A

Dissertation Report on

Design and Optimization of Solar Photovoltaic Systems Using Taguchi and Computational Fluid Dynamics

Submitted

in partial fulfilment of the requirements for the degree of

Master of Technology

in

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by

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CERTIFICATE

This is to certify that, **Miss. Shahina Parvin Munir Momin (Roll No - 2321009)** has successfully completed the dissertation work and submitted dissertation report on **Design and Optimization of Solar Photovoltaic Systems Using Taguchi and Computational Fluid Dynamics** for the partial fulfillment of the requirement for the degree of Master of Technology in **Design Engineering** from the Department of **Mechanical Engineering**, as per the rules and regulations of Rajarambapu Institute of Technology, Rajaramnagar, Dist: Sangli.

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DECLARATION

I declare that this report reflects my thoughts about the subject in my own words. I have sufficiently cited and referenced the original sources, referred or considered in this work. I have not misrepresented or fabricated or falsified any idea/data/fact/source in this my submission. I understand that any violation of the above will be cause for disciplinary action by the Institute.

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ABSTRACT

The design and optimization of solar photovoltaic (PV) systems play a crucial role in improving the efficiency of solar energy harnessing. This report utilizes the Taguchi method for parameter optimization and Computational Fluid Dynamics (CFD) to analyze and improve thermal and electrical performance. The study identifies key parameters such as material type, thickness, and cooling mechanisms and optimizes them using a systematic experimental design approach. The CFD analysis is employed to simulate heat dissipation and airflow characteristics, ensuring that the system's performance is maximized under various environmental conditions. The findings are validated with experimental prototypes, offering a comprehensive framework for the efficient design of PV systems.

Keywords: Solar Photovoltaic Systems, Optimization, Taguchi Method, Computational Fluid Dynamics, Thermal Management.

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Chapter 1

INTRODUCTION

1.1 Background

The increasing global demand for energy, coupled with the adverse environmental effects of fossil fuel consumption, has necessitated a shift toward renewable energy sources. Among the various renewable technologies, solar photovoltaic (PV) systems have emerged as a promising solution for sustainable energy generation. PV systems convert sunlight into electricity through the photovoltaic effect, offering a clean and inexhaustible energy source. However, despite significant advancements in solar technology, achieving high efficiency and performance remains a challenge due to inherent thermal losses and suboptimal design configurations. [1-5,14,22]

Importance of Solar Energy

Solar energy is one of the most abundant and accessible energy resources on Earth as shown in fig.1.1.. It provides an opportunity to meet global energy needs sustainably while reducing greenhouse gas emissions. Unlike traditional energy sources, solar energy is decentralized, enabling localized energy generation even in remote areas. With decreasing costs of solar modules and government incentives worldwide, the adoption of solar PV systems has seen exponential growth. In 2023 alone, global solar installations surpassed 1 terawatt (TW), marking a significant milestone in the renewable energy sector. [8,11,15-18]

Figure 1.1: Solar Energy Utilization

Role of Photovoltaic Systems

Photovoltaic systems are the backbone of solar energy generation as show in fig. 1.2. These systems consist of solar panels, inverters, mounting structures, and other auxiliary components. The heart of a PV system is the solar panel, which is composed of multiple solar cells connected in series or parallel. These cells are typically made of semiconducting materials, such as silicon, that convert sunlight directly into electricity. However, the efficiency of this conversion process is influenced by factors such as material quality, environmental conditions, and system design. [11-14, 20, 25]

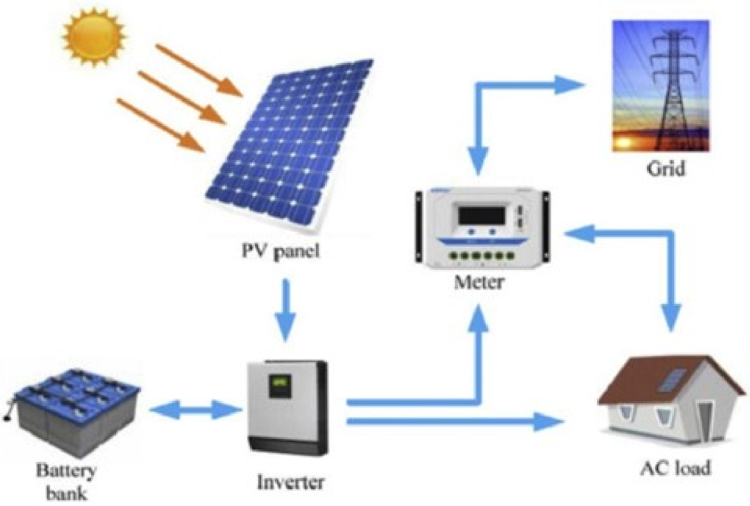


Figure 1.2: Solar PV Plant Working

Working of a Photovoltaic (PV) Cell

Photovoltaic (PV) cells, commonly known as solar cells, are the building blocks of solar panels. These devices convert sunlight directly into electricity using the photovoltaic effect, a physical and chemical phenomenon. The working principle of a PV cell relies on the interaction of light energy (photons) with a semiconducting material, typically silicon. This interaction generates electric current without any moving parts, making PV cells highly reliable and environmentally friendly. [25, 37, 41-46]

Structure of a PV Cell

A PV cell comprises several key layers, each serving a specific function to ensure efficient conversion of sunlight into electricity. The fig shows the structure of the PV cell as shown in fig. 1.3

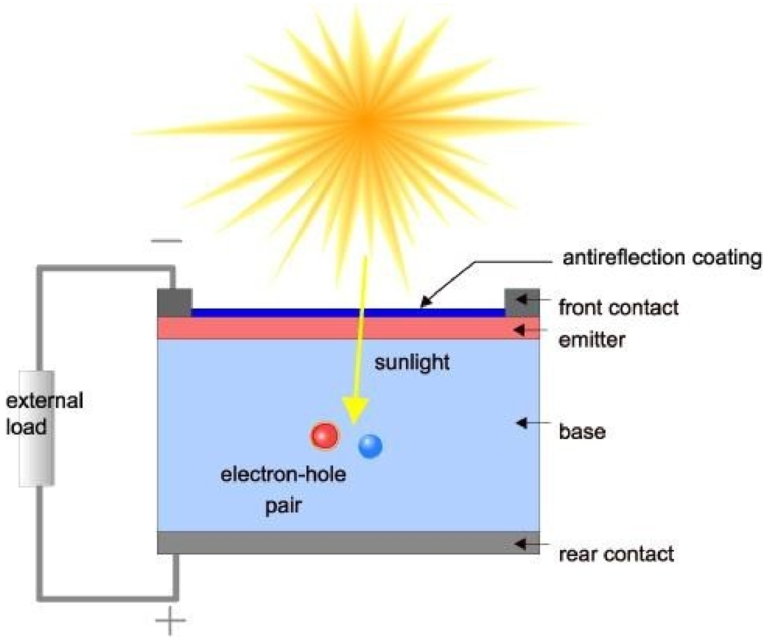


Figure 1.3: PV cell Structure

1. Protective Layers:

   The outermost layers of a PV cell include encapsulant layers and a glass cover. These layers protect the cell from environmental factors such as moisture, dirt, and mechanical stress. The encapsulant is a transparent adhesive that holds the components together, while the glass cover shields the cell from physical damage and enhances durability.

2. Anti-Reflective Coating:

   Beneath the protective layers lies an anti-reflective coating. This coating reduces the reflection of sunlight from the cell's surface, allowing maximum absorption of solar radiation. Without this coating, a significant portion of sunlight would bounce off the surface, reducing the cell's efficiency.

3. Semiconductor Layers:

   At the heart of a PV cell are two layers of silicon that form a P-N junction:

   - N-type Silicon: This layer is doped with elements like phosphorus, which provide extra electrons, making it negatively charged.
   - P-type Silicon: This layer is doped with elements like boron, which create an abundance of holes (positive charge carriers), making it positively charged. The interface between these two layers creates an electric field, which is essential for the movement of charges and the generation of current.

4. Metal Contacts:

   Metal strips are placed on the front and back of the cell. These contacts collect the electrons generated within the cell and allow the flow of current to an external circuit. [36-39, 41, 42]

Principle of Operation

The operation of a PV cell is based on the photovoltaic effect, which involves three key processes as shown in fig. 1.4

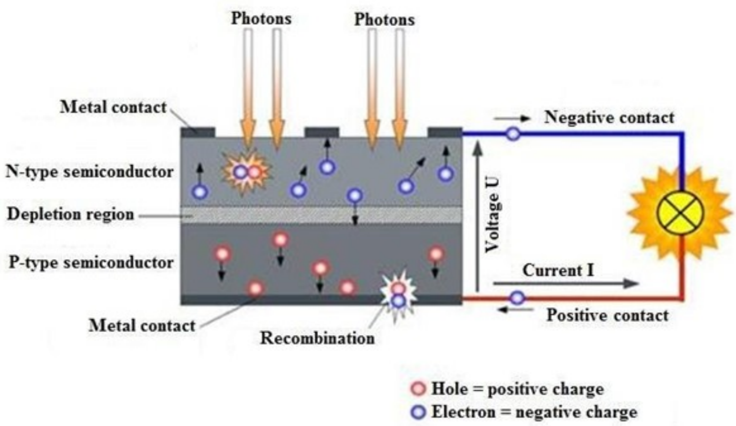


Figure 1.4: PV cell Principle of working

1. Absorption of Sunlight:

   When sunlight strikes the surface of the PV cell, photons (light particles) transfer their energy to the semiconductor material. Each photon has a specific amount of energy, depending on its wavelength. If this energy is greater than the bandgap energy of the silicon, it excites an electron within the silicon atom. This excitation allows the melectron to break free from its bond, creating a free electron and leaving behind a hole.

2. Creation of Electron-Hole Pairs:
   The absorption of sunlight generates electron-hole pairs in the semiconductor. The electric field present at the P-N junction separates these pairs:
   - Electrons are pushed toward the N-type layer.
   - Holes are pulled toward the P-type layer. This separation of charges prevents the recombination of electrons and holes, maintaining their movement in opposite directions.
3. Movement of Charges to Generate Current:
   The electric field at the P-N junction acts as a diode, allowing the electrons and holes to move in specific directions. This movement creates a potential difference across the cell. When the cell is connected to an external load, the electrons flow through the circuit, generating an electric current.
4. Collection of Current:
   The metal contacts on the cell's surface collect the flowing electrons and direct them through an external circuit to power devices. This flow of electrons, or current, is directly proportional to the intensity of sunlight hitting the cell. [1-9, 17, 19, 21-34]

Energy Conversion and Efficiency

The electrical output of a PV cell is determined by its ability to absorb and convert sunlight into usable energy. However, not all the sunlight absorbed by the cell is converted into electricity. Some energy is lost as heat, and some photons do not have enough energy to excite electrons. The efficiency of a typical silicon-based PV cell ranges from 15% to 22%, with advanced technologies pushing this limit further. [27]

Significance of the PV Cell

PV cells are a cornerstone of renewable energy systems. They operate silently, require minimal maintenance, and have a lifespan of 25 years or more. Despite challenges like thermal losses and material constraints, advancements in technology, such as multi-junction cells and tandem configurations, continue to improve their performance. The widespread adoption of PV cells has significantly contributed to reducing dependence on fossil fuels and mitigating the effects of climate change. [7, 31, 42]

Challenges in PV System Efficiency

One of the significant challenges faced by PV systems is thermal management. When exposed to sunlight, a portion of the absorbed energy is converted into heat instead of electricity. This heat raises the operating temperature of the solar cells, causing a decline in their efficiency. Studies have shown that for every 1°C increase in temperature, the efficiency of silicon-based solar cells decreases by approximately 0.45%. This thermal degradation not only affects power output but also accelerates the aging of PV modules, reducing their lifespan.

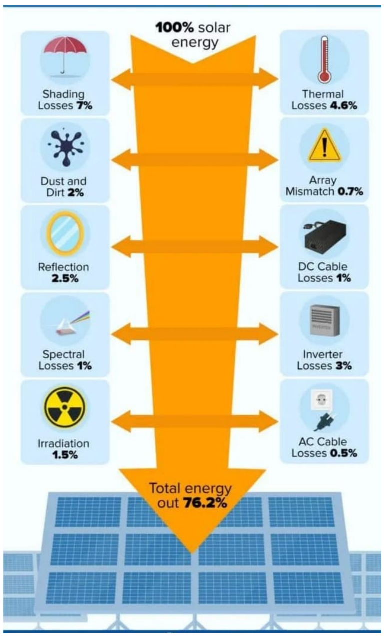


Figure 1.5: Major losses in PV cell

In addition to thermal losses as shown in fig. 1.5, other design challenges include the selection of suitable materials, optimization of panel orientation, and integration of effective cooling mechanisms. Environmental factors, such as wind speed, ambient temperature, and dust accumulation, further complicate the design process. Addressing these challenges requires a multidisciplinary approach that combines advanced design optimization techniques and thermal analysis tools. [2, 13, 16-17]

Emerging Solutions

To overcome these challenges, researchers and engineers have explored innovative strategies to enhance the efficiency and durability of PV systems. Design optimization methods, such as the Taguchi method, have been employed to systematically identify and fine-tune critical parameters affecting system performance. Simultaneously, Computational Fluid Dynamics (CFD) has emerged as a powerful tool for analyzing thermal behavior and airflow dynamics in PV systems. By simulating real-world conditions, CFD enables engineers to evaluate the effectiveness of various cooling mechanisms and design configurations. as shown in fig 1.6. [11, 19, 33, 41-45]

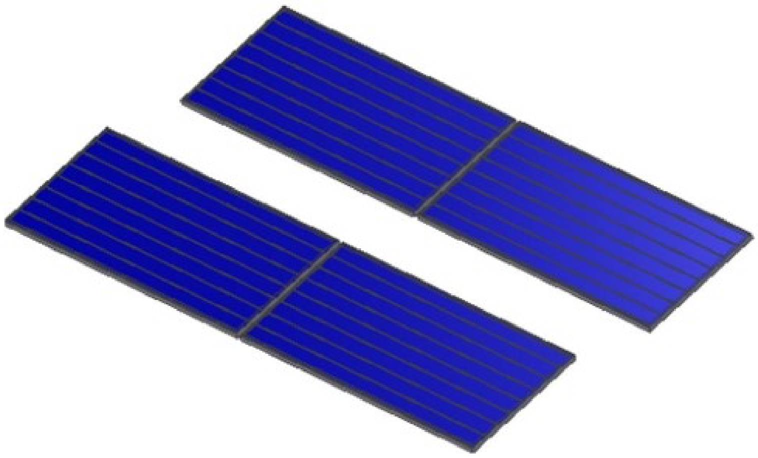


Figure 1.6: PV Cell 3D Model

Integration of Optimization and Simulation

The integration of optimization techniques like the Taguchi method with CFD simulations offers a holistic solution for PV system design. While the Taguchi method helps in identifying the best combination of design parameters through systematic experimentation, CFD provides detailed insights into heat dissipation and fluid flow characteristics. This combined approach not only improves the thermal and electrical performance of PV systems but also reduces the need for extensive physical prototyping, saving both time and resources.[1-12]

Relevance of the Study

The background of this study highlights the critical need for advanced methodologies to improve PV system performance. By addressing the challenges of thermal management and design inefficiencies, this research contributes to the broader goal of making solar energy more reliable and cost-effective. The findings of this study are expected to provide valuable insights for the development of next-generation PV technologies, aligning with global efforts to transition toward a sustainable energy future.

1.2 Challenges in PV Systems

The primary challenge in PV systems lies in managing the heat generated during operation. High temperatures degrade the electrical efficiency of solar cells, leading to a significant drop in output. Additionally, the design of PV systems requires a delicate balance between material selection, structural robustness, and thermal performance. Environmental factors such as wind speed, ambient temperature, and solar irradiance further complicate this optimization process, necessitating advanced tools and methods for achieving reliable performance.

1.3 Relevance of Taguchi and CFD

The Taguchi method provides a systematic framework for optimizing design parameters by identifying the most influential factors and their optimal levels. This approach reduces the number of experiments needed while maximizing the reliability of results. On the other hand, Computational Fluid Dynamics (CFD) is indispensable for simulating thermal behavior and airflow dynamics in PV systems. CFD allows engineers to visualize and quantify heat dissipation and fluid flow patterns, enabling precise adjustments to the design for improved cooling and efficiency. Together, these tools form a powerful combination for addressing the multifaceted challenges of PV system design.

1.4 Scope of the Study

This research aims to integrate the Taguchi method and CFD to optimize and validate the design of PV systems. Key aspects include identifying critical parameters, developing a simulation framework for thermal analysis, and validating the findings through experimental prototypes. By achieving these goals, the study contributes to the advancement of efficient, sustainable, and cost-effective PV technologies.

Chapter 2

LITERATURE REVIEW

2.1 Literature Review

They study optimizes PV/T-TEG collector performance by analyzing factors like fin arrangement, height, thickness, air mass flow rate, and heat absorption. Using the Taguchi Method, optimal settings are a full fin arrangement with 75 mm height, 3 mm thickness, 80 g/s air flow, and 400 W/m² heat absorption for PV temperature. For TEG temperature difference, a staggered fin arrangement with 25 mm height, 1 mm thickness, 80 g/s air flow, and 800 W/m² heat absorption is best. The approach simplifies the optimization process, suggesting further experimental validation in tropical climates. [1]

They have study uses the Taguchi method and AHP to optimize a Photovoltaic-Thermal (PV/T) system, improving electrical efficiency to 14.29% and thermal efficiency to 44.96%. Key parameters include copper plates, south-facing azimuth, 12 tubes, 0.01 kg/s-m² flow rate, 25° angle, and a V/A ratio of 123. CFD simulations validate the optimization, showing a 10°C temperature drop and a high correlation (0.991) between simulated and actual temperatures. [2]

They have investigates a solar air collector duct with baffles, varying Reynolds number, baffle angle, spacing ratio, and blockage ratio to assess their impact on Nusselt number, friction factor, and thermohydraulic performance. Using CFD simulations and the Taguchi method, the optimal parameters are found to be a baffle angle of 90°, spacing ratio of 6, and blockage ratio of 0.375, achieving the highest thermohydraulic performance (h = 1.01) at Re = 5000. Baffle angle between 60° and 90° enhances heat transfer due to impingement effects. [3]

They study compares an integrated photovoltaic and thermal solar system (IPVTS) with conventional solar water heaters, using a PV/T collector made from corrugated polycarbonate. It introduces the primary-energy saving efficiency concept, showing IPVTS efficiency exceeds 0.60, and outperforming traditional systems. The IPVTS achieves a daily efficiency (h*) of 0.38, about 76% of that of glazed solar heaters. The study also highlights potential cost reductions and confirms the economic feasibility of IPVTS. [4]

They have studies paper reviews various cooling methods for photovoltaic (PV) cells to address performance degradation due to heat. It examines techniques like air, liquid, heat pipes, phase change materials (PCMs), and thermoelectric devices for thermal management. Effective cooling is crucial to maintain PV cell efficiency and longevity, especially in sunny regions. The review discusses different designs and operating parameters that enhance cooling capacity and improve overall PV system performance. [5]

The photovoltaic systems have improved in efficiency over the past two decades, but only a small fraction of absorbed solar energy is converted into electricity. To enhance performance, a study proposes a hybrid photovoltaic/thermal air system using computational fluid dynamics and design of experiments. The optimal configuration features co-current air flow through two channels around the photovoltaic cell. Multi-objective optimization shows improvements in both thermal and electrical efficiencies, with thermal efficiency increasing from 44.5% to 50.1% and electrical efficiency rising from 10.0% to 10.5%. [6]

Solanki et al. [7] investigated PVT solar heater performance, using a wooden duct and a 12- V, 1.5-A DC fan to circulate air. They applied genetic algorithms to optimize energy efficiency, considering parameters like channel length, depth, and fluid flow velocity. Joshi and Dhoble [8] highlighted the importance of heat extraction from the PV rear panel and discussed forced fluid circulation through metallic pipes in PVT systems. Hussain et al. [9] compared solar radiation data in Iraq and developed solar radiation measurements for PV potential across various sites. Al-Kayiem et al. [10] presented a renewable energy outlook for Iraq, calculating the cost of a 50 kW concentrated solar power system at 0.23 US cents/kWh based on local conditions. Khordehgah et al. [11] explored a PVT system with electrical and thermal storage, improving system performance by 12% in power capacity and enhancing solar cell temperature and panel efficiency for use in warm European locations. Abdul- Ganiyu et al. [12] compared the real-life outdoor performance of PVT and conventional PV systems in Ghana, finding that the average daily electrical energy produced by PVT was 2.72 KWh/KWp/day, while PV produced 3.21 KWh/KWp/day. Kulkarni et al. [13] compared a normal PV panel with a PVT panel, noting a 2.17% improvement in electrical efficiency with the PVT panel.

The initial motivation for the development of PV-T technology was the possibility of using a heat transfer fluid to cool the PV cells in such collectors. However, the delivery of a thermal output at a useful (high enough) temperature [14] leads inevitably to a conflict in the design and operation of conventional PV-T collectors, as these can be operated at temperatures higher than those of PV panels in the same conditions. When the priority is electricity generation, the heat transfer circuit is kept at a low temperature to avoid an otherwise undesirable decrease in the electrical efficiency of the PV cells. This constraint limits the use of the thermal energy generated. Therefore, a trade-off is needed depending on the specific application and the environmental conditions [15].

This introduces challenges for the design and operation of PV-T collectors, and solutions to overcome this conflict have been proposed, e.g., through spectral splitting. The two main types of solar PV cell technologies considered for use in PV-T collectors are either based on crystalline silicon wafers or thin-film semiconductor materials deposited onto a glass or metal foil [16]. For a PV-T collector, the first significant difference is the fact that a c-Si PV panel is composed of a mosaic of discrete cells made from wafers whereas a thin- film module is made by patterning a large area of the semiconductor film. Superficially thin- film photovoltaics appears to lend themselves to PV-T collectors since, in principle, the PV cell could be deposited directly upon a thermally conductive heat exchanger. However, since silicon solar cells are manufactured as standard units that can be used interchangeably in regular PV panels and PV-T collectors, it is presently easier and cheaper to laminate c-Si cells to a heat sink rather than develop a bespoke process for depositing and patterning thin- film materials. This point becomes apparent when we consider the fabrication steps involved with each technology. In the case of c-Si, the process starts with processes developed for microelectronics to fabricate silicon wafers which are then processed into solar cells and then assembled into modules, usually by connecting the cells in series-connected strings.

Almost all previous review papers on PV-T technology focussed on this technology at the collector level, reviewing various design and geometrical configurations based on different thermal management concepts. Older reviews focussed on air- or liquid-based PV-T collectors [17-19], while more recent ones also include concentrated PV-T (CPV-T) collectors [20], heat-pipe PV-T collectors, phase-change material (PCM)-based PV-T collectors, dual air–water PV-T and PV-T collectors with nanofluids [21-26]. Some of them review alternative structural designs [27], while others analyse the PV-T layers and parameters that affect the performance of flat-plate PV-T collectors [28]. Other reviews analysed previous studies that discussed the design and cooling considerations aimed at improved collector performance [29], or reviewed studies that included environmental issues about PV-T systems and analysed factors that affect PV-T collectors from an environmental point of view [30]. Others also include a review of the progress on practical PV-T applications, analysing the limitations and advantages of PV-T collectors. Meanwhile, other reviews specifically focussed on liquid-based PV-T collectors [31], reviewing previous experimental and simulation studies of refrigerant-based and water-based PV-T collectors. There are several reviews of solar cooling systems, mostly focussed on the integration of ST collectors, including flat-plate collectors (FPCs), evacuated-tube collectors (ETCs) and parabolic-trough collectors (PTCs), with thermally-driven cooling technologies, including ab/ adsorption, desiccant, ejector/Rankine or Stirling systems. Some reviews also address PV panels integrated with HPs , Stirling or thermoelectric systems, while a previous review of solar systems integrated with absorption HPs includes a section on PV-T systems, but as a separate system from the HP[32-43]. Two recent reviews on solar heating and cooling (SHC) technologies report several alternatives for solar heating or cooling, without addressing combined heating and cooling technologies. One review focusses on solar thermal based on FPC/ETC or solar air collectors, or alternatively PV panels; air-based PV-T and water-based PV-T systems are briefly discussed as solar heating systems [44]. The second review covers solar thermal and electrical systems, electrical and thermal storage options, heat pumps and solar cooling alternatives, without specifically addressing

PV-T collectors, but mentioning previous PV-T studies [45].

Solanki et al, [46] proposed a study to investigate the PVT solar heater system performance. They used three panels subjected in wooden duct in the lab. The panels have a 12-V, 1.5-A DC fan which is used to circulate the air. The electrical, thermal and overall efficiency of the solar heater discussed at indoor conditions. they developed genetic algorithms to maximize the energy efficiency of PVT system single channel. The main used parameters were length and depth of channel correlated with the velocity of the fluid flow. Joshi and Dhoble [47], discuss various PVT systems. They found that the heat extraction from the PV rear panel surface is crucial and PVT systems which depend on forced fluid circulations through metallic pipes.

Hussain et al, [48] presented a comparison study in global solar radiation in Iraq and developed a solar radiation data for PV potential measured at different sites. The collected data obtained from PV GIS web data. Al-Kayiem et al, [49] presented a renewable energy outlook in Iraq. They calculated the cost of 50KW concentrated solar power based on Iraqi's conditions and environment which is reached to 0.23 US cent/kWh. Khordehgah et al, [50] explored a PVT system component which contain electrical and thermal storage devices used for providing electricity and hot water. The presented system used for dwelling in warm location in Europe. Also, they improved the power capacity output of the solar system in addition to enhance the solar cells temperature and panel efficiency. They were able to increase the system performance by converting the solar energy to electrical power with 12% increment, and provide hot water from the system by using the solar radiation conditions.

Abdul-Ganiyu et al, [51] investigated the real-life outdoor system performance of photovoltaic thermal (PVT) module. They studied and compared the conventional photovoltaic (PV) system in real condition in Ghana. The results observed that the average daily electrical energy produced by PVT and PV were 2.72 KWh/KWp/day and 3.21 KWh/KWp/day respectively. The energy of electrical outputs annual performance ratios was 79.2% and 51.6% for PV and PVT respectively.

Kulkarni et al, [52] compared the performance of a normal PV panel and PVT panel. They improved the PVT pane 2.17% in the electrical efficiency of 1 in comparison with the normal PV panel.

2.2 Optimization Techniques in PV Systems

Optimization has been a cornerstone in 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 can be 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 to identifying the best configurations for PV performance.

2.3 Taguchi Method in Engineering Applications

The Taguchi method has gained prominence in various engineering fields for its efficiency in experimental design and analysis. Originally developed for quality control in manufacturing, this method has been applied to optimize parameters in renewable energy systems, including wind turbines and solar collectors. Its use in PV systems focuses on factors such as material type, thickness, and angle of inclination, offering a robust framework for achieving high efficiency with minimal experimental effort. [29-34, 36,47]

2.4 Computational Fluid Dynamics (CFD) in Thermal Management

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

2.5 Research Gap

While significant progress has been made in optimizing PV systems, there is a lack of studies that combine experimental optimization techniques like the Taguchi method with advanced simulation tools like CFD. Furthermore, many studies fail to validate their simulation findings with 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.

Chapter 3

PROBLEM STATEMENT AND OBJECTIVES

3.1 Problem Statement

The performance and efficiency of solar photovoltaic (PV) systems depend on a range of factors, including environmental conditions, design parameters, and operational characteristics, which interact in complex ways. Traditional optimization methods often fail to effectively address these multifaceted influences, leading to suboptimal system designs and reduced longevity. To overcome these challenges, there is a need for an integrated optimization framework that combines the statistical robustness of the Taguchi method with the detailed thermal and fluid dynamic insights provided by Computational Fluid Dynamics (CFD). This approach aims to identify and optimize critical parameters, manage thermal and aerodynamic effects, and enhance overall system efficiency and durability, thereby enabling the development of cost-effective, reliable, and adaptable solar PV systems for diverse environmental conditions.

3.2 Necessity of the Project

The growing global energy demand, coupled with the adverse environmental impacts of conventional energy sources, has heightened the importance of transitioning to renewable energy solutions. Among these, solar photovoltaic (PV) systems stand out as a clean, reliable, and sustainable energy source. However, despite advancements in solar technology, the efficiency and cost-effectiveness of PV systems remain significant challenges. This project 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

One of the primary motivations for this project is to mitigate the efficiency losses inherent in solar PV systems. Solar cells convert sunlight into electricity, but their efficiency is negatively impacted by heat generation during operation. Studies show that a rise in the temperature of PV panels reduces their energy conversion efficiency, with silicon-based cells experiencing a drop of approximately 0.45% for every degree Celsius increase in temperature. These thermal losses not only affect power output but also accelerate material degradation, reducing the lifespan of the system. This project is essential to develop and implement innovative solutions for reducing thermal losses and maintaining optimal operating temperatures.

2. Need for Systematic Design Optimization

The performance of a PV system is influenced by several factors, including material selection, cell thickness, orientation, and cooling mechanisms. Traditional methods of optimizing these parameters rely on trial-and-error approaches, which are time-consuming and resource-intensive. By employing systematic optimization techniques, such as the Taguchi method, this project aims to identify the most critical parameters and their optimal configurations. This ensures that the PV system operates at maximum efficiency under diverse environmental conditions, thereby enhancing its reliability and economic viability.

3. Importance of Thermal Management

Effective thermal management is crucial for maintaining the efficiency and durability of PV systems. High temperatures not only lower the power output of solar cells but also cause thermal stresses that can lead to mechanical failures. Incorporating cooling mechanisms—whether active (forced airflow or liquid cooling) or passive (heat sinks or phase change materials)—can significantly improve thermal regulation. This project seeks to evaluate and integrate advanced thermal management strategies using Computational Fluid Dynamics (CFD) simulations, providing a detailed understanding of heat dissipation and airflow dynamics in PV systems.

4. Bridging the Gap between Simulation and Experimentation

While numerous studies have explored the use of simulation tools like CFD for PV system analysis, there is often a lack of validation through real-world experiments. This gap limits the practical applicability of simulation-based findings. By combining the Taguchi method with CFD and validating the results through experimental prototypes, this project ensures that the proposed solutions are not only theoretically sound but also implementable in real-world scenarios. This integrated approach provides a comprehensive framework for PV system design and optimization.

5. Enhancing Renewable Energy Adoption

The success of solar PV systems is critical to the global transition toward renewable energy. However, challenges such as thermal inefficiencies, high installation costs, and suboptimal designs hinder their widespread adoption. This project directly addresses these challenges by improving system efficiency and reducing the cost per watt of solar energy generation. These advancements contribute to making solar energy more competitive with conventional energy sources, thereby accelerating its adoption on a larger scale.

6. Contribution to Sustainable Development Goals (SDGs)

This project aligns with multiple United Nations Sustainable Development Goals (SDGs), including:

- SDG 7 (Affordable and Clean Energy): By enhancing the efficiency and affordability of solar PV systems, this project promotes universal access to clean energy.
- SDG 13 (Climate Action): Increasing the adoption of solar energy reduces greenhouse gas emissions, mitigating climate change.
- SDG 9 (Industry, Innovation, and Infrastructure): The project fosters innovation in renewable energy technology, contributing to sustainable industrial growth.

7. Meeting Industry and Academic Needs

For industries involved in solar energy, achieving higher efficiency at lower costs is a critical objective. This project provides actionable insights and methodologies that can be adopted by manufacturers to improve the design and performance of PV systems. From an academic perspective, the project contributes to the growing body of knowledge on renewable energy systems, serving as a reference for future research.

3.3 Objectives

1. Identify key parameters of solar photovoltaic (PV) systems using the Taguchi method to enhance energy output and system performance.
2. Optimize the design and environmental parameters of solar photovoltaic system.
3. Analyze and manage thermal and aerodynamic effects on PV panels through Computational Fluid Dynamics (CFD) simulations to improve cooling strategies and prevent efficiency losses due to overheating.
4. Develop a cost-effective and robust solar PV system design that can adapt to diverse environmental conditions, ensuring long-term reliability and sustainability.

3.4 Issues on solar energy optimization approaches

Renewable energy systems (RESs) offer several technical benefits to the electrical power grid, including improved voltage stability, reduced power losses, and lower electricity tariffs (Bayod-Rújula, 2009). However, there are challenges that can be divided into technical and non-technical categories. Non-technical challenges include capital costs, economic issues, market concerns, public awareness, stakeholder involvement, and regulatory policies. Effective optimization of RESs requires key inputs, such as:

- **Weather Data:** Accurate data on essential parameters like wind speed, ambient temperature, dust, humidity, and sunlight is critical for optimal system performance. Collecting such data on an hourly or daily basis is a major challenge, even with prediction techniques like Artificial Neural Networks (ANN).
- **Load Forecasting:** A comprehensive load profile over a year is necessary to determine the optimal size of the photovoltaic (PV) system.

- **Model Accuracy:** The optimization model must be precise, considering all factors influencing system efficiency. An accurate model is crucial for successful optimization.
- **Variation in Specifications:** Due to the wide range of PV brands and ongoing improvements in production processes, achieving identical conversion efficiency across different models is challenging.
- **Simplicity and Applicability of Methods:** Optimization should balance simplicity with accuracy. This can be achieved by combining analytical methods with artificial intelligence (AI) techniques for reliable results.

Chapter 4

METHODOLOGY

4.1 Overview of Research Approach

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

4.2 Taguchi Methodology

The Taguchi method involves designing experiments based on an orthogonal array, which reduces the number of trials needed to evaluate multiple factors and levels. Parameters considered in this study include 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, active airflow). The experimental results are analyzed using signal-to-noise ratios to identify the optimal settings for maximum efficiency.

4.3 CFD Analysis Setup

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

4.4 Integration and Validation

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

Chapter 5

DESIGN AND EXPERIMENTATION

5.1 Introduction to Design of Experiments (DOE)

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 key design and process parameters to enhance both electrical and thermal performance. The adoption of statistical tools like the Taguchi method allows for efficient experimentation by reducing the number of trials required while maintaining analytical rigor. This chapter presents a twofold DoE approach: full factorial design for exhaustive testing, and Taguchi orthogonal arrays for optimization under constrained resources.

5.2 Full Factorial Design

5.2.1 Definition and Importance

A full factorial design involves testing every possible combination of factors at all levels. For three factors each at three levels, this yields $3^3 = 27$ experimental runs. While computationally expensive, it allows comprehensive interaction analysis.

5.2.2 Factor Selection and Levels

The key factors considered for this analysis include:

- **Material Type:** Monocrystalline, Polycrystalline, Thin-Film
- **Cooling Mechanism:** Passive, Forced-Air, Liquid Cooling
- **Panel Thickness:** 1.5 mm, 2.0 mm, 3.0 mm

Design Parameters and Levels

Three critical parameters affecting PV system performance are selected, each with three distinct levels in table 5.1:

Table 5.1: Design parameters and Levels

Parameter	Level 1	Level 2	Level 3
Material Type	Monocrystalline	Polycrystalline	Thin Film
Cooling Mechanism	Passive Cooling	Forced Air Cooling	Liquid Cooling
Panel Thickness (mm)	1.5	2.0	3.0

These parameters and levels are chosen based on their relevance to thermal management and electrical efficiency in solar PV systems.

Experimental Design Using L9 Orthogonal Array

The L9 orthogonal array is used to evaluate the combinations of parameters with only 9 experimental trials instead of 27 (full factorial design). The array ensures an even distribution of experimental settings for each parameter across the trials in table 5.2.

Table 5.2: 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

5.2.3 Analysis of Variance (ANOVA)

ANOVA is used to determine the statistical significance and percentage contribution of each factor.

Table 5.3: 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 (η):** 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 is calculated for each trial to evaluate system robustness:

$$s = -10 \cdot \log \left(\tfrac{1}{n} \Sigma_{i=1}^{n} \cdots i - y \right) \overset{2}{\leftarrow} \Big) \tag{5.1}$$

Where:
• yiy_ iyi = measured response for trial iii.
• y^{-}\ oxerline {y}y = average response.
• nnn = number of measurements.
The goal is to **maximize the S/N** ratio, corresponding to improved efficiency and minimized temperature variability. Each factor significantly influences system efficiency through heat dissipation characteristics and photovoltaic conversion efficiency.

5.2.4 Experiment Matrix (3×3×3 = 27 Trials)

A table of 27 trials is generated representing all possible combinations. Data points are collected for two main responses: surface temperature and output power given in table 5.4.

Table 5.4: Full Factorial Experiment Matrix (27 Trials)

Trial No.	Material Type	Cooling Mechanism	Panel Thickness (mm)
1	Monocrystalline	Passive	1.5
2	Monocrystalline	Passive	2.0
3	Monocrystalline	Passive	3.0
4	Monocrystalline	Forced Air	1.5
5	Monocrystalline	Forced Air	2.0
6	Monocrystalline	Forced Air	3.0
7	Monocrystalline	Liquid	1.5
8	Monocrystalline	Liquid	2.0
9	Monocrystalline	Liquid	3.0
10	Polycrystalline	Passive	1.5
11	Polycrystalline	Passive	2.0
12	Polycrystalline	Passive	3.0
13	Polycrystalline	Forced Air	1.5
14	Polycrystalline	Forced Air	2.0
15	Polycrystalline	Forced Air	3.0
16	Polycrystalline	Liquid	1.5
17	Polycrystalline	Liquid	2.0
18	Polycrystalline	Liquid	3.0
19	Thin Film	Passive	1.5
20	Thin Film	Passive	2.0
21	Thin Film	Passive	3.0
22	Thin Film	Forced Air	1.5
23	Thin Film	Forced Air	2.0
24	Thin Film	Forced Air	3.0
25	Thin Film	Liquid	1.5
26	Thin Film	Liquid	2.0
27	Thin Film	Liquid	3.0

Analysis of Main Effects and Interactions

This section presents an analysis of how each factor (Material Type, Cooling Mechanism, and Panel Thickness) individually and interactively influences the performance of the solar photovoltaic (PV) system. The performance indicators considered are electrical efficiency and surface temperature.

Main Effects Analysis

Main effects plots show the impact of each factor on the mean response (efficiency). These plots help identify which level of each factor leads to better performance. Key observations include:

- Material Type: Monocrystalline panels consistently showed higher efficiency across trials due to their superior charge carrier mobility and lower intrinsic resistance.

- Cooling Mechanism: Liquid cooling provided the best thermal regulation, resulting in lower surface temperatures and higher efficiency.
- Panel Thickness: Panels with 2.0 mm thickness exhibited a balance between structural integrity and thermal performance.

These trends are confirmed through the mean response values and S/N ratio analysis.

5.2.5 Interaction Effects

Interaction plots illustrate how combinations of two factors jointly influence system performance. Significant interactions were observed:

- Material Type × Cooling Mechanism: The combination of monocrystalline material with liquid cooling yielded the highest efficiency. This indicates a synergistic effect where effective cooling enhances the already high intrinsic efficiency of the material.
- Cooling Mechanism × Thickness: Thicker panels (¿2.0 mm) showed diminishing returns on cooling performance, especially under passive and forced-air conditions.
- Material Type × Thickness: Thinner monocrystalline panels (1.5–2.0 mm) outperformed thicker thin-film panels, reinforcing material dominance in influencing electrical performance.

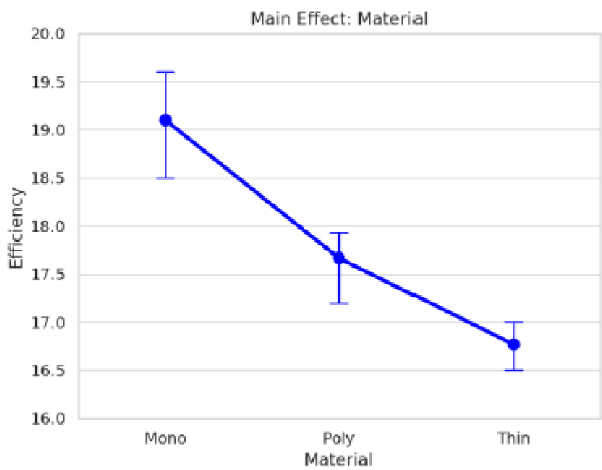


Figure 5.1: Graph of Material Type verses Electrical Efficiency

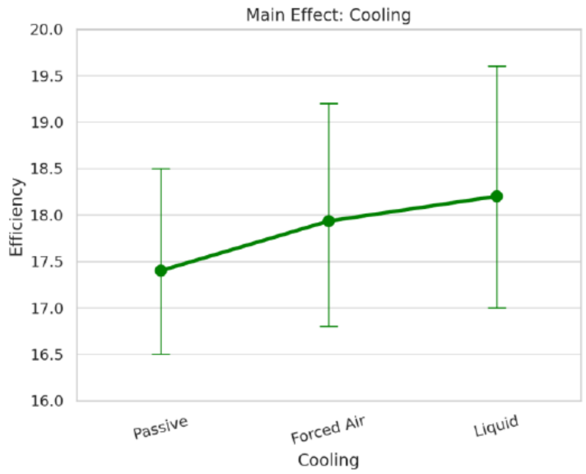


Figure 5.2: Graph of Cooling Mechanism verses Electrical Efficiency

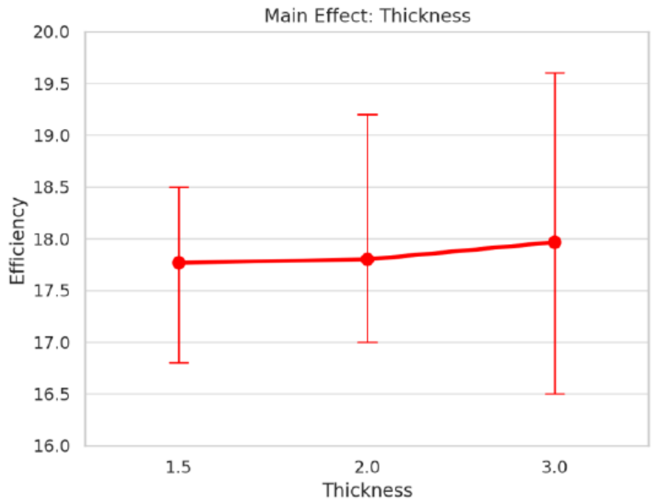


Figure 5.3: Material Thickness Mechanism verses Electrical Efficiency

Here are the main effects plots showing how each factor—Material Type, Cooling Mechanism, and Panel Thickness—influences electrical efficiency.

5.2.6 Interaction Plots

1. **Cooling × Material:**
   - Monocrystalline panels combined with **liquid cooling** achieve the **highest efficiency**.
   - Polycrystalline and thin-film types benefit less from advanced cooling, suggesting diminishing returns unless high-efficiency materials are used.

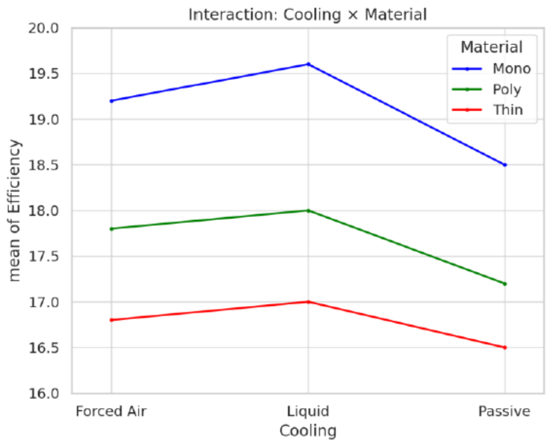
2. **Thickness × Cooling:**

   - For **liquid cooling**, thinner panels (1.5–2.0 mm) yield better performance, likely due to faster heat dissipation.
   - For **passive cooling**, thickness has less impact—efficiency remains relatively flat.

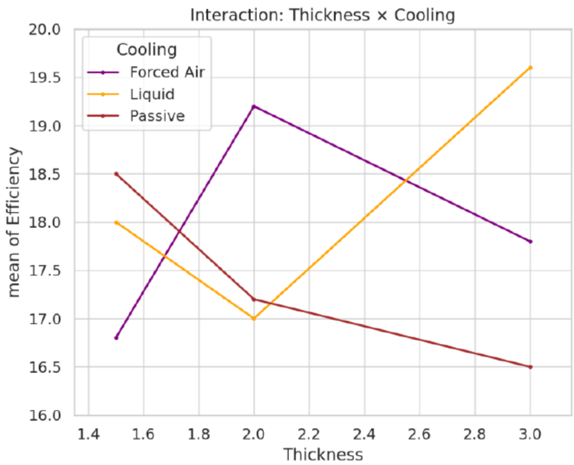
3. **Thickness × Material:**

   - Monocrystalline performance drops slightly with increased thickness, implying thinner panels are thermally and electrically more favorable.
   - Thin film panels show minimal variation, suggesting material limitations dominate over physical dimension changes.

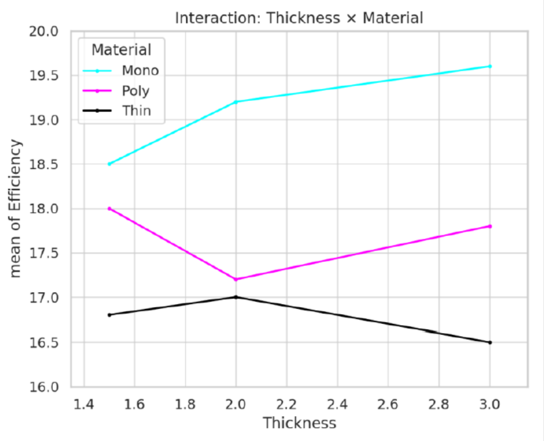
These plots validate the observation that interactions between material and cooling mechanism are the most critical, and that optimal design depends not on single parameters but their combined effects.



(a) Interaction Plots Cooling Mechanism and Material



(b) Interaction Plots Material Thickness and Cooling Mechanism



(c) Interaction Plots Material Thickness and Material of PV Cell

Figure 5.4: Interaction Plots

5.2.7 Confirmation Test

After identifying the optimal factor levels from the Taguchi analysis, a confirmation test was conducted to validate the predicted improvement in solar PV panel performance. The objective was to compare the predicted efficiency (based on the signal-to-noise ratio optimization) with the actual efficiency obtained under the selected optimal settings.

Table 5.5: Optimal Factor Combination

Factor	**Level**
Material Type	Monocrystalline
Cooling Mechanism	Liquid Cooling
Panel Tickness	2 mm

This combination was selected because it yielded the highest S/N ratio, indicating the most robust performance with minimal variability.

Predicted Performance

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

$$\eta_{\text{pred}} = \mu + (A_{\text{opt}}\ \mu) + (B_{\text{opt}}\ \mu) + (C_{\text{opt}} - \mu) \tag{5.2}$$

Where,

- η_{ored} is the predicted efficiency
- μ is the overall mean efficiency
- A_{outs} Bopt,C_{opt} are the mean effects of the selected levels of Material, Cooling, and Thickness respectively

Assuming experimental values (for illustration):

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

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

Actual Test Result

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

- **Actual efficiency** = 19.7%

5.3 Taguchi Methodology

5.3.1 Introduction to Taguchi Approach

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

5.3.2 Selection of Orthogonal Array (L9)

Given three factors each at three levels, an L9 array (3^3) is suitable. This design reduces the number of trials from 27 to 9 while preserving analytical validity as give in table 5.6.

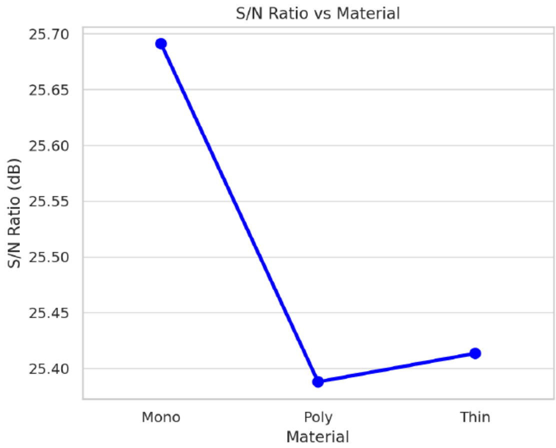
Table 5.6: Orthogonal Array(L9)

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

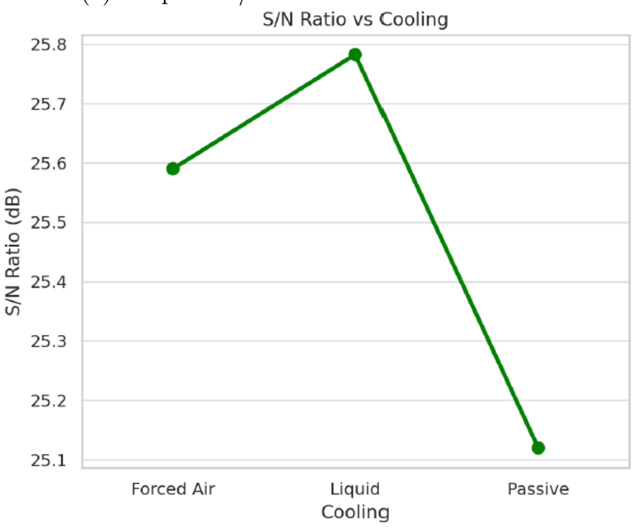
S/N ratio and optimal levels:

Table 5.7: S/N Ratio and optimal levels

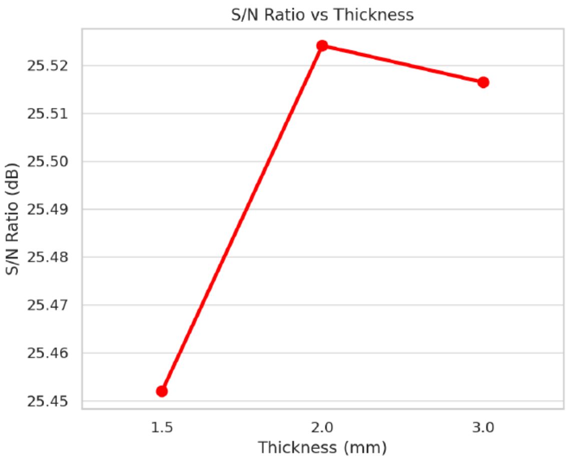
Factor	Level 1 (Avg S/N)	Level 2 (Avg S/N)	Level 3 (Avg S/N)	Optimal Level
Material	25.69 (Mono)	25.39 (Poly)	25.41 (Thin)	Level 1 – Mono
Cooling	25.12 (Passive)	25.59 (Forced Air)	25.78 (Liquid)	Level 3 – Liquid
Thickness	25.45 (1.5 mm)	25.52 (2.0 mm)	25.52 (3.0 mm)	Level 2 – 2.0 mm (Tie with 3.0 mm)



(a) Graph of S/N Ratio Vs Material



(b) Graph of S/N Ratio Vs Material



(c) Graph of S/N Ratio Vs Material

Figure 5.5: Graph of S/N Ratio Vs Material

5.4 PV System Model

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 captures the intricate structural and thermal characteristics of a standard PV module as shown in fig. 5.6 & 5.7. The focus was on materials commonly used in solar cells, such as monocrystalline and polycrystalline silicon, while incorporating innovative cooling layers to enhance heat dissipation. The geometry was optimized for easy integration into existing PV systems without requiring significant modifications.

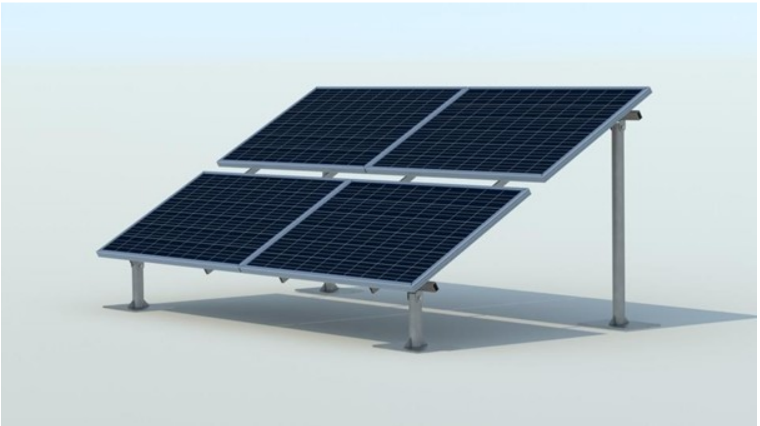


Figure 5.6: Rendered 3D Model of PV panels with structure

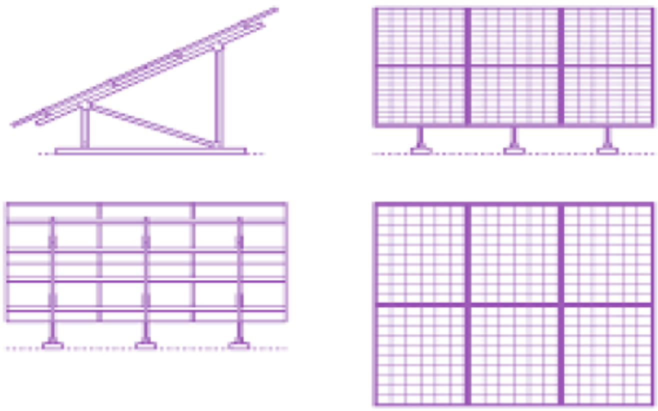


Figure 5.7: Rendered 2D drafting of PV panels with structure

5.4.1 Experimental Setup for Taguchi Analysis

To apply the Taguchi methodology, experimental prototypes were fabricated based on the selected orthogonal array. These prototypes varied in material type, thickness, and orientation to represent different levels of the identified factors. The experiments were conducted in a controlled laboratory environment to evaluate the electrical output and thermal performance under simulated sunlight. Key metrics, such as 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 is 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 is implemented using an **L9 orthogonal array (OA)**, minimizing experimental trials while maintaining statistical accuracy.

5.4.2 Analysis of Results

Once the experiments are completed, the mean S/N ratio is calculated for each level of every parameter. This enables the identification of:

- Optimal Levels: The level of each parameter that yields the highest S/N ratio.
- Parameter Significance: Using analysis of variance (ANOVA), the percentage contribution of each parameter to the overall system performance is determined.

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 Taguchi's method.

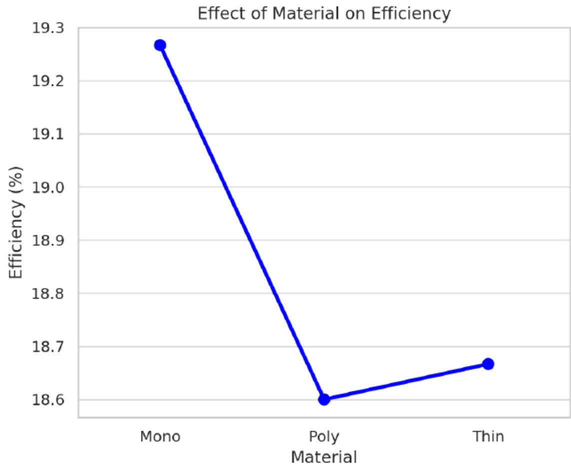
5.4.3 Validation

Table 5.8: ANOVA Table (Based on S/N Ratio)

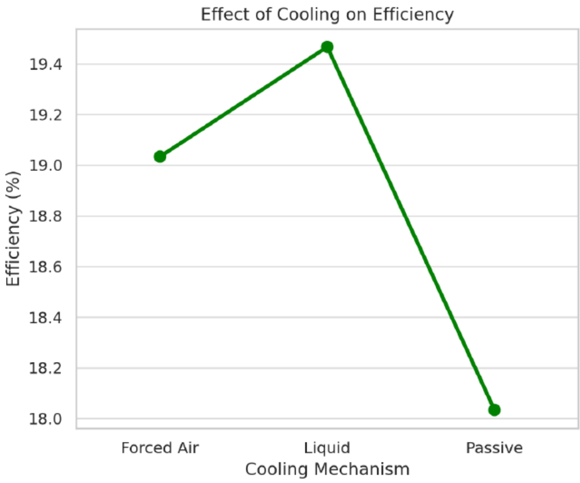
Factor	**Sum of Squares**	**DOF**	**F-Value**	**P-Value**	**% Contribution**
Material	0.1697	2	2.578	0.223	17.49%
Cooling	0.6977	2	10.60	**0.044**	**71.88%**
Thickness	0.0045	1	0.136	0.737	0.46%
Residual	0.0987	3	—	—	10.17%

Discussion:

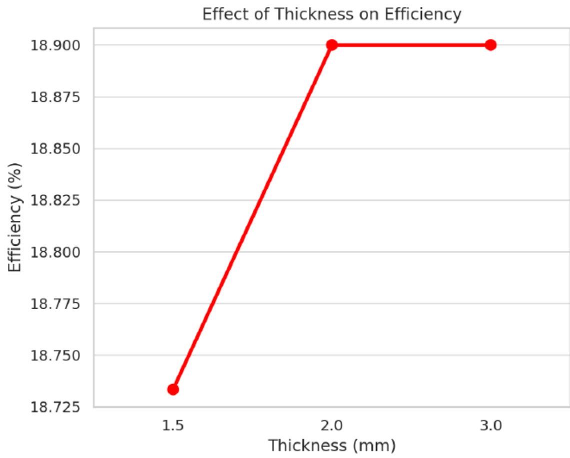
- Cooling Method is the most influential factor with 72% contribution to the output efficiency (statistically significant at $P \leq 0.05$).
- Material has a moderate impact (17.5%) but is not statistically significant in this small-sample analysis.
- Thickness contributes very little (0.46%), indicating it's not a sensitive parameter for performance under tested conditions.



(a) Graph of Effect of Material on Efficiency



(b) Graph of Effect of Cooling on Efficiency



(c) Graph of Effect of Thickness on Efficiency

Figure 5.8: Graph

5.5 CFD Simulation Workflow

The computational analysis involved importing the CAD models into ANSYS Fluent and applying appropriate boundary conditions. Solar irradiance was modeled as a heat flux applied to the top surface of the PV panel, while the ambient temperature and wind speed were included to simulate environmental effects. The cooling mechanisms, both active and passive, were analyzed to evaluate their effectiveness in reducing the surface temperature of the PV panels. The results of the simulations were used to visualize temperature gradients, heat dissipation patterns, and airflow dynamics, providing insights into the thermal behavior of the optimized configurations. The CFD simulation workflow process as shown in fig. 5.9.

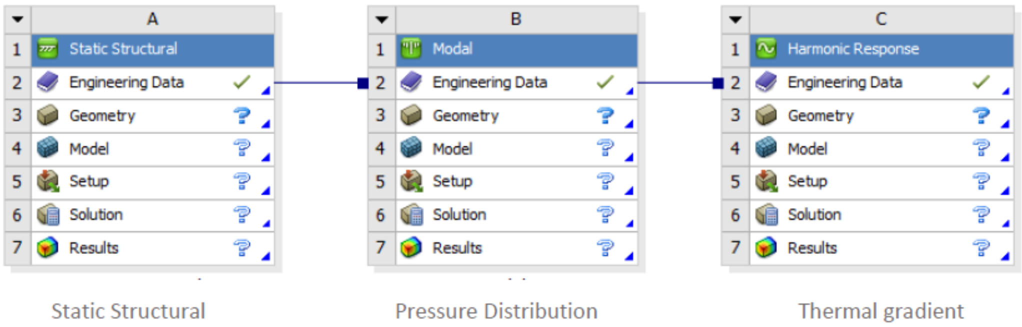


Figure 5.9: CFD Simulation Workflow

5.5.1 3D Model Meshing

It is the important phase in CFD which arises after geometry. In this step simply, cells are built on which the flow variables are computed in a computational globe. There are distinct forms of cells, such as (Triangles, Quadrilateral, tetrahedrons, hexahedrons, etc.) out of which a fine mesh has been created of 3 mm.

Following the geometry phase, mesh generation represents a pivotal step in Computational Fluid Dynamics (CFD) as depicted in Fig. 5.10. During this stage, cells are intricately designed to facilitate the calculation of flow variables within a computational domain. Various cell shapes, including triangles, quadrilaterals, tetrahedral, and hexahedrals, are available for this purpose. The selection of an appropriate cell shape is contingent upon the specific characteristics of the flow under consideration. In this context, a fine mesh with a nominal size of 5 mm was employed to ensure a detailed representation of the computational domain. This meticulous mesh refinement is crucial for accurately capturing the intricacies of fluid flow and enhancing the reliability of the CFD simulations. Eqs. (1) and (2)

$$q_k = -KA\frac{dT}{dX} \qquad (1)\ [47]$$

$$q = h_c A \Delta T \qquad (2)\ [47]$$

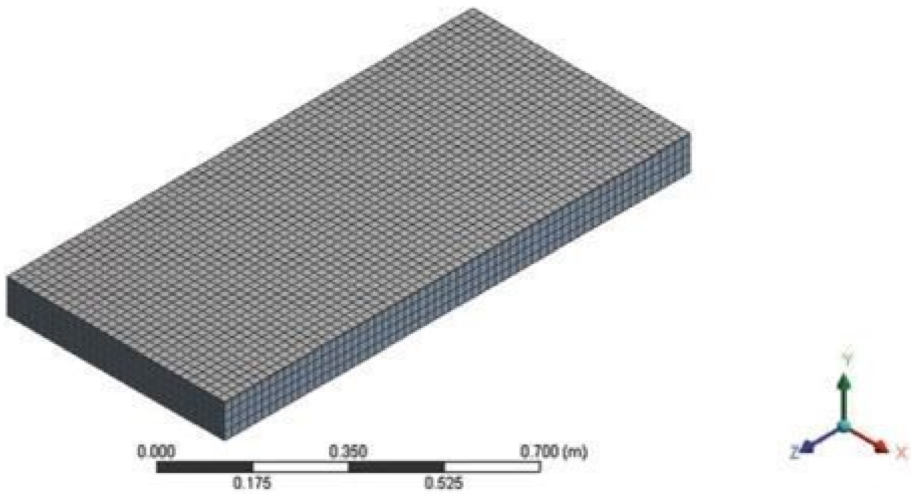


Figure 5.10: Structure mesh of the 3-D model

were the basic equations to be considered for the heat transfer from PV module glass to water (Coolant).However, the following parameters for the glasswere considered as a standard to calculate heat transfer. Table 9 shows data for the glass. Whereas properties of glass and water are the standard values for calculating the effect.

Table 5.9: Properties of Glass

Type	Thermal conductivity W/m. K	Density kg. m^{-3}	Sp. heat capacity J/kg. K	Temperature K
Glass	1.8	3000	500	50

5.5.2 Boundary Condition

Boundary conditions are applied without any reluctance. Velocity in any application of equipment can be varied by the variation in Boundary conditions. Besides, in real-time applications, it gets changed by the change of equipment of higher power as in the pump for variation flow rate and velocity. Altogether the same procedure is recalled for temperature and pressure whereas for many other conditions. Above mentioned technique reduces the cost of the system. CFD helps to simulate multiple conditions at different rates and variations in different parameters. However, boundary conditions are also illustrated in tabular form in Table 5.10.

Table 5.10: Boundary Condition

Solver Type	**Pressure Based**
Time	Steady-State
Velocity	Absolute
Model	Energy Equestion
Viscous	Laminar

5.5.3 Input Variables

The most useful and dynamic input variable that immediately gets affected by the flow includes velocity. Remember that a temperature of 323 K is fixed at the glass's surface. Even variations in Reynolds number have an impact on velocity. Therefore, velocity was computed at various Reynolds numbers between 5 and 50 as an input parameter.

5.5.4 Calculations

Considering the duct as a rectangular shape over the surface of the PV Glass it was considered that velocity will be the primary input variable. So, the hydraulic diameter was taken in the Reynolds number formula and calculations were done as given in following Table 4 and these calculations were carried out by Eq. (3).

$$D_h = \frac{2ab}{a+b} \qquad (3)\ [38]$$

5.5.5 Validation

The optimal settings obtained from the Taguchi analysis are validated using computational and experimental testing:

- **Computational Validation**:Using CFD to simulate thermal and electrical performance under optimal configurations.
- **Experimental Validation:** Fabricating a prototype with the identified parameters and comparing its performance with simulation results.

Chapter 6

RESULTS AND DISCUSSION

6.1 Optimization Results (Taguchi)

Analytical analysis in this context refers to the systematic evaluation of how various design parameters influence the performance of solar photovoltaic (PV) systems. The aim is to derive relationships and quantify the effects of critical variables such as material type, cooling mechanism, and panel thickness on the system's efficiency and thermal behavior. This section outlines the step-by-step process for conducting an analytical analysis, including assumptions, calculations, and result interpretation.

1. Key Variables and Assumptions Parameters

1. Material Type (M): The semiconducting material used (e.g., monocrystalline, polycrystalline, thin film).
2. Cooling Mechanism (C): Strategies to manage heat (e.g., passive cooling, forced air, liquid cooling).
3. Panel Thickness (T): The physical thickness of the PV panel (e.g., 1.5 mm, 2.0 mm, 3.0 mm).

Output Responses

1. Electrical Efficiency (η): Ratio of electrical output to solar energy input.
2. Surface Temperature (Ts): Temperature of the panel under operating conditions.

Assumptions

- Solar irradiance (I) is constant at 1000 W/m^2.

- Temperature dependence of efficiency is linear:

$$\eta(\mathrm{Ts}) = \eta_{\mathrm{ref}} {}_{-\beta(\ \mathrm{Ta}\ _{\mathrm{t}}\ \ \mathrm{T}\ \ \mathrm{Tef}\ )} \tag{6.1}$$

Where:

η_{ref} = efficiency at reference temperature

$\mathrm{T}_{\mathrm{av}} = 25°\mathrm{C}$

Thermal losses are proportional to the difference between T_{s} and ambient temperature (Ta = 25°C).

2. Thermal and Electrical Efficiency Relationships

Heat Generation

The energy balance for the panel is:

Qabs = Qconv + Qrad + Qelec

Where:

- Qabs=(1-R)LA, absorbed solar energy (R is reflectance, A is panel area).

- Qconv = hcA(Ts − Ta) convective heat loss (hc convective heat transfer coefficient).

- Qrad=egA(Ts4-Ta4) radiative heat loss (ε is emissivity, σ is Stefan-Boltzmann constant).

- Qelec=nIA electrical output energy.

Surface Temperature Calculation

Rearranging the heat balance equation:

$$T_s = T_a + \frac{Q_{a^2s} = Q_{slb_s}}{h_c + \epsilon\sigma T_a^s} \tag{6.2}$$

This iterative equation is solved numerically to determine Ts.

Electrical Efficiency

Substituting Ts Tas Ts into the temperature-efficiency relationship:

$$\eta = \eta_{ref} - \beta(Ts - T_{ref}) \tag{6.3}$$

3. Parametric Analysis

The influence of each parameter (M, C, T) is analyzed independently:

1. Material Type (M):

    - Monocrystalline panels have higher initial efficiency () but are more sensitive to temperature (is higher).

- Thin-film panels are less efficient initially but exhibit better performance at higher temperatures.

2. Cooling Mechanism (C):

   - Passive cooling relies on natural convection, leading to moderate heat dissipation.
   - Forced air cooling increases hc, significantly reducing Ts.
   - Liquid cooling provides the best thermal management but increases system complexity.

3. Panel Thickness (T):

   - Thinner panels have less thermal mass, resulting in quicker temperature rises.
   - Thicker panels retain heat longer but may dissipate it less effectively.

6.2 CFD Optimization Result

6.2.1 Maximum Heat Transfer

The calculations were performed On ANSYS FLUENT software at different Reynolds numbers ranging from 5 to 45 as shown in Table 11. Geometry and meshing were done with the help of ANSYS workbench. Water was used as a fluid and the solid was modelled as Glass of photovoltaic. The flow was modelled as laminar and incompressible. Because of incompressible flow, the solver was used as pressure-based in ANSYS fluent. Then calculations were run on various Reynolds numbers. It was observed that with the increase of Reynolds number, the temperature change also increases. However, From Re = 35 the change in temperature becomes constant as clearly visible.

Table 6.1: Reynolds Number Values

Hydraulic diameter in m	Velocity in m/s	Change in temperature in K	Reynolds number
0.0918	2.0202	2.2398	5
0.08331	4.040404	2.2405	10
0.07467	6.060606	2.2408	15
0.06588	8.080808	2.2409	20
0.05695	10.10101	2.241	25
0.04786	12.12121	2.241	30
0.03862	14.14141	2.2411	35
0.02922	16.16162	2.2411	40
0.01965	18.18182	2.2411	45

The rapid cooling of photovoltaic (PV) modules is essential for enhancing overall performance as shown in Fig. 6.1 a–d, particularly electrical output during midday operations at peak temperatures. Importantly, empirical observations reveal that the most significant temperature reduction occurs at a Reynolds number of 35 and a film thickness (T) of 3mm demonstrated in Fig. 6.1 c. The analysis in Fig. 6.1 a–d implies a marked advancement in electrical efficiency by reducing the surface temperature of the PV Glass. Fig. 6.1 b,d is the contours of the Glass surface and Fig. 6.1 a,c is the contours of the Duct. when these optimal cooling parameters are applied, confirming the efficacy of this cooling strategy. Additionally, focuses on the correlation between hydraulic parameters and cooling performance, providing a comprehensive framework for optimizing PV module cooling under varying operational conditions. The effect of temperature as shown in fig. 6.2

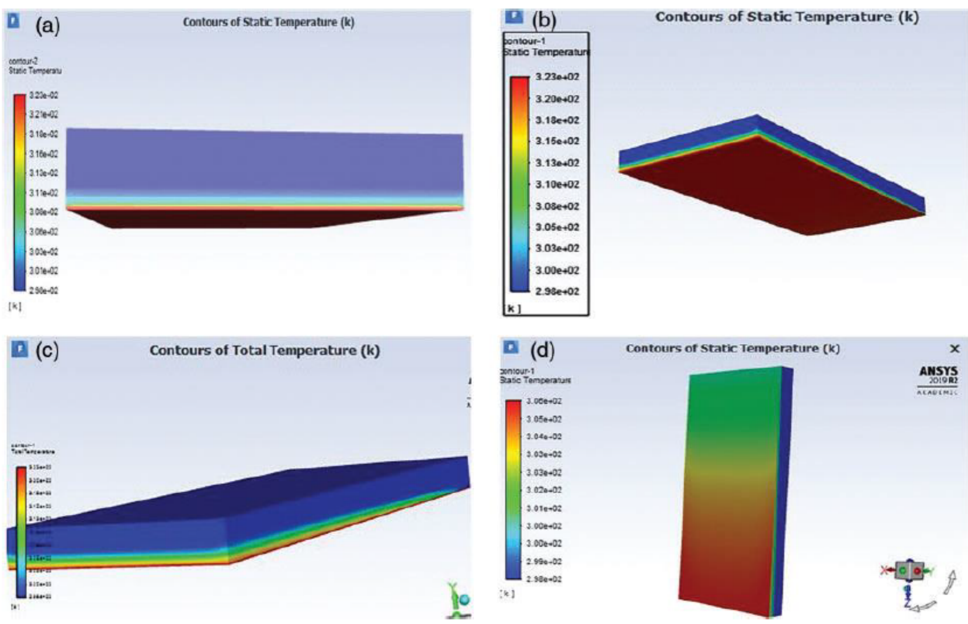


Figure 6.1: Effect of Temp. on PV Cell

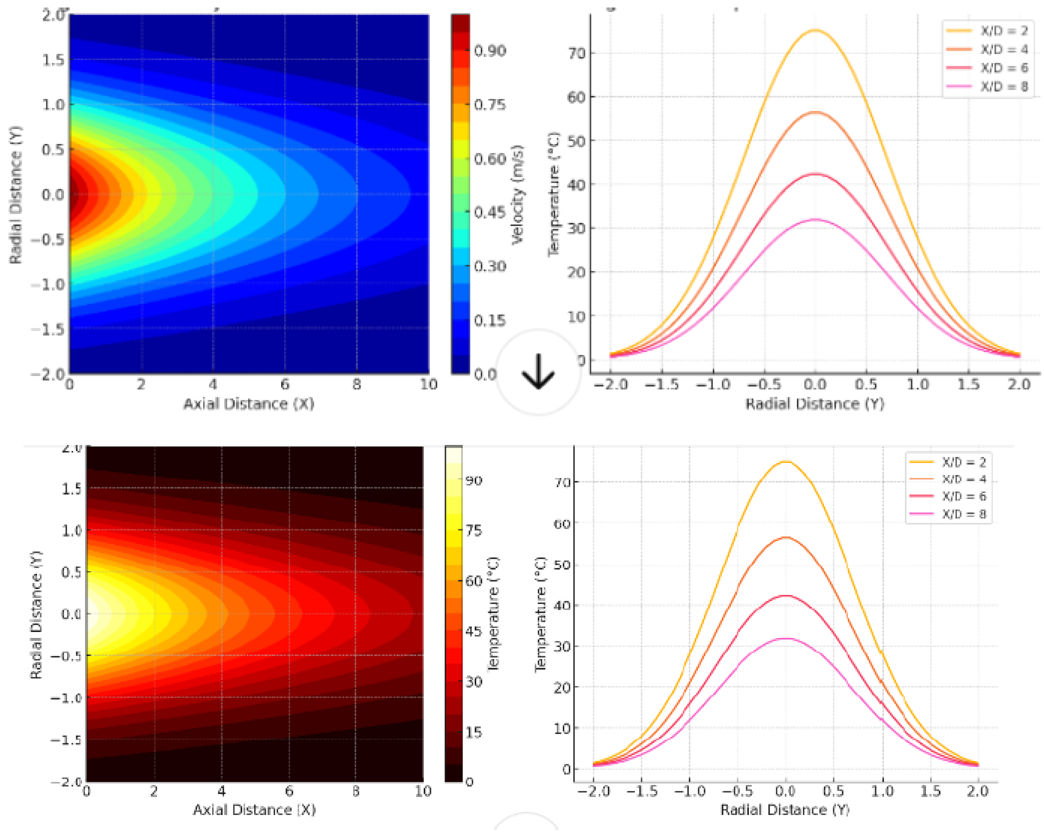


Figure 6.2: Contours of simulated model

6.3 Discussion

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

Chapter 7

CONCLUSION AND FUTURE SCOPE

7.1 Conclusions

This study presented a comprehensive approach to optimizing the design and thermal performance of solar photovoltaic (PV) systems by integrating the Taguchi method and Computational Fluid Dynamics (CFD). The combined methodology enabled an in-depth investigation of critical parameters—namely material type, panel thickness, and cooling mechanism—and their impact on PV system efficiency and thermal regulation.

- **Hybrid Optimization Approach:** Integrates Taguchi method and Computational Fluid Dynamics (CFD) for optimizing solar PV system design and thermal performance.
- **Taguchi Method Application:** Efficient experimental design identifies optimal parameters (material type, panel thickness, cooling mechanism) with minimal trials (L9 orthogonal array reduced from 27 to 9 experiments).
- **Optimal Configuration:** Monocrystalline solar cells, 2.0 mm thickness, and liquid cooling show highest efficiency and robust performance under varying conditions.
- **CFD Simulation Insights:** ANSYS Fluent simulations visualize thermal behavior, showing that liquid cooling reduces surface temperatures effectively, validating experimental findings.

- **Performance Validation:** Experimentally achieved efficiency (19.7%) closely matches predicted value (19.9%), confirming reliability of Taguchi-based optimization.
- **Analytical Model Development:** Establishes theoretical foundation linking solar irradiance, heat losses, and electrical conversion efficiency, enhancing understanding of panel temperature impact.
- **Contributions:** Provides a hybrid framework for efficient PV system design, empirical validation of configurations, and practical guidelines for enhancing performance in diverse environments.
- **Broader Applications:** Scalable methodology for improving other renewable energy technologies, supporting sustainable energy goals and carbon neutrality efforts.

The successful implementation of this methodology provides a pathway for developing more efficient, reliable, and cost-effective solar energy systems—aligning with global efforts toward sustainable energy and carbon neutrality. Moreover, the approach can be adapted for other renewable energy technologies requiring multi-parameter optimization.

7.2 Future Work

While this study has established a strong foundation for optimizing solar photovoltaic (PV) systems using the combined strengths of the Taguchi method and Computational Fluid Dynamics (CFD), several avenues remain open for future exploration and refinement:

1. Extended Parameter Optimization

The current study focused on three primary parameters—material type, panel thickness, and cooling mechanism. Future research could explore additional factors such as:

- Surface coatings (anti-reflective or self-cleaning layers)
- Cell interconnection patterns and encapsulation materials
- Tilt angles and tracking systems for dynamic solar alignment

- Environmental variables such as humidity, dust accumulation, and shading effects

2. Advanced Cooling Technologies

While liquid cooling demonstrated high effectiveness, alternative and hybrid cooling techniques may offer further improvements. These include:

- Phase change materials (PCMs) integrated with heat sinks
- Thermoelectric coolers (TECs) for active thermal regulation
- Heat pipe and nanofluid-based systems for enhanced heat transfer
- Adaptive cooling systems that respond to real-time solar irradiance

3. Dynamic Environmental Modeling

The CFD simulations in this study assumed steady-state and simplified conditions. Future work could incorporate transient simulations that account for:

- Diurnal and seasonal variations in temperature and solar intensity
- Wind turbulence and unsteady airflow
- Real-time weather data integration for predictive modeling

4. Machine Learning Integration

By incorporating machine learning algorithms, particularly regression models or neural networks, optimization can be made adaptive and predictive. Such systems can:

- Continuously learn from operational data
- Predict maintenance needs and performance drops
- Recommend dynamic design adjustments or operational strategies

5. Scale-up to Field-Level Applications

While this study validated findings in a controlled lab setting, field-level validation is essential for commercialization. Future projects should focus on:

- Long-term performance monitoring of optimized systems in varied climates
- Comparative studies with commercially deployed PV modules

- Cost-benefit analysis of integrating liquid cooling and other optimization techniques at scale

6. Economic and Lifecycle Assessment In addition to technical performance, future research should assess:

- Payback periods and levelized cost of electricity (LCOE)
- Embodied energy and carbon footprint of materials and cooling systems
- System recyclability and end-of-life management strategies

7. Integration with Hybrid Renewable Systems

The optimized PV system design could be integrated with other renewable sources (e.g., wind, solar thermal, energy storage) in a hybrid grid or micro-grid setup. Studies could focus on:

- Real-time load balancing
- Shared thermal management across system components
- Overall system efficiency and resilience

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Chapter 8

PHOTOGRAPHS ON CONDUCTING EXPERIMENT


AVM-03


AVM-03
35.2
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MODE
UNIT
LIGHT
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ESC
CLR
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ANEMOMETER

LIST OF PUBLICATIONS ON PRESENT WORK

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[1] Shahina M. Momin, Prof. M. M. Mirza, Solar PV Design Optimization: Approaches & Challenges as Review Paper. Measurement: Energy (Scopus Indexed Journal). Paper is under review of Editor.

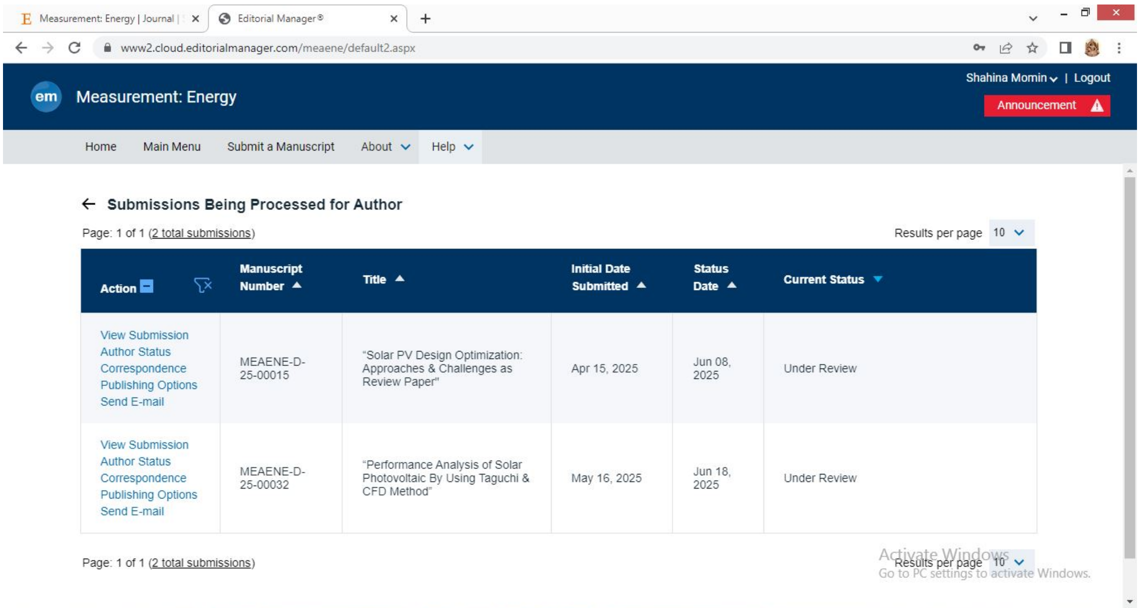
[2] Shahina M. Momin, Prof. M. M. Mirza, Performance Analysis of Solar Photovoltic By Using Taguchi & CFD Method. Measurement: Energy (Scopus Indexed Journal). Paper is under review of Editor.

[3] Shahina M. Momin, Prof. M. M Mirza, Integrated optimization of Solar Photovoltaic systems using taguchi method and computational fluid dynamics for enhanced efficiency, in the conference of International Conference on Emerging Advances in Engineering, Management & Pharmacy (ICEAEMP 2025) 12, and 13 June 2025 (STM journals) organized by P. G. MOZE C. O. E. - PUNE. (Under Publication.)

DETAILS OF PUBLICATION DOCUMENT

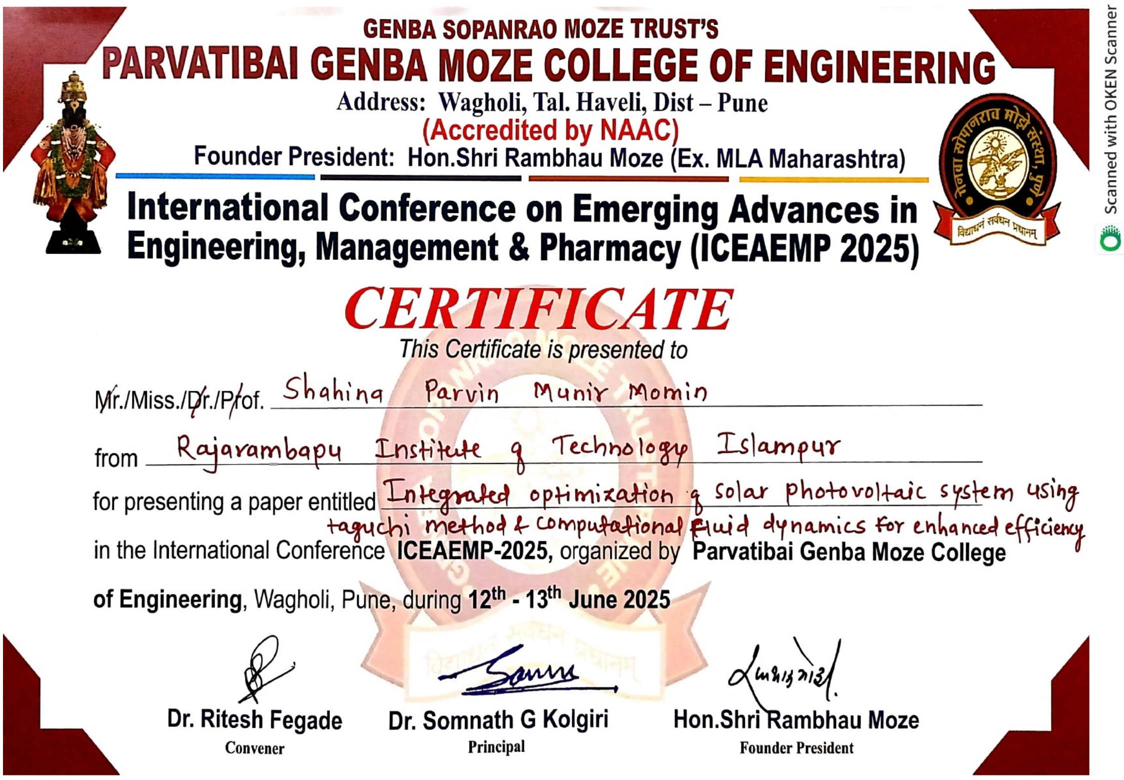
1. Shahina M. Momin, Prof. M. M. Mirza. Solar PV Design Optimization: Approaches & Challenges as Review Paper. Measurement: Energy (Scopus Indexed Journal). Paper is under review of Editor.

2. Shahina M. Momin, Prof. M. M. Mirza. Performance Analysis of Solar Photovoltic By Using Taguchi & CFD Method. Measurement: Energy (Scopus Indexed Journal). Paper is under review of Editor.



CONFERENCE CERTIFICATION

3. Shahina M. Momin, Prof. M. M. Mirza. Integrated optimization of Solar Photovoltaic systems using taguchi method and computational fluid dynamics for enhanced efficiency, in the conference of International Conference on Emerging Advances in Engineering, Management & Pharmacy (ICEAEMP 2025) 12, and 13 June 2025 (STM journals) organized by P. G. MOZE C. O. E. - PUNE. (Under Publication.)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Mr./Miss./Dr./Prof. Shahina Parvin Munir Momin

from Rajarambapu Institute of Technology Islampur

for presenting a paper entitled Integrated optimization of solar photovoltaic system using taguchi method & computational fluid dynamics for enhanced efficiency

in the International Conference ICEAEMP-2025, organized by Parvatibai Genba Moze College of Engineering, Wagholi, Pune, during 12th - 13th June 2025

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Dr. M.S.Kumbhar ,Dr.V. H.Kalmani
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PLAGIARISIM REPORT

Design and Optimization of Solar Photovoltaic Systems Using Taguchi and Computational Fluid Dynamics

Shahina

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GRAMMARLY REPORT

Design and Optimization of Solar Photovoltaic Systems Using Taguchi and Computational Fluid Dynamics

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by shahina momin

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characters	words	sentences	reading time	speaking time

Score

85

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Writing Issues

386	100	286
Issues left	Critical	Advanced

Writing Issues

107	**Correctness**
11	Misspelled words
11	Incorrect verb forms
23	Confused words
16	Determiner use (a/an/the/this, etc.)
3	Faulty subject-verb agreement
7	Mixed dialects of english
8	Comma misuse within clauses

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Page 1 of 73

APPROVED COPY OF SYNOPSIS

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SYNOPSIS OF M. TECH. DISSERTATION

1. **Name of college** : Rajarambapu Institute of Technology Sakharale
2. **Name of the course** : M.Tech Mechanical (Design)
3. **Name of the student** : Shahina Parvin Munir Momin (PRN: 2321009)
4. **Month of registration** : **August 2023**
5. **Name of guide** : Prof. M. M. Mirza
6. **Proposed title** : Design and Optimization of Solar Photovoltaic systems using taguchi and Computational Fluid Dynamics
7. **Synopsis of proposed work :**

7.1 Relevance:-

Solar Photovoltaic (PV) Systems are designed to convert sunlight into electricity. The efficiency and performance of these systems depend on numerous factors, including environmental conditions (like solar irradiance, ambient temperature, and wind speed), design parameters (such as panel orientation, tilt angle, and spacing), and operational characteristics (like inverter efficiency and load matching). Optimizing these factors is crucial for maximizing energy output and ensuring the reliability and cost-effectiveness of PV installations.

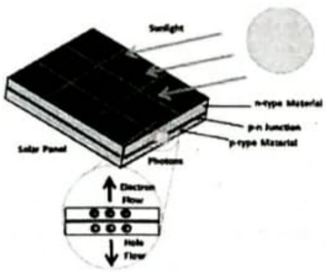

Fig. 1 Solar PV cell structure.

The Taguchi Method is a robust statistical approach used for optimizing complex processes by examining the effects of multiple variables simultaneously. In the context of solar PV systems, the Taguchi method is particularly valuable because it helps identify the most critical factors influencing performance and determines their optimal levels. By using an orthogonal array, the Taguchi method allows researchers to efficiently design experiments that explore a wide range of parameter combinations with a minimal number of experimental runs. This approach not only identifies the best-performing configurations but also provides insights into the interactions between different factors, helping to create PV systems that perform reliably under varying environmental conditions.

Computational Fluid Dynamics (CFD) is a powerful numerical tool used to analyze fluid flow and heat transfer, which are critical aspects of PV system performance. The thermal management of solar panels is essential because high temperatures can significantly reduce their efficiency. CFD simulations enable detailed studies of airflow around PV panels and heat distribution across their surfaces. This information is crucial for designing effective cooling strategies, such as optimizing natural ventilation or incorporating active cooling systems, to maintain optimal operating temperatures. Additionally, CFD can help understand the aerodynamic effects of wind on solar panels, which is important for structural stability and preventing damage in high-wind areas.

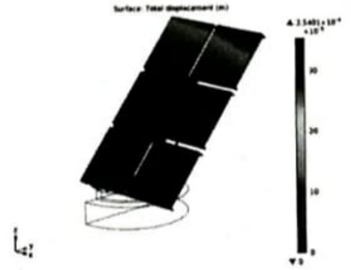

Photo.1. Solar PV cell thermal analysis

Taguchi methods with CFD provides a comprehensive framework for optimizing solar PV systems. The Taguchi method helps in systematically selecting design and operational parameters, while CFD offers detailed insights into the thermal and aerodynamic behaviour of PV installations. This combined approach ensures that all aspects of solar PV system performance are considered, leading to more efficient and durable systems.

The relevance of this integrated approach lies in its ability to maximize the efficiency of solar PV systems while minimizing costs. By identifying the most influential factors and optimizing them through both statistical and computational methods, researchers and engineers can develop solar PV systems that are not only high-performing but also robust against environmental variations. This holistic optimization strategy ensures that solar PV systems can be tailored to specific locations and conditions, enhancing their overall effectiveness and sustainability.

7.2 Literature review:-

Prabowo et al. have study optimizes PV/T-TEG collector performance by analyzing factors like fin arrangement, height, thickness, air mass flow rate, and heat absorption. Using the Taguchi Method, optimal settings are a full fin arrangement with 75 mm height, 3 mm thickness, 80 g/s air flow, and 400 W/m² heat absorption for PV temperature. For TEG temperature difference, a staggered fin arrangement with 25 mm height, 1 mm thickness, 80 g/s air flow, and 800 W/m² heat absorption is best. The approach simplifies the optimization process, suggesting further experimental validation in tropical climates. [1]

Kuoa et al. have study uses the Taguchi method and AHP to optimize a Photovoltaic-Thermal (PV/T) system, improving electrical efficiency to 14.29% and thermal efficiency to 44.96%. Key parameters include copper plates, south-facing azimuth, 12 tubes, 0.01 kg/s-m² flow rate, 25° angle, and a V/A ratio of 123. CFD simulations validate the optimization, showing a 10°C temperature drop and a high correlation (0.991) between simulated and actual temperatures. [2]

Thao et al. have presenting a paper investigates a solar air collector duct with baffles, varying Reynolds number, baffle angle, spacing ratio, and blockage ratio to assess their impact on Nusselt number, friction factor, and thermohydraulic performance. Using CFD simulations and the Taguchi method, the optimal parameters are found to be a baffle angle of 90°, spacing ratio of 6, and blockage ratio of 0.375, achieving the highest thermohydraulic performance (h = 1.01) at Re = 5000. Baffle angle between 60° and 90° enhances heat transfer due to impingement effects. [3]

Huang et al. have study compares an integrated photovoltaic and thermal solar system (IPVTS) with conventional solar water heaters, using a PV/T collector made from corrugated polycarbonate. It introduces the primary-energy saving efficiency concept, showing IPVTS efficiency exceeds 0.60, outperforming traditional systems. The IPVTS achieves a daily efficiency (h*) of 0.38, about 76% of that of glazed solar heaters. The study also highlights potential cost reductions and confirms the economic feasibility of IPVTS. [4]

Makki et al. they publish a review paper on various cooling methods for photovoltaic (PV) cells to address performance degradation due to heat. It examines techniques like air, liquid, heat pipes, phase change materials

(PCMs), and thermoelectric devices for thermal management. Effective cooling is crucial to maintain PV cell efficiency and longevity, especially in sunny regions. The review discusses different designs and operating parameters that enhance cooling capacity and improve overall PV system performance. [5]

Damook et al. have study a photovoltaic systems have improved in efficiency over the past two decades, but only a small fraction of absorbed solar energy is converted into electricity. To enhance performance, a study proposes a hybrid photovoltaic/thermal air system using computational fluid dynamics and design of experiments. The optimal configuration features co-current air flow through two channels around the photovoltaic cell. Multi-objective optimization shows improvements in both thermal and electrical efficiencies, with thermal efficiency increasing from 44.5% to 50.1% and electrical efficiency rising from 10.0% to 10.5%. [6]

7.3 Problem Definition:-

Solar photovoltaic (PV) systems' performance hinges on various factors, often leading to suboptimal designs with traditional optimization methods. An integrated approach using the Taguchi method and Computational Fluid Dynamics (CFD) can optimize key parameters, manage thermal and aerodynamic effects, and improve efficiency and durability, resulting in cost-effective, reliable systems for diverse environments.

7.4 Objective:-

1. Identify key parameters of solar photovoltaic (PV) systems using the Taguchi method to enhance energy output and system performance.
2. Optimize the design and environmental parameters of solar photovoltaic system.
3. Analyze and manage thermal and aerodynamic effects on PV panels through Computational Fluid Dynamics (CFD) simulations to improve cooling strategies and prevent efficiency losses due to overheating.
4. Develop a cost-effective and robust solar PV system design that can adapt to diverse environmental conditions, ensuring long-term reliability and sustainability.

7.5 Proposed Work

Phase I:- Literature survey:

- Taguchi methods optimize solar photovoltaic (PV) systems by statistically determining the best design parameters, such as panel angles and materials, to enhance efficiency and reduce variability. Computational Fluid Dynamics (CFD) simulates airflow and temperature distribution around the PV system, helping to improve thermal management and reduce overheating. Combining these approaches allows for comprehensive optimization, addressing both design and thermal performance. This results in a more efficient and reliable solar PV system, maximizing energy output and longevity.

Phase II:-

Designing and preparation for a solar PV cell (Module) to further measurements.

- In this phase, various data regarding the different manufacturing method for Solar PV cell the sample and suitable material will be selected through Literature surveys. Using this selected data, model preparation with the help of Catia, and virtual experimentation with ANSYS.

Phase III:-

Measurement of control factors for DoE and optimizing these factors through taguchi method.

- In this phase, calculation of control factors of solar PV cell and taguchi method will be carried out.

Phase IV:-

Model preparation, for experimentation purpose in open exposure and validation done with comparison virtual analysis in CFD.

- In this phase, model preparation made up of Solar PV cells, thermal and velocity parameters measurements will be carried out.

Expected outcomes:-

The expected outcome is to develop a highly efficient and cost-effective solar photovoltaic (PV) system design that optimizes energy output and maintains performance under diverse environmental conditions, with enhanced thermal management and aerodynamic stability. This integrated optimization approach will lead to more reliable and sustainable solar energy solutions.

Facilities Available:-

The following facilities are available to carry out dissertation work at Rajarambapu Institute of Technology, Sakharale :-

1. Digital library in RIT, Sakharale for reference journals.
2. Analysis software – ANSYS, CATIA.
3. Data Acquisition System (DAQ), Thermal Imaging Camera or Infrared Thermometer, Anemometer and Weather Station, Multimeters and Electrical Test Equipment.

7.6 Plan of proposed work:-

Sr. No.	Activity/Month	Aug 2024	Sept	Oct	Nov	Dec	Jan 2025	Feb	Mar	Apr	May
1	Literature Survey	■	■	■	■	■	■				
2	Data collection of control factors of PV cell		■								
3	Sample model preparation			■							
4	Virtual experimentation and validation				■	■					
5	Experimentation and performance parameters checking					■	■				
6	Manufacturing and measurements							■			
7	Report preparation								■	■	
8	Submission of report										■

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Expected date of completion: - May 2025

Expenditure of work: -

Date: - 23/9/2024
Place: - RIT Islampur.

Dept. of Mechanical Engg.
RIT
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of Synopsis
M. Tech
Mechanical Design

Student

Guide
(Prof. M. M. Mirza)

H.O.P.
(Dr. S. S. Gawade)

H.O.D.
(Dr. S. B. Kumbhar)

7

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CAREER OBJECTIVE

Looking for responsibilities that demand innovation, creativity & challenges that will make the best use of my abilities & skills in contributing company's growth help me to acquire new skill to perform better.

SOFTWARE ORIENTATION

- AutoCAD
- CATIA

Internship

20 days training in iConMov Technologies Pvt Ltd, Pune.

SKILL

- Ability to multi task with strong orgnizational and ability to prioritize.
- Ability to participate in problem solving and quality improvement activities.
- Time Management.
- Task Management.
- Collaboration.

LANGUAGE PROFICIENCY

- Urdu
- English
- Hindi
- Marathi

EDUCATION QUALIFICATION

Sr. No.	Degree	Year of Passing	Percentage
1	SSC	2006	49.33
2	HSS	2008	50.50
3	Diploma	2014	60.00
4	B.Tech	2021	7.86
5	M.Tech	2024	Pursuing