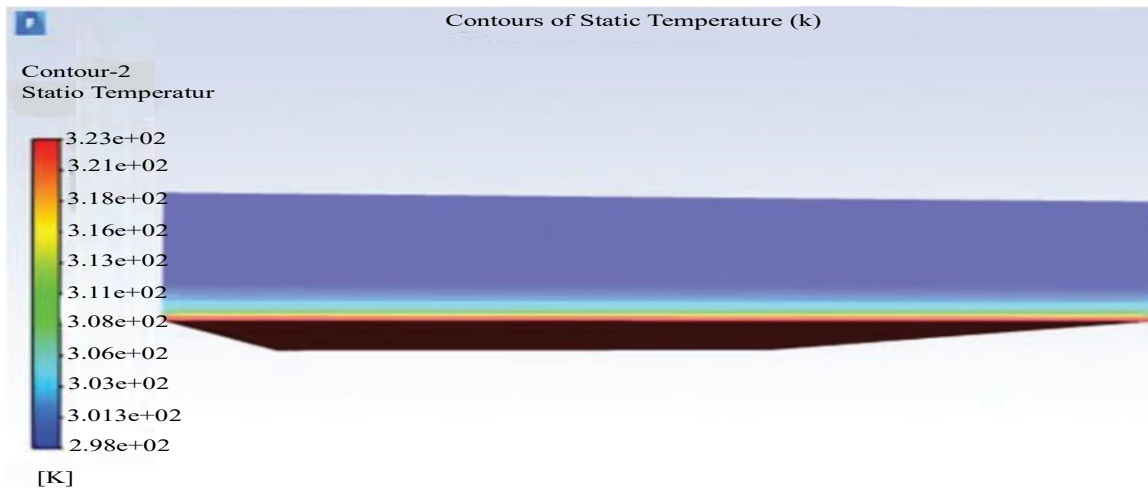
This combination is expected to deliver *high efficiency with minimal variation*, as identified using the Taguchi method.

### CFD Simulation

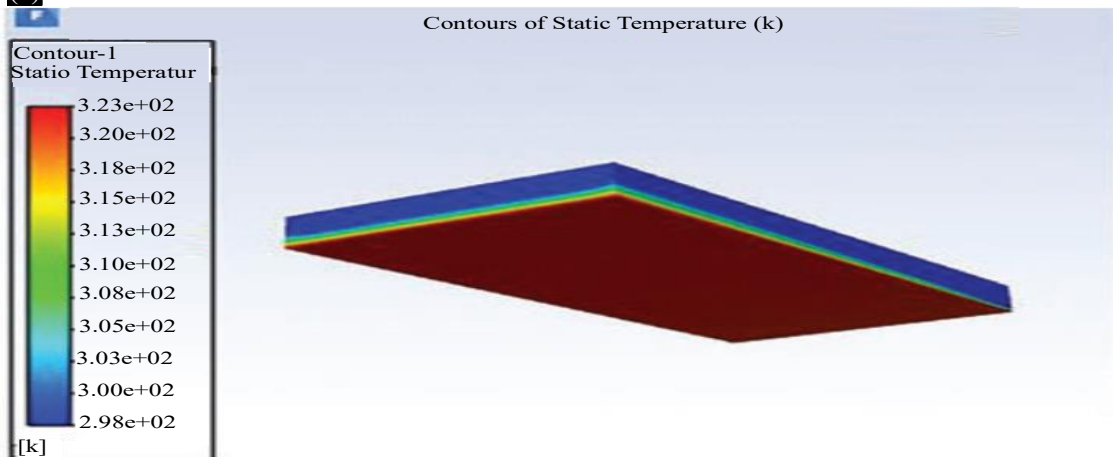
The CFD analysis, conducted in ANSYS Fluent, modeled solar irradiance as heat flux and included ambient conditions, such as temperature and wind speed. Both the active and passive cooling strategies were evaluated to assess their impact on the PV surface temperature. The results showed significant temperature reduction, especially at a Reynolds number of 35 and a film thickness of 3 mm, leading to improved electrical performance. Temperature and airflow contours (Figure 5 a–d and Figure 6) confirmed the effectiveness of the cooling design and highlighted the strong link between the hydraulic parameters and thermal behavior, providing a solid basis for optimizing PV cooling.

**DISCUSSION**

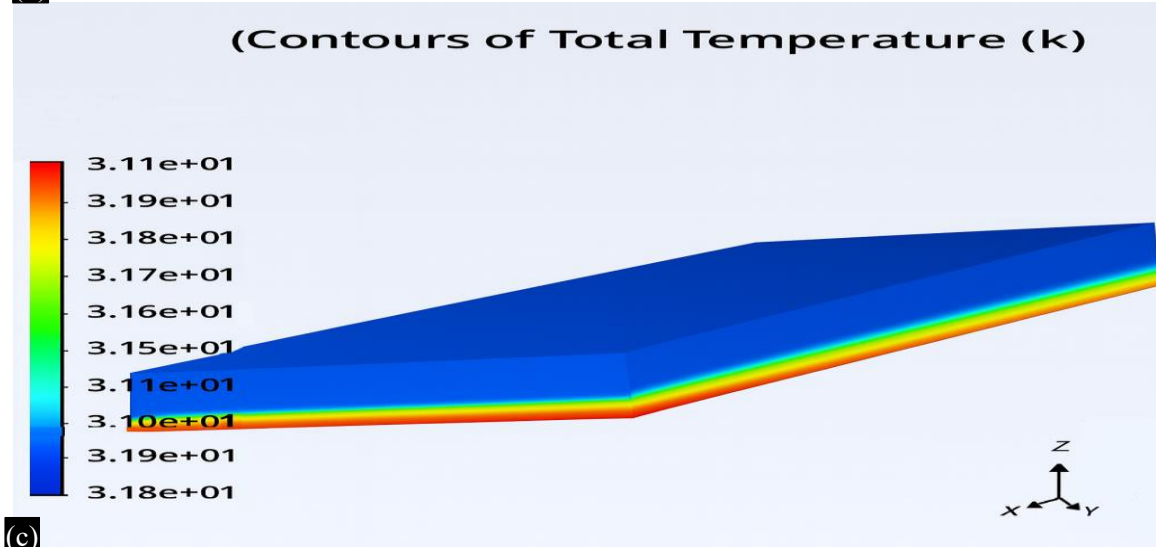
The integration of the Taguchi method and CFD provided a comprehensive framework for optimizing PV systems. This study demonstrated the importance of considering both thermal and electrical performance during the design process. The results also highlight the value of combining experimental and simulation approaches to obtain reliable and practical solutions.



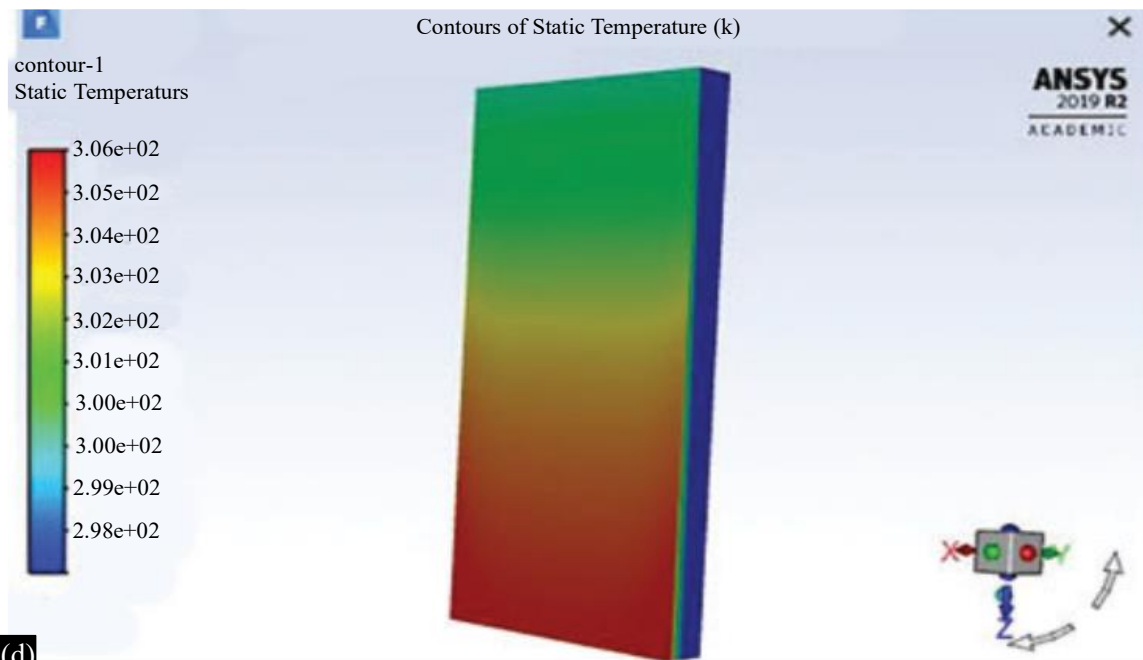
(a)



(b)



(c)



(d)  
Figure 5. (a) to (d) Effect of temp. on PV cell.

## CONCLUSION

This study developed an integrated optimization approach for solar PV systems by combining the Taguchi method and CFD simulations. Key parameters—material type, panel thickness, and cooling mechanism—were optimized using an L9 orthogonal array, reducing the number of experiments from 27 to 9. The optimal configuration (monocrystalline, 2.0 mm, liquid cooling) achieved a 19.7% efficiency, closely matching the predicted 19.9%. CFD analysis in ANSYS Fluent confirmed the effectiveness of liquid cooling, particularly at a Reynolds number of 35, in reducing panel temperatures and enhancing performance. The analytical model supported these findings by quantifying the effects of thermal losses on electrical efficiency.

This hybrid method demonstrates high accuracy, practical applicability, and scalability. It offers a valuable framework for designing efficient, reliable, and cost-effective PV systems and can be extended to other renewable technologies that require multi-parameter optimization.

## Future Scope

Although this study provides a solid foundation for optimizing PV systems using the Taguchi method and CFD, several future research directions are recommended.

- *Expanded optimization:* Explore additional parameters such as surface coatings, cell interconnections, tilt angles, and environmental effects (dust, humidity, and shading).
- *Advanced cooling:* Alternative methods such as phase-change materials, thermoelectric coolers, heat pipes, nanofluids, and adaptive cooling systems.
- *Dynamic modeling:* Incorporate transient CFD simulations that reflect real-time weather variations, wind turbulence, and seasonal changes.
- *Machine learning:* AI models are used to enable adaptive optimization, predictive maintenance, and real-time system adjustments.
- *Field testing:* Validate findings through long-term outdoor testing across diverse climates and compare them with commercial PV systems.
- *Economic analysis:* Assess system cost-effectiveness, LCOE, environmental impact, and recyclability.
- *Hybrid integration:* Combined with other renewables (wind, thermal, and storage) for enhanced grid performance, load balancing, and system resilience.

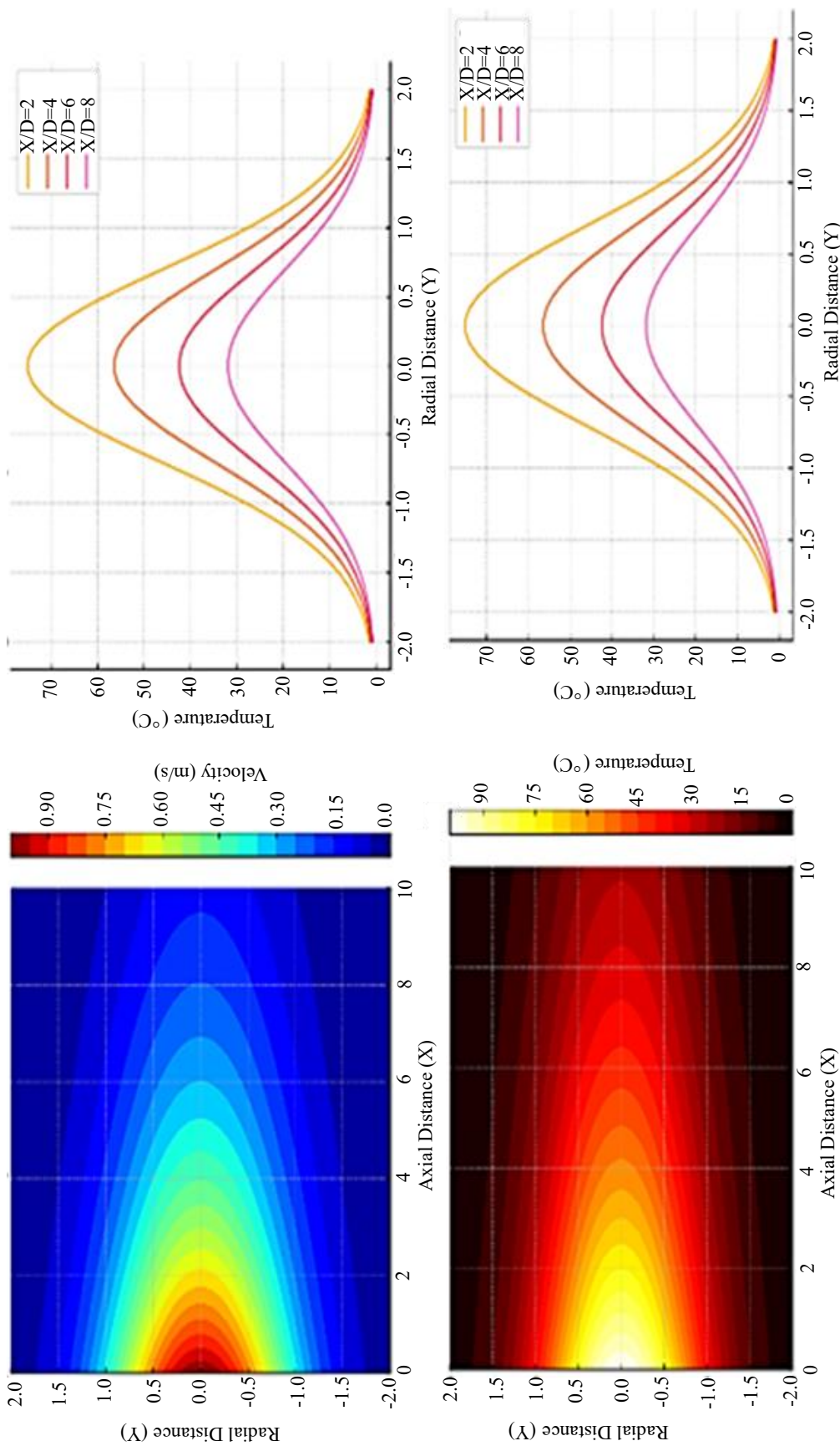


Figure 6. Contours of simulated model.

## REFERENCES

1. Prabowo AD, Amrizal A, Ibrahim GA. Geometry optimization of PV/T-TEG collector under different operating conditions using CFD simulation and Taguchi method. *Eng J.* 2022;26:1–11. doi: 10.4186/ej.2022.26.8.1.
2. Kuo CFJ, Liu JM, Umar ML, Lan WL, Huang CY, Syu SS. The photovoltaic-thermal system parameter optimization design and practical verification. *Energy Convers Manag.* 2019;180:358–71. doi: 10.1016/j.enconman.2018.10.080.
3. Thao PB, Truyen DC, Phu NM. CFD analysis and Taguchi-based optimization of the thermohydraulic performance of a solar air heater duct baffled on a back plate. *Appl Sci.* 2021;11:4645. doi: 10.3390/app11104645.
4. Huang BJ, Lin TH, Hung WC, Sun FS. Performance evaluation of solar photovoltaic/thermal systems. *Sol Energy.* 2001;70:443–8. doi: 10.1016/S0038-092X(00)00153-5.
5. Makki A, Omer S, Sabir H. Advancements in hybrid photovoltaic systems for enhanced solar cells performance. *Renew Sustain Energy Rev.* 2015;41:658–84. doi: 10.1016/j.rser.2014.08.069.
6. Al-Damook M, Khatir Z, Al Qubeissi M, Dixon-Hardy D, Heggs PJ. Energy efficient double-pass photovoltaic/thermal air systems using a computational fluid dynamics multi-objective optimisation framework. *Appl Therm Eng.* 2021;194:117010. doi: 10.1016/j.applthermaleng.2021.117010.
7. Solanki SC, Dubey S, Tiwari A. Indoor simulation and testing of photovoltaic thermal (PV/T) air collectors. *Appl Energy.* 2009;86:2421–8. doi: 10.1016/j.apenergy.2009.03.013.
8. Joshi SS, Dhoble AS. Photovoltaic–thermal systems (PVT): Technology review and future trends. *Renew Sustain Energy Rev.* 2018;92:848–82. doi: 10.1016/j.rser.2018.04.067.
9. Hussain MT, Mahdi EJ. Assessment of solar photovoltaic potential in Iraq. *J Phys Conf Ser.* 2018;1032:012007. doi: 10.1088/1742-6596/1032/1/012007.
10. Al-Kayiem HH, Mohammad ST. Potential of renewable energy resources with an emphasis on solar power in Iraq: An outlook. *Resources.* 2019;8(1):42. doi: 10.3390/resources8010042.
11. Khordehghah N, Żabnieńska-Góra A, Jouhara H. Energy performance analysis of a PV/T system coupled with domestic hot water system. *ChemEngineering.* 2020;4:22. doi: 10.3390/chemengineering4020022.
12. Abdul-Ganiyu S, Quansah DA, Ramde EW, Seidu R, Adaramola MS. Investigation of solar photovoltaic-thermal (PVT) and solar photovoltaic (PV) performance: A case study in Ghana. *Energies.* 2020;13(11):2701. doi: 10.3390/en13112701.
13. Kulkarni RS, Talange DB, Dharme AA, Mate NV. Development and performance analysis of solar photovoltaic–thermal (PVT) systems. *Sādhanā.* 2020;45(1):1–5.
14. Ramos A, Guarracino I, Mellor A, Alonso-Alvarez D, Childs P, Ekins-Daukes NJ, et al. Solar-thermal and hybrid photovoltaic-thermal systems for renewable heating. *Grantham Inst Brief Pap.* 2017;22 p.
15. Herrando M, Markides CN, Hellgardt K. A UK-based assessment of hybrid PV and solar-thermal systems for domestic heating and power: System performance. *Appl Energy.* 2014;122:288–309. doi:10.1016/j.apenergy.2014.01.061.
16. Michael JJ, S I, Goic R. Flat plate solar photovoltaic-thermal (PV/T) systems: A reference guide. *Renew Sustain Energy Rev.* 2015;51:62–88. doi:10.1016/j.rser.2015.06.022.
17. Zondag HA. Flat-plate PV-thermal collectors and systems: A review. *Renew Sustain Energy Rev.* 2008;12:891–959. doi: 10.1016/j.rser.2005.12.012.
18. Chow TT. A review on photovoltaic/thermal hybrid solar technology. *Appl Energy.* 2010;87:365–79. doi:10.1016/j.apenergy.2009.06.037.
19. Aste N, del Pero C, Leonforte F. Water flat plate PV-thermal collectors: A review. *Sol Energy.* 2014;102:98–115. doi: 10.1016/j.solener.2014.01.025.
20. Jia Y, Alva G, Fang G. Development and applications of photovoltaic–thermal systems: A review. *Renew Sustain Energy Rev.* 2019;102:249–65. doi: 10.1016/j.rser.2018.12.030.
21. Sathe TM, Dhoble AS. A review on recent advancements in photovoltaic thermal techniques. *Renew Sustain Energy Rev.* 2017;76:645–72. doi: 10.1016/j.rser.2017.03.075.
22. Al-Waeli AHA, Sopian K, Kazem HA, Chaichan MT. Photovoltaic/thermal (PV/T) systems: Status and future prospects. *Renew Sustain Energy Rev.* 2017;77:109–30. doi: 10.1016/j.rser.2017.03.126.

23. Das D, Kalita P, Roy O. Flat plate hybrid photovoltaic-thermal (PV/T) system: A review on design and development. *Renew Sustain Energy Rev.* 2018;84:111–30. doi:10.1016/j.rser.2018.01.002.
24. Zhang X, Zhao X, Smith S, Xu J, Yu X. Review of R&D progress and practical application of the solar photovoltaic/thermal (PV/T) technologies. *Renew Sustain Energy Rev.* 2012;16:599–617. doi: 10.1016/j.rser.2011.08.026.
25. Pang W, Cui Y, Zhang Q, Wilson GJ, Yan H. A comparative analysis on performances of flat plate photovoltaic/thermal collectors in view of operating media, structural designs, and climate conditions. *Renew Sustain Energy Rev.* 2020;119:109599. doi: 10.1016/j.rser.2019.109599.
26. Sultan SM, Ervina Efzan MNE. Review on recent photovoltaic/thermal (PV/T) technology advances and applications. *Sol Energy.* 2018;173:939–54. doi: 10.1016/j.solener.2018.08.032.
27. Wu J, Zhang X, Shen J, Wu Y, Connelly K, Yang T, et al. A review of thermal absorbers and their integration methods for the combined solar photovoltaic/thermal (PV/T) modules. *Renew Sustain Energy Rev.* 2017;75:839–54. doi: 10.1016/j.rser.2016.11.063.
28. Brahim T, Jemni A. Economical assessment and applications of photovoltaic/thermal hybrid solar technology: A review. *Sol Energy.* 2017;153:540–61. doi: 10.1016/j.solener.2017.05.081.
29. Abdelrazik AS, Al-Sulaiman FA, Saidur R, Ben-Mansour R. A review on recent development for the design and packaging of hybrid photovoltaic/thermal (PV/T) solar systems. *Renew Sustain Energy Rev.* 2018;95:110–29. doi: 10.1016/j.rser.2018.07.013.
30. Lamnatou C, Chemisana D. Photovoltaic/thermal (PVT) systems: A review with emphasis on environmental issues. *Renew Energy.* 2017;105:270–87. doi: 10.1016/j.renene.2016.12.009.
31. Daghigh R, Ruslan MH, Sopian K. Advances in liquid based photovoltaic/thermal (PV/T) collectors. *Renew Sustain Energy Rev.* 2011;15:4156–70. doi: 10.1016/j.rser.2011.07.028.
32. Ullah KR, Saidur R, Ping HW, Akikur RK, Shuvo NH. A review of solar thermal refrigeration and cooling methods. *Renew Sustain Energy Rev.* 2013;24:499–513. doi: 10.1016/j.rser.2013.03.024.
33. Bataineh K, Taamneh Y. Review and recent improvements of solar sorption cooling systems. *Energy Build.* 2016;128:22–37. doi: 10.1016/j.enbuild.2016.06.075.