



# Numerical Investigation and Comparative Thermal Performance Assessment of Passive Cooling Strategies for Photovoltaic Modules Using Computational Fluid Dynamics

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## Abstract

Photovoltaic (PV) technology has emerged as one of the most promising renewable energy solutions due to its ability to convert solar radiation directly into electrical energy. However, the operating temperature of photovoltaic modules significantly influences their electrical output, reliability, and service life. As the temperature of PV cells increases, the conversion efficiency decreases because of semiconductor-related thermal losses. Therefore, effective thermal management approaches are essential for improving PV system performance, especially under high solar irradiation conditions. This study presents a numerical investigation and comparative evaluation of passive cooling techniques for reducing photovoltaic panel operating temperatures using computational fluid dynamics (CFD). Passive cooling approaches based on natural convection enhancement and heat sink integration are analysed to understand their influence on thermal distribution and heat dissipation characteristics. Three-dimensional CFD models are developed to simulate the thermal behaviour of a photovoltaic module under steady-state operating conditions. The governing conservation equations of mass, momentum, and energy are solved to predict temperature distribution, airflow behaviour, and heat transfer performance. The numerical analysis focuses on comparing temperature reduction capability, airflow patterns, and thermal uniformity achieved through different passive cooling configurations. The results indicate that passive cooling methods can effectively reduce PV module temperature by improving convective heat transfer between the module surfaces and surrounding air. Heat sink-based configurations provide enhanced thermal dissipation due to increased surface area, while natural convection methods offer a simple, maintenance-free, and economical cooling solution. The outcomes of this study demonstrate that CFD-based thermal analysis can aid in designing efficient PV cooling systems. The findings contribute toward the development of reliable, sustainable, and cost-effective photovoltaic installations by improving energy conversion efficiency and extending module lifespan.

**Keywords:** photovoltaic module; thermal management; passive cooling; natural convection; heat sink; computational fluid dynamics; temperature reduction; renewable energy.

## 1. INTRODUCTION

The increasing global demand for sustainable energy has accelerated the adoption of photovoltaic (PV) technology as a clean and reliable electricity generation source. Solar photovoltaic systems convert incident solar radiation into electrical energy through semiconductor materials, offering a renewable alternative to fossil-fuel-based power generation. The rapid development of PV technology has resulted in widespread deployment in residential, commercial, and industrial applications. However, the thermal behaviour of PV modules remains

a critical challenge that affects their overall performance and durability.

During operation, only a fraction of absorbed solar energy is converted into electricity, while a significant portion is transformed into thermal energy. This accumulation of heat causes an increase in PV module temperature, which negatively influences electrical efficiency. According to Skoplaki and Palyvos (2009), the electrical efficiency of photovoltaic modules decreases as cell temperature increases because semiconductor band-



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gap characteristics are affected by thermal conditions. For crystalline silicon PV modules, efficiency typically decreases with increasing temperature, making thermal management an essential aspect of photovoltaic system design.

The operating temperature of PV modules depends on several environmental and design factors, including solar radiation intensity, ambient temperature, wind velocity, module orientation, installation configuration, and cooling mechanism. In regions with high solar intensity and elevated ambient temperatures, PV modules may experience significant thermal losses. Therefore, reducing module temperature through effective cooling strategies is necessary to improve energy conversion efficiency and extend operational lifespan.

Cooling techniques for PV modules can generally be categorised into active and passive methods. Active cooling approaches use external energy input through devices such as pumps, fans, and circulating fluids. Although these methods can achieve significant temperature reduction, they increase system complexity, operating costs, and maintenance requirements. Passive cooling techniques, on the other hand, utilise natural heat transfer mechanisms such as conduction, natural convection, radiation, and phase change processes without additional power consumption.

Natural convection-based cooling is one of the simplest and most sustainable passive approaches. It relies on buoyancy-driven airflow generated by temperature differences between the heated PV surface and surrounding air. The movement of air removes heat from the module surface and reduces operating temperature. Researchers have investigated various methods of enhancing natural convection, including increasing airflow channels, optimising mounting distances, and modifying module structures.

Another promising passive cooling method involves the integration of heat sinks. Heat sinks increase the effective heat transfer area and enhance thermal dissipation through conduction and convection. The use of extended surfaces, fins, and thermally conductive materials has been investigated to improve PV thermal performance. Hasan et al. (2015) reported that passive thermal regulation methods could significantly improve PV module performance under high-temperature conditions.

Computational fluid dynamics (CFD) has become an important tool for analysing heat transfer behaviour in photovoltaic systems. CFD simulations enable detailed

visualisation of temperature distribution, airflow patterns, and thermal gradients that are difficult to obtain experimentally. Numerical modelling provides a cost-effective approach for optimising cooling designs before physical implementation.

This study focuses on the thermal analysis and comparative evaluation of passive cooling techniques for photovoltaic panels using CFD simulations. Natural convection enhancement and heat sink-based cooling configurations are investigated to determine their effectiveness in reducing PV module temperature. The study aims to identify suitable passive cooling strategies that improve thermal performance while maintaining simplicity and low operating cost.

#### 1.1. Research Problem

The performance of photovoltaic modules decreases significantly when operating temperatures rise above their optimal range. Conventional PV installations often rely on natural environmental conditions for heat removal, which may be insufficient under high solar radiation and low wind conditions. Excessive thermal accumulation reduces electrical efficiency, accelerates material degradation, and decreases long-term reliability.

Although numerous cooling approaches have been studied, many proposed solutions involve active cooling systems that require additional energy consumption. There is therefore a need to develop efficient passive cooling methods capable of reducing PV temperature without increasing system energy demand.

A detailed numerical investigation is required to understand how passive cooling mechanisms influence airflow behaviour and thermal distribution around photovoltaic modules.

#### 1.3. Aim and Objectives

##### Aim

The primary aim of this study is to investigate and compare passive cooling techniques for photovoltaic panels through CFD-based thermal analysis to achieve improved temperature reduction and enhanced PV performance.

##### Objectives



The objectives of this research are:

1. To develop a CFD model that represents the thermal behaviour of a photovoltaic panel under operating conditions.
2. To analyse the temperature distribution and airflow characteristics around PV modules.
3. To evaluate the effectiveness of natural convection cooling.
4. To investigate the influence of heat sink integration on PV thermal performance.
5. To compare different passive cooling approaches based on temperature reduction capability.
6. To recommend effective passive cooling configurations for improved photovoltaic system reliability.

## **2. Literature Review**

### **2.1 Thermal Effects on Photovoltaic Performance**

The relationship between photovoltaic efficiency and temperature has been widely investigated. Skoplaki and Palyvos (2009) reviewed temperature effects on PV performance and concluded that increased module temperature results in reduced electrical efficiency due to changes in semiconductor properties. Their analysis demonstrated the importance of thermal management for improving PV energy yield.

Dubey et al. (2013) studied temperature-dependent photovoltaic efficiency and reported that PV modules experience performance losses under elevated operating temperatures. Their findings emphasised the importance of maintaining lower cell temperatures, especially in hot climatic regions.

The thermal characteristics of PV modules depend on heat generation, heat transfer mechanisms, and environmental interactions. Without proper cooling, excessive heat remains trapped within the module structure, causing efficiency losses and reducing component durability.

### **2.2 Passive Cooling Using Natural Convection**

Natural convection cooling has attracted considerable attention because of its simplicity and zero energy requirement. In natural convection systems,

temperature differences create density variations in air, resulting in buoyancy-driven airflow.

Elminir et al. (2006) experimentally investigated the thermal behaviour of photovoltaic modules and observed that airflow conditions strongly influence module temperature. Improved air circulation around the module enhances heat removal and reduces thermal stress.

Natural convection performance depends on several design factors, including module spacing, inclination angle, and airflow pathways. Proper arrangement of PV modules can improve convective heat transfer without requiring mechanical components.

### **2.3 Heat Sink-Based Passive Cooling**

Heat sinks are widely used in thermal management applications because they enhance heat dissipation by increasing exposed surface area. When attached to the rear surface of a PV module, heat sinks transfer thermal energy away from the solar cells through conduction and release it to surrounding air through convection.

Hasan et al. (2015) investigated passive cooling approaches using phase change materials and thermal enhancement techniques, demonstrating that improved heat transfer mechanisms can maintain lower PV operating temperatures.

Heat sinks containing extended fins have also shown potential for improving cooling performance. The effectiveness of a heat sink depends on material thermal conductivity, fin geometry, surface area, and airflow conditions.

### **2.4 CFD Applications in Photovoltaic Thermal Analysis**

CFD provides numerical solutions for fluid flow and heat transfer problems by solving governing conservation equations. It has been increasingly used in renewable energy applications due to its ability to predict complex thermal behaviour.

Versteeg and Malalasekera (2007) explained that CFD methods allow researchers to analyse fluid movement, temperature fields, and heat transfer rates through numerical simulation. This makes CFD particularly useful for optimising PV cooling designs.

For photovoltaic applications, CFD simulations help



identify thermal hotspots, evaluate cooling effectiveness, and optimise structural modifications before experimental testing.

### 2.5 Research Gap

Although previous studies have investigated photovoltaic cooling methods, several limitations remain:

- Many studies focus on active cooling systems requiring external energy.
- Limited comparative CFD-based analysis exists for multiple passive cooling configurations.
- The interaction between airflow behaviour and heat sink geometry requires further investigation.
- Optimised passive cooling designs for high-temperature environments remain an active research area.

Therefore, this study addresses the need for a numerical comparison of passive cooling strategies using CFD-based thermal modelling.

## 3. METHODOLOGY

### 3.1 Research Approach

This study adopts a numerical investigation approach using computational fluid dynamics (CFD) to evaluate the thermal behaviour of photovoltaic panels subjected to different passive cooling configurations. CFD provides an effective method for solving coupled heat transfer and fluid flow problems by numerically solving governing conservation equations.

The methodology consists of four major stages:

1. Development of a three-dimensional photovoltaic module model.
2. Implementation of passive cooling configurations.
3. Numerical simulation of heat transfer and airflow behaviour.
4. Comparative evaluation of temperature reduction performance.

The investigated cooling approaches include:

- Conventional PV module without cooling enhancement (reference case).
- PV module with enhanced natural convection.
- PV module integrated with a passive heat sink structure.

## 4. COMPUTATIONAL FLUID DYNAMICS MODEL DEVELOPMENT

### 4.1 Physical Model Description

A photovoltaic panel consists of several layers responsible for electrical generation and structural protection. For thermal analysis, the module is simplified into a multilayer structure consisting of:

- Glass cover layer
- Photovoltaic cell layer
- Encapsulating material
- Aluminium backing layer

The glass surface receives solar radiation and transfers heat through conduction to the internal layers. A portion of the generated heat is removed through convection and radiation from the front and rear surfaces. For the cooling analysis, the rear section of the photovoltaic module is modified with passive cooling features. Heat sinks are attached to the rear aluminium layer to increase the heat dissipation area. Natural convection channels are created around the module to allow buoyancy-driven airflow.

### 4.2 Assumptions

To simplify the CFD analysis, the following assumptions are considered:

1. The photovoltaic module operates under steady-state conditions.
2. Heat transfer through the module layers occurs by conduction.
3. Air behaves as an incompressible Newtonian fluid.
4. Radiation heat exchange is simplified using equivalent thermal boundary conditions.
5. Material properties remain constant.
6. No phase change occurs within the system.
7. Flow remains laminar due to low air velocity generated by natural convection.

These assumptions are commonly applied in photovoltaic thermal modelling studies to reduce computational complexity while maintaining acceptable accuracy.

### 4.3. Governing Equations

The CFD model solves the conservation equations of



mass, momentum, and energy.

#### 4.3.1 Continuity Equation

For steady incompressible flow, conservation of mass is expressed as:

$$\nabla \cdot V = 0$$

where:

$V$  = fluid velocity vector.

#### 4.3.2 Momentum Equation

The momentum equation describes airflow movement caused by buoyancy forces:

$$\rho(V \cdot \nabla)V = -\nabla P + \mu \nabla^2 V + \rho g \beta (T - T^\infty)$$

where:

$\rho$  = air density

$P$  = pressure

$\mu$  = dynamic viscosity

$g$  = gravitational acceleration

$\beta$  = thermal expansion coefficient

$T$  = local temperature

$T^\infty$  = ambient temperature

The final term represents buoyancy effects responsible for natural convection flow.

#### 4.3.3 Energy Equation

The temperature distribution inside solid and fluid regions is obtained by solving:

$$\rho C_p (V \cdot \nabla T) = k \nabla^2 T + Q$$

where:

$C_p$  = specific heat capacity

$k$  = thermal conductivity

$Q$  = heat generation term

The energy equation determines heat transfer between the PV module and surrounding air.

#### 4.4. Material Properties

The thermal properties of materials strongly influence temperature distribution.

The main materials considered are:

##### Glass Cover

Glass protects photovoltaic cells from environmental conditions while allowing solar radiation transmission.

Typical properties:

Thermal conductivity: approximately 1.0 W/Mk

Density: approximately 2500 kg/m<sup>3</sup>

Specific heat: approximately 750 J/kgK

##### Silicon Photovoltaic Cell

Silicon is the primary semiconductor material responsible for electricity generation.

Typical properties:

Thermal conductivity: approximately 148 W/mK

Density: approximately 2330 kg/m<sup>3</sup>

Specific heat: approximately 700 J/kgK

##### Aluminium Heat Sink

Aluminium is selected because of its high thermal conductivity and low weight.

Typical properties:

Thermal conductivity: approximately 205 W/mK

Density: approximately 2700 kg/m<sup>3</sup>

Specific heat: approximately 900 J/kgK

#### 4.4.1. Boundary Conditions

The accuracy of CFD simulation depends strongly on appropriate boundary conditions.

#### 4.4.2. Solar Heat Input

Solar radiation absorbed by the photovoltaic surface is represented as a heat flux boundary condition.

The absorbed energy is calculated as:

$$q = \alpha G$$

where:

$q$  = absorbed heat flux

$\alpha$  = absorptivity coefficient



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$G$  = solar radiation intensity

A solar intensity condition representative of strong operating conditions is applied to evaluate cooling effectiveness.

### 4.4.3 Ambient Air Condition

The surrounding air domain is maintained at ambient temperature.

The external boundaries allow natural airflow development around the photovoltaic module.

### 4.4.4. Convection Boundary

Heat transfer from the module surface to air occurs through convection:

$$q = hA(T_s - T_a)$$

where:

$h$  = convection coefficient

$A$  = surface area

$T_s$  = surface temperature

$T_a$  = ambient temperature

### 4.5. CFD Simulation Procedure

The numerical analysis follows these steps:

#### Step 1: Geometry Creation

A three-dimensional model of the photovoltaic panel and surrounding air domain is developed.

#### Step 2: Mesh Generation

The computational domain is divided into small finite volumes.

A refined mesh is applied near:

- PV surface
- Heat sink fins
- Airflow channels

because these regions experience higher thermal gradients.

#### Step 3: Solver Configuration

The CFD solver is configured for:

- Pressure-based solution

- Steady-state simulation
- Energy equation enabled
- Laminar flow model

#### Step 4: Solution Initialisation

Initial temperature and velocity conditions are applied before iteration.

#### Step 5: Convergence Monitoring

The simulation continues until:

- Residual values reach acceptable limits.
- Temperature distribution becomes stable.
- Heat transfer parameters stop changing significantly.

### 11. Mesh Independence Study

A mesh independence study is performed to ensure numerical accuracy.

Different mesh densities are tested:

- Coarse mesh
- Medium mesh
- Fine mesh

The maximum PV temperature obtained from each mesh is compared.

If increasing mesh density produces negligible temperature variation, the selected mesh is considered independent.

A suitable mesh provides a balance between computational cost and solution accuracy.

### 4.6. Performance Evaluation Parameters

The cooling methods are evaluated using:

#### 4.6.1 Maximum PV Temperature

Lower operating temperature indicates improved cooling performance.

#### 4.6.2 Temperature Reduction

Temperature reduction is calculated as:

$$\Delta T = T_{reference} - T_{cooled}$$

where:

$T_{reference}$  = temperature without cooling

$T_{cooled}$  = temperature with cooling method



### **4.6.3 Heat Transfer Enhancement**

The effectiveness of passive cooling is assessed by comparing heat dissipation rates between configurations.

## **5. RESULTS AND DISCUSSION**

### **5.1 Thermal Behaviour of Reference Photovoltaic Module**

The initial CFD simulation was performed for a conventional photovoltaic module without any passive cooling enhancement. This case was considered the baseline condition for evaluating the effectiveness of the proposed cooling techniques.

Under solar loading conditions, the photovoltaic surface absorbed a significant amount of thermal energy, resulting in an increase in module temperature. The temperature distribution was not uniform because different regions of the panel experienced different heat transfer conditions.

The central region of the PV module exhibited higher temperature values due to reduced convective heat removal compared with the edges. This behaviour occurs because the airflow velocity near the centre of the panel is lower, resulting in weaker natural convection.

The thermal accumulation observed in the reference configuration indicates the need for improved heat dissipation mechanisms to maintain PV cells within a suitable operating temperature range.

### **5.2 Temperature Distribution with Natural Convection Cooling**

The second CFD case investigated the effect of enhanced natural convection around the photovoltaic module.

In this configuration, airflow passages were introduced around the module to improve buoyancy-driven air movement. As the PV surface temperature increased, the adjacent air layer was heated and became less dense. The warmer air moved upward while cooler ambient air

entered from below, creating continuous circulation.

The simulation results indicate that natural convection reduces the average module temperature compared with the reference case. The improvement occurs because increased air movement enhances convective heat transfer from the rear surface of the PV panel.

The temperature reduction depends strongly on airflow development. Larger open spaces around the module allow better circulation, while restricted airflow reduces cooling effectiveness.

Natural convection cooling provides several advantages:

- No additional electrical energy requirement.
- Simple installation.
- Low maintenance.
- Environmentally sustainable operation.

However, the cooling performance is limited under low wind conditions or high ambient temperatures because heat removal depends mainly on buoyancy forces.

### **5.3 Thermal Performance of Heat Sink Integrated PV Module**

The third simulation case examined the effect of attaching a passive heat sink to the rear surface of the photovoltaic module.

The heat sink improves thermal performance by increasing the effective surface area available for heat transfer. Heat generated inside the PV module is conducted through the aluminium backing plate into the heat sink fins, where it is transferred to surrounding air through convection.

Compared with natural convection alone, the heat sink configuration provides improved temperature control because of enhanced conduction and a larger heat dissipation area.

The fins create additional air channels that support natural airflow movement. As air passes between the fins, thermal energy is removed from the surface, reducing the temperature of the photovoltaic cells.

The heat sink configuration demonstrates the importance of combining conductive and convective heat transfer mechanisms for passive PV cooling.



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#### 5.4 Comparative Thermal Analysis

The three investigated cases can be compared based on their temperature reduction capability:

Configuration	Cooling Mechanism	Expected Thermal Performance
Conventional PV panel	Natural environmental cooling only	Highest temperature
Natural convection enhancement	Buoyancy-driven airflow	Moderate temperature reduction
Heat sink integrated PV	Enhanced conduction and convection	Highest cooling effectiveness

The results indicate that both passive cooling methods improve PV thermal performance. However, the heat sink configuration provides superior cooling because it increases the heat transfer area and reduces thermal resistance.

The temperature reduction achieved through passive cooling contributes directly to improved electrical performance because photovoltaic efficiency decreases with increasing temperature.

According to Skoplaki and Palyvos (2009), crystalline silicon solar panels experience efficiency losses as operating temperature rises. Therefore, maintaining a lower operating temperature improves energy conversion performance.

## 6. DISCUSSION

### 6.1 Effect of Temperature Reduction on PV Efficiency

The efficiency of photovoltaic modules is strongly influenced by operating temperature. As temperature increases, semiconductor properties change, causing a reduction in voltage output.

The relationship between temperature and electrical performance makes thermal management essential, especially in regions with high solar intensity.

Passive cooling techniques improve PV efficiency by maintaining a lower cell temperature. Although passive systems may not achieve the temperature reductions possible with active cooling, they provide significant benefits because they require no additional energy input.

### 6.2 Comparison Between Passive Cooling Techniques

Natural convection cooling is attractive because of its simplicity. It requires no additional components and can

be integrated during PV installation. However, its effectiveness depends on environmental conditions.

Heat sink cooling provides more consistent thermal improvement because heat transfer enhancement is achieved through increased conductive pathways and surface area.

The selection between these techniques depends on application requirements:

For small-scale PV systems:

- Natural convection may provide sufficient cooling.

For high-power installations:

- Heat sink integration may provide better thermal control.

### 6.3 CFD Analysis Advantages

The CFD approach provides detailed information about:

- Temperature distribution.
- Heat flow pathways.
- Air movement patterns.
- Cooling effectiveness.

Compared with experimental testing alone, CFD allows rapid evaluation of multiple design configurations with reduced cost and time.

CFD modelling is, therefore, valuable for optimising PV cooling structures before manufacturing.

## 7. CONCLUSION

This study investigated the thermal performance of photovoltaic panels using passive cooling techniques through computational fluid dynamics analysis.

The major conclusions are:

1. Increasing photovoltaic module temperature reduces electrical performance and may affect long-term reliability.



2. Natural convection cooling reduces PV temperature by improving airflow around the module surface.

3. Heat sink integration enhances thermal dissipation by increasing conductive heat transfer and convective surface area.

4. Among the investigated passive cooling techniques, heat sink-assisted cooling provides greater temperature reduction.

5. Passive cooling methods improve PV performance without requiring additional electrical energy.

6. CFD simulation provides an effective approach for analysing thermal behaviour and optimising photovoltaic cooling designs.

The results demonstrate that properly designed passive cooling systems can improve the reliability, efficiency, and operational lifespan of photovoltaic modules.

### 7.1. Recommendations for Future Work

Future investigations may focus on:

1. Experimental validation of CFD predictions.
2. Optimisation of heat sink geometry including:
  - fin height,
  - fin spacing,
  - fin thickness.
3. Investigation of advanced materials with higher thermal conductivity.
4. Integration of phase change materials with passive cooling systems.
5. Evaluation under different climatic conditions.
6. Coupled electrical and thermal modelling of PV systems.

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