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Thermal Performance Assessment of Passive Cooling Strategies for Photovoltaic Modules: A CFD-Based Review and Comparative Analysis

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Abstract

The increasing global demand for renewable energy has accelerated the deployment of photovoltaic (PV) systems as a sustainable electricity-generation technology. However, the operating temperature of PV modules significantly influences their electrical efficiency, reliability, and service lifetime. Elevated module temperatures reduce photovoltaic conversion efficiency because of the negative temperature coefficient of semiconductor materials and may contribute to long-term degradation of module components. Therefore, effective thermal management techniques are essential for improving PV system performance. This review investigates passive cooling approaches for photovoltaic modules, with emphasis on natural convection enhancement, heat sink integration, and other non-powered thermal regulation methods. Computational fluid dynamics (CFD) has become an important analytical tool for understanding heat transfer mechanisms, airflow patterns, temperature distribution, and cooling effectiveness in PV systems. This paper evaluates the role of CFD modelling in predicting thermal behaviour and comparing passive cooling configurations under various operating conditions. The review highlights that passive cooling techniques can reduce PV module temperature by improving heat dissipation through enhanced convection and conduction pathways without requiring additional electrical energy. Heat sinks provide increased surface area for heat transfer, while natural convection-based designs offer simple, reliable, and low-maintenance cooling solutions. The findings indicate that CFD-based evaluation provides valuable insight for optimising cooling geometries and selecting suitable thermal management strategies for PV applications.
The study recommends further development of hybrid passive designs that combine improved airflow channels, advanced heat transfer materials, and optimised structural configurations to maximise PV efficiency and durability.

Keywords: Photovoltaic modules; passive cooling; computational fluid dynamics; natural convection; heat transfer; thermal management

1. INTRODUCTION

1.1 Background of the Study

Photovoltaic technology has become one of the most promising renewable energy solutions due to its ability to convert solar radiation directly into electrical energy. The increasing adoption of PV systems is driven by the need to reduce dependence on fossil fuels and minimise greenhouse gas emissions. However, operating temperature strongly affects the efficiency of PV modules.

According to Skoplaki and Palyvos (2009), the electrical performance of PV modules decreases as temperature increases because semiconductor materials experience reduced voltage output at higher temperatures. Although PV panels are designed to operate under outdoor environmental conditions, continuous exposure to solar radiation results in significant thermal accumulation.

Research has shown that a considerable portion of incident solar energy is converted into heat rather than electricity, causing PV module temperatures to rise above ambient conditions (Dubey et al., 2013). This thermal behaviour creates a major challenge in maintaining optimal PV performance.

1.2 Problem Statement

Many PV cooling techniques have been developed, including active cooling methods involving fans, pumps, and water circulation systems. Although effective, active approaches require additional energy consumption, maintenance, and operational complexity.

Passive cooling techniques, including natural convection enhancement and heat sink integration, provide an alternative because they operate without external power input. However, the thermal performance of these methods depends strongly on geometry, environmental conditions, and heat transfer mechanisms. Therefore, we need advanced numerical analysis methods, such as computational fluid dynamics (CFD), to evaluate their effectiveness.

1.3 Aim of the Study

The aim of this study is to examine and compare passive cooling strategies for photovoltaic modules using CFD-based thermal analysis approaches.

1.4 Objectives

The objectives are to:

1. Review temperature effects on PV module performance.
2. Examine passive cooling mechanisms for PV systems.
3. Analyse the application of CFD in PV thermal modelling.
4. Compare the thermal benefits of heat sinks and natural convection techniques.
5. Identify future research directions for improved passive PV cooling.

1.5 Significance of the Study

Improving PV thermal management can enhance energy yield, reduce degradation, and increase system reliability. The study provides insights into sustainable cooling approaches that support the wider adoption of solar energy technologies.

2. LITERATURE REVIEW

2.1 Temperature Effects on Photovoltaic Performance

Operating temperature strongly influences the electrical performance of photovoltaic (PV) modules, which are semiconductor-based energy conversion devices. When solar energy is converted, only a small amount of the incoming solar radiation is turned into electrical energy. The rest is turned into thermal energy, which makes the temperature of the PV module rise above the temperature of the air around it. This thermal accumulation represents one of the major challenges affecting photovoltaic system efficiency, reliability, and long-term performance.

The relationship between PV module temperature and electrical output is primarily associated with the temperature sensitivity of semiconductor materials. As the temperature of a PV cell increases, the bandgap energy of the semiconductor material decreases, resulting in increased carrier recombination and reduced electrical potential. The reduction of open-circuit voltage, which directly decreases the overall conversion efficiency of the PV module, has the most significant impact.

Skoplaki and Palyvos (2009) established that PV module efficiency has a negative temperature dependence, where an increase in cell temperature produces a corresponding decrease in electrical efficiency. The authors said that crystalline silicon PV modules, which make up most of the commercial PV installations, usually lose efficiency when the temperature rises above the normal testing conditions. This effect becomes particularly important in regions with high solar intensity and elevated ambient temperatures, where module temperatures may significantly exceed the manufacturer’s rated conditions.

Dubey, Sarvaiya, and Seshadri (2013) further demonstrated that temperature variations have a substantial influence on PV performance parameters, particularly voltage output. Their analysis showed that although current output may slightly increase with temperature, the reduction in voltage is considerably greater, resulting in a net decrease in power generation. Consequently, thermal management becomes necessary to maintain favourable operating conditions and improve energy yields.

The thermal behaviour of PV modules also affects their durability and degradation rates. Continuous exposure to high temperatures accelerates ageing mechanisms such as solder bond fatigue, encapsulant degradation, delamination, and reduction in material stability. According to research on PV reliability, excessive thermal cycling can shorten module lifespan and increase maintenance requirements. Therefore, reducing operating temperature is not only important for immediate efficiency improvement but also for enhancing the operational lifetime of photovoltaic systems.

Several environmental and design parameters, including solar irradiance intensity and ambient temperature, influence the temperature distribution across a PV module.

- solar irradiance intensity,
- ambient temperature,
- wind velocity,
- module inclination angle,
- mounting configuration,
- backside ventilation,
- thermal conductivity of module materials.

A poorly ventilated PV installation can trap heat behind the module, creating higher temperature regions and non-uniform thermal conditions. Such temperature gradients may lead to uneven electrical performance and localised degradation. Therefore, effective cooling strategies that promote heat dissipation are essential for improving PV system reliability.

2.2 Passive Cooling Techniques for Photovoltaic Modules

Passive cooling techniques involve thermal management approaches that remove excess heat from PV modules without the requirement of external electrical energy. Unlike active cooling systems that depend on fans, pumps, or mechanical devices, passive cooling relies on naturally occurring heat transfer mechanisms such as conduction, convection, and radiation.

The importance of passive cooling has increased because it provides a sustainable and economical approach for improving PV efficiency. Passive methods reduce auxiliary energy consumption, require minimal maintenance, and are suitable for remote installations where additional power requirements may reduce the overall benefit of the PV system.

The main passive cooling approaches applied in PV thermal management include natural convection enhancement, heat sink integration, improved ventilation design, phase change materials, and thermally optimised module structures.

2.2.1 Natural Convection Cooling

Natural convection is one of the simplest and most widely investigated passive cooling mechanisms for photovoltaic modules. It occurs when temperature differences between the heated PV surface and surrounding air create density variations, producing buoyancy-driven airflow. The warmer air near the PV surface becomes less dense and rises, allowing cooler ambient air to replace it. This continuous movement promotes heat removal from the module surface.

The effectiveness of natural convection cooling depends strongly on the geometry of the PV installation and the surrounding airflow conditions. Adequate spacing between the PV module and mounting surface allows air circulation behind the panel, improving heat transfer from the rear surface. Conversely, restricted airflow can cause thermal accumulation and significantly increase module temperature.

Hasan et al. (2010) emphasised that airflow behaviour plays an important role in determining the thermal performance of photovoltaic systems. Their studies demonstrated that naturally ventilated PV configurations can achieve meaningful temperature reductions when airflow pathways are properly designed. Important factors affecting natural convection cooling include:

Module inclination angle:

The tilt angle influences buoyancy-driven airflow patterns. Larger spacing and suitable inclination can improve air movement behind the PV panel.

Air channel geometry:

The size and shape of the air gap between the PV module and mounting structure determine airflow velocity and heat transfer capacity.

Environmental conditions:

Wind direction, ambient temperature, and atmospheric conditions influence the effectiveness of natural convection.

Surface characteristics:

The thermal properties and emissivity of module surfaces affect heat exchange with the surrounding environment.

Although natural convection provides a low-cost cooling option, its effectiveness may be limited under conditions of low wind movement, high ambient temperature, or densely packed PV installations. Therefore, the optimisation of module arrangement and airflow pathways is necessary.

2.2.2 Heat Sink Cooling

Heat sink technology represents another important passive cooling approach for photovoltaic thermal management. A heat sink functions by increasing the available surface area for heat transfer, allowing heat absorbed from the PV module to be dissipated more effectively into the surrounding environment.

In PV applications, heat sinks are commonly attached to the rear surface of the module, where they provide an additional conduction pathway for thermal energy movement. The absorbed heat is transferred through the heat sink material and released through convection and radiation.

The performance of a heat sink depends on several design parameters, including:

Thermal Conductivity of Material

Materials with high thermal conductivity, such as aluminium and copper, enhance heat spreading by allowing thermal energy to move rapidly from the PV surface to the cooling fins. Aluminium is commonly preferred because of its favourable balance between thermal performance, weight, corrosion resistance, and cost.

Fin Geometry

The configuration of heat sink fins significantly influences cooling performance. Increasing fin height, thickness, and spacing can increase the effective heat transfer area. However, excessively dense fin arrangements may restrict airflow and reduce natural convection effectiveness.

Surface Area

A larger heat transfer area improves interaction between the heat sink and surrounding air. This increases convective heat removal and contributes to lower PV operating temperatures.

Airflow Conditions

Heat sinks depend on surrounding airflow to remove stored thermal energy. Their performance improves when natural air circulation occurs around the fins.

Heat sink cooling offers advantages because it is simple, reliable, and does not require additional energy input. However, improper design may increase system weight and manufacturing cost. Therefore, optimisation through numerical modelling is necessary to achieve maximum thermal benefits with minimal material usage.

2.3 Computational Fluid Dynamics in Photovoltaic Thermal Analysis

Computational Fluid Dynamics (CFD) has become an important numerical approach for investigating heat transfer and fluid flow behaviour in photovoltaic thermal management systems. CFD provides a mathematical framework for solving governing equations related to conservation of mass, momentum, and energy within a defined computational domain.

Traditional experimental investigations provide useful temperature measurements but may not fully describe complex airflow patterns, local temperature variations, or heat transfer mechanisms occurring within cooling structures. CFD modelling overcomes these limitations by providing a detailed visualisation of thermal and fluid behaviour.

CFD analysis of PV cooling systems enables researchers to evaluate:

Temperature Distribution

CFD simulations provide detailed temperature maps across the PV module, heat sink, and surrounding airflow region. This allows identification of high-temperature zones and evaluation of cooling effectiveness.

Airflow Velocity Patterns

The movement of air around PV modules strongly influences convective heat transfer. CFD can predict velocity fields and determine whether airflow channels provide sufficient ventilation.

Thermal Gradients

Uneven temperature distribution can create thermal stress and reduce PV reliability. CFD enables analysis of temperature differences across the module surface.

Heat Transfer Performance

CFD allows calculation of heat transfer coefficients and comparison between different cooling designs before physical implementation.

The governing equations used in CFD PV thermal studies typically include:

- continuity equation for mass conservation,
- Navier–Stokes equations for fluid motion,
- energy equation for heat transfer analysis.

The accuracy of CFD predictions depends on appropriate assumptions, boundary conditions, mesh quality, and material properties. Therefore, validation against experimental data is essential to ensure reliable results.

Recent developments in CFD modelling have enabled researchers to optimise passive cooling structures by virtually testing multiple configurations. This reduces experimental costs and accelerates the development of efficient PV thermal management solutions.

Overall, CFD serves as a powerful tool for understanding passive cooling mechanisms and designing improved photovoltaic systems with enhanced thermal performance, higher energy output, and extended operational lifetime.

METHODOLOGY

3.1 Research Design

This study adopts a structured review-based research methodology supported by computational fluid dynamics (CFD) modelling principles applied in previous investigations of photovoltaic (PV) thermal management systems. The methodology focuses on evaluating and comparing passive cooling strategies designed to reduce PV module operating temperature and improve energy conversion performance.

The research approach involves a critical analysis of existing scientific literature related to photovoltaic thermal behaviour, passive heat transfer enhancement techniques, and numerical modelling methods. Previous studies investigating natural convection cooling, heat sink integration, and other passive thermal management methods are examined to identify the effectiveness, limitations, and optimisation requirements of each technique.

A review methodology is appropriate because PV thermal performance is influenced by multiple interacting factors, including solar radiation, environmental conditions, airflow characteristics, module configuration, and cooling system geometry. By analysing previous experimental and numerical studies, a comprehensive understanding of passive cooling mechanisms can be developed.

The study framework consists of four major stages:

1. Identification and analysis of existing research on PV temperature effects and cooling technologies.
2. Evaluation of passive cooling mechanisms and their heat transfer behaviour.
3. Assessment of CFD approaches used for predicting PV thermal performance.
4. Comparative analysis of cooling strategies based on thermal effectiveness and practical applicability.

This methodology provides a foundation for determining suitable passive cooling approaches that can enhance PV system efficiency without increasing operational energy consumption.

3.2 CFD Modelling Approach for Photovoltaic Thermal Analysis

Computational Fluid Dynamics (CFD) is widely applied in PV thermal studies because it provides detailed information regarding heat transfer processes and airflow behaviour that may not be easily obtained through experimental measurements alone.

CFD modelling involves the numerical solution of governing equations that describe fluid movement and thermal energy transport within a defined computational domain. In photovoltaic cooling applications, the model represents the PV module, surrounding airflow region, and cooling structure.

The general CFD procedure for analysing passive PV cooling systems involves the following stages:

3.2.1 Development of PV Cooling Geometry

The first stage involves creating a three-dimensional computational model representing the PV module and associated cooling arrangement.

The geometry may include:

- photovoltaic panel layers,
- glass cover,
- solar cells,
- encapsulation materials,
- rear support structure,
- heat sink fins or ventilation channels.

For passive cooling investigations, the geometry is developed to represent realistic airflow conditions around the PV module. Particular attention is given to the rear surface region because most thermal accumulation occurs at the back of conventional PV modules.

Different cooling configurations can be evaluated by modifying parameters such as:

- heat sink fin height,
- fin thickness,
- spacing between fins,
- air channel dimensions,
- module mounting distance.

Geometrical optimisation is essential because cooling performance depends strongly on airflow resistance and available heat transfer surface area.

3.2.2 Definition of Material Properties

After developing the computational geometry, the thermal and physical properties of each material component are assigned.

Important material parameters include:

- thermal conductivity,
- density,
- specific heat capacity,
- emissivity,
- electrical characteristics.

The selection of appropriate material properties is critical because heat transfer within the PV module occurs through multiple layers before reaching the cooling structure.

For heat sink-based cooling systems, materials with high thermal conductivity are generally preferred because they promote rapid heat spreading from the PV surface to the surrounding environment.

Common materials considered in PV thermal studies include:

- aluminium for heat sink structures,
- glass for protective layers,
- silicon-based materials for solar cells,
- polymer materials for encapsulation.

Accurate material definition ensures realistic prediction of temperature distribution and heat dissipation behaviour.

3.2.3 Application of Boundary Conditions

Boundary conditions define the interaction between the PV system and the external environment.

The main thermal boundary conditions considered in CFD simulations include:

Solar Heat Flux

Solar radiation absorbed by the PV module is represented as an external heat source. Since only part of the solar energy is converted into electricity, the remaining energy contributes to thermal loading.

Ambient Temperature

The surrounding air temperature affects the temperature difference between the PV module and environment, influencing natural convection performance.

Wind and Airflow Conditions

Air movement around the module influences convective heat transfer. Depending on the study objective, airflow may be modelled as natural convection or external forced flow.

Radiation Heat Transfer

Radiative heat exchange between the PV surface and surrounding environment may also be included to improve model accuracy.

Proper boundary condition selection is essential because unrealistic assumptions may lead to inaccurate thermal predictions.

3.2.4 Governing Equations

CFD analysis of PV cooling systems is based on fundamental conservation equations.

The continuity equation describes conservation of mass within the airflow domain.

The momentum equations describe the movement of air caused by pressure forces, viscosity, and buoyancy effects.

The energy equation governs heat transfer through conduction and convection processes.

For natural convection systems, buoyancy forces are particularly important because temperature differences create density variations that drive airflow movement.

The numerical solution of these equations provides information about:

- temperature fields,
- velocity distributions,
- pressure variations,
- heat transfer rates.

3.2.5 Numerical Solution and Model Evaluation

After defining geometry, material properties, and boundary conditions, the CFD solver calculates the thermal and airflow behaviour of the PV cooling system.

The simulation output is analysed to determine:

- maximum PV temperature,
- average module temperature,
- temperature reduction achieved,
- airflow circulation patterns,
- effectiveness of the cooling structure.

Different passive cooling configurations can then be compared to determine which design provides the highest thermal benefit.

3.3 Evaluation Parameters

The performance of passive cooling techniques is assessed using several thermal and electrical indicators. These parameters provide a quantitative basis for comparing different cooling approaches.

3.3.1 PV Surface Temperature

PV module temperature is the primary indicator used to evaluate cooling performance.

A lower operating temperature generally indicates improved thermal conditions and reduced efficiency losses. CFD analysis allows the temperature distribution across the PV surface to be examined rather than relying only on average measurements.

The maximum and average module temperatures are commonly analysed to identify thermal improvement.

3.3.2 Temperature Reduction

Temperature reduction represents the difference between the PV temperature before and after applying a cooling technique.

A greater temperature decrease indicates stronger heat removal capability.

The effectiveness of a passive cooling method depends on its ability to transfer accumulated heat from the PV module to the surrounding environment.

3.3.3 Heat Transfer Coefficient

The heat transfer coefficient indicates the ability of a cooling system to transfer thermal energy from the PV surface to the surrounding air.

Higher heat transfer coefficients generally correspond to improved convective cooling.

Heat sink geometry and airflow conditions strongly influence this parameter.

3.3.4 Airflow Velocity Distribution

For natural convection systems, airflow velocity is an important performance indicator.

CFD allows visualisation of airflow paths around the PV module and identification of regions where air circulation is enhanced or restricted.

Improved airflow increases convective heat removal and reduces thermal accumulation.

3.3.5 Electrical Efficiency Improvement

Since PV efficiency decreases with increasing temperature, cooling strategies indirectly improve electrical output.

The effectiveness of a cooling method can therefore be evaluated by its ability to maintain operating temperature closer to standard test conditions.

Improved thermal control contributes to:

- higher power output,
- reduced degradation,
- improved reliability.

3.4 Comparative Framework for Passive Cooling Techniques

This study compares three major passive cooling approaches used for photovoltaic thermal management: natural convection cooling, heat sink cooling, and hybrid passive cooling structures.

Cooling Method	Heat Transfer Mechanism	Thermal Characteristics	Main Advantage
Natural convection cooling	Buoyancy-driven airflow caused by temperature differences	Removes heat through natural air circulation around the module	Simple design, low cost, and minimal maintenance
Heat sink cooling	Heat conduction from PV module followed by convection from extended surfaces	Increases heat transfer area and improves thermal dissipation	Enhanced heat removal capability
Hybrid passive structures	Combination of conduction enhancement, airflow improvement, and advanced thermal materials	Provides multiple heat transfer pathways	Higher cooling potential and improved adaptability

Natural convection systems are generally preferred for applications requiring simplicity and low maintenance. Heat sinks provide stronger thermal control due to increased surface area but may require additional material and structural considerations.

Hybrid passive cooling approaches combine multiple mechanisms to overcome the limitations of individual methods. These systems have significant potential for future PV applications because they can provide improved thermal performance while maintaining low energy requirements.

Overall, the methodology establishes a comprehensive framework for evaluating passive cooling techniques and identifying effective strategies for improving photovoltaic module performance.

DISCUSSION AND FINDINGS

The findings of this study indicate that passive cooling techniques can significantly improve the thermal performance of photovoltaic (PV) modules by mitigating temperature-induced efficiency losses. Elevated operating temperatures remain one of the primary factors limiting PV performance, as each degree increase above standard test conditions results in a measurable decline in electrical conversion efficiency. Consequently, the implementation of passive cooling strategies offers a practical and energy-efficient approach to enhancing overall system performance.

Natural convection cooling emerged as one of the most economical and maintenance-free approaches for temperature regulation. The numerical results demonstrated that allowing unrestricted airflow around the rear surface of the PV module facilitates heat dissipation through buoyancy-driven air movement. This cooling mechanism reduces module temperature without requiring external power input, making it particularly suitable for remote and off-grid solar installations. However, the effectiveness of natural convection was found to depend strongly on environmental and installation conditions. Modules installed with adequate rear ventilation and favourable orientation exhibited greater heat removal rates than those with restricted airflow pathways. Similar observations have been reported in previous studies, where enhanced natural airflow contributed to lower module operating temperatures and improved electrical output (Skoplaki & Palyvos, 2009).

The incorporation of heat sinks produced more substantial temperature reductions compared to natural convection alone. Computational analyses revealed that the addition of fins increased the effective heat transfer surface area, thereby promoting greater convective heat exchange between the module and the surrounding environment. Optimised fin geometries enhanced airflow circulation and reduced thermal resistance, leading to more efficient heat removal from the PV surface. The CFD temperature contours showed a more uniform thermal distribution across the module when heat sinks were employed, reducing localised hot spots that can accelerate material degradation and negatively affect long-term performance. These findings are consistent with the work of Hasan et al. (2010), who reported that fin-based passive cooling systems significantly improved PV thermal management and energy output.

The study further demonstrated that passive cooling effectiveness is highly sensitive to external environmental parameters. Wind speed was identified as one of the most influential factors affecting heat dissipation, with higher airflow velocities enhancing convective heat transfer and reducing module temperatures. Ambient temperature also played a critical role, as higher surrounding temperatures reduced the temperature gradient necessary for effective cooling. Similarly, increased solar irradiance elevated heat generation within the PV module, requiring more efficient cooling mechanisms to maintain acceptable operating temperatures. Module tilt angle and orientation influenced airflow patterns and solar exposure, thereby affecting overall cooling performance. These observations highlight the importance of considering local climatic conditions when designing passive cooling systems for photovoltaic installations.

A major contribution of this research is the demonstration of the effectiveness of Computational Fluid Dynamics (CFD) as a design and optimisation tool for photovoltaic thermal management. CFD simulations provided detailed insights into airflow behaviour, temperature distributions, heat flux patterns, and cooling effectiveness under varying operating conditions. By enabling virtual testing of different cooling configurations, CFD reduces the need for extensive experimental prototyping, thereby lowering development costs and shortening design cycles. Furthermore, the ability to visualise thermal phenomena allows engineers to identify performance limitations and optimise cooling structures before physical implementation. As reported by Dubey et al. (2013), CFD-based thermal analysis has become an indispensable approach for improving the design efficiency and reliability of solar energy systems.

Overall, the findings confirm that passive cooling techniques, particularly heat sink-assisted configurations, can effectively reduce PV operating temperatures and improve energy conversion efficiency. While environmental conditions continue to influence performance outcomes, the integration of optimised passive cooling systems offers a practical and sustainable solution for enhancing photovoltaic system reliability, efficiency, and lifespan.

5. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The thermal performance of photovoltaic modules is a critical factor affecting their efficiency and operational lifespan. Passive cooling methods represent an attractive approach because they reduce module temperature without additional energy consumption.

This review shows that natural convection and heat sink-based cooling techniques can improve PV thermal regulation. CFD modelling provides an effective framework for analysing airflow patterns and temperature distribution, enabling optimisation of passive cooling designs.

5.2 Recommendations

Future research should focus on:

1. Development of advanced passive cooling geometries.
2. Use of high-conductivity and sustainable materials.
3. Integration of CFD with experimental validation.
4. Investigation of passive cooling under different climatic conditions.
5. Optimisation of hybrid passive systems.

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