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Improving the Performance of Photovoltaic Cells Using Pure and Combined Phase Change Materials: Numerical Study Using ANSYS Fluent

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Thanks

In the Name of Allah, the Most Gracious, the Most Merciful

All praise is due to Allah, who granted us success and support in completing this work, making our efforts and perseverance a source of pride in our academic journey.

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الإهداء

إلى من غرسا فيّ القيم، وصنعا لي طريق النجاح حرفًا بحرف...

إلى والديّ الكريمين، اللذين لم يبخلا عليّ بالدعاء، ولا بالبذل، ولا بالصبر، فلهما كل الوفاء والامتنان.

إلى إخوتي وأخواتي،

الذين كانوا دومًا العون والسند، في لحظات التعب قبل الفرح، وفي كل خطوة نحو هذا الإنجاز.

إلى أصدقائي الحقيقيين،

الذين شاركوني مشقة الطريق، وكانوا النور في عتمة التحديات.

وإلى كل من قدّم لي يد المساعدة، كلمة طيبة، أو دعمًا ولو كان بسيطًا،

أُهديكم هذا العمل، عربون شكر واعتراف بالجميل.

Abstract

Photovoltaic (PV) systems suffer from performance losses in hot climates due to excessive heat. This study investigates the use of phase change material (PCM) for passive thermal regulation of PV panels. A 2D transient numerical model was developed in ANSYS Fluent to simulate heat transfer and phase change under desert-like conditions. Results show that integrating RT28HC paraffin PCM reduced surface temperature by up to 6.1 °C and improved electrical efficiency by 2.75%. These findings confirm the effectiveness of PCM as a passive cooling solution to enhance PV performance in high-temperature environments.

Keywords

Photovoltaic panels; Passive cooling; Phase change material; ANSYS Fluent; Thermal performance; Efficiency enhancement

.

Résumé

Les systèmes photovoltaïques (PV) subissent des pertes de performance dans les climats chauds en raison de l'accumulation de chaleur. Cette étude analyse l'effet d'un matériau à changement de phase (PCM) pour la régulation thermique passive des panneaux PV. Un modèle numérique transitoire en 2D a été développé sous ANSYS Fluent pour simuler le transfert de chaleur et le changement de phase dans des conditions désertiques. Les résultats montrent que l'intégration du PCM à base de paraffine RT28HC a permis de réduire la température de surface jusqu'à 6,1 °C et d'améliorer le rendement électrique de 2,75%. Ces résultats confirment l’efficacité du PCM comme solution de refroidissement passif pour améliorer la performance des panneaux photovoltaïques en climat chaud.

Mots-clés :*Panneaux photovoltaïques , Refroidissement passif , Matériau à changement de phase , ANSYS Fluent , Performance thermique , Amélioration du rendement.*

ملخص:

تعاني الأنظمة الكهروضوئية من انخفاض في الأداء في المناطق الحارة بسبب تراكم الحرارة. تهدف هذه الدراسة إلى تحليل تأثير استخدام مادة متغيرة الطور (PCM)كحل تبريد سلبي للألواح الشمسية. تم تطوير نموذج عددي ثنائي الأبعاد غير مستقر باستخدام برنامج ANSYS Fluent لمحاكاة انتقال الحرارة وتغير الطور في ظروف مناخية صحراوية. أظهرت النتائج أن دمج مادة البارافين RT28HCأدى إلى خفض درجة حرارة السطح بما يصل إلى 6.1 °C وتحسين الكفاءة الكهربائية بنسبة 2.75%. تؤكد هذه النتائج فعالية المواد متغيرة الطور كحل تبريد سلبي لتحسين أداء الألواح الشمسية في المناطق الحارة.

الكلمات المفتاحية:ا لألواح الكهروضوئية، التبريد السلبي، المواد متغيرة الطور، ANSYS Fluent، الأداء الحراري، تحسين الكفاءة

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List of Abbreviations

Symbol / Abbreviation	Description
PV	Photovoltaic
PCM	Phase Change Material
RT28HC	Commercial paraffin wax used as PCM
CFD	Computational Fluid Dynamics
STC	Standard Test Conditions (usually 25°C, 1000 W/m^2, AM1.5)
H	PV module efficiency [%]
η_ref	Reference efficiency at STC [%]
Δη	Efficiency difference (gain or loss) [%]
T	Operating temperature [°C or K]
T_ref	Reference temperature (typically 25°C)
ΔT	Temperature difference T_ref − T [°C]
Γ	Temperature coefficient of efficiency [%/°C]
Q	Heat flux [W/m^2]
Q	Total heat input [W]
H	Convective heat transfer coefficient [W/m^2·K]
ρ (rho)	Density [kg/m^3]
Cp	Specific heat capacity [J/kg·K]
K	Thermal conductivity [W/m·K]
L	Latent heat of fusion [J/kg]
β (beta)	Liquid fraction of PCM [0–1]
H	Total enthalpy [J/kg]
Hsens	Sensible heat [J/kg]
Hlat	Latent heat [J/kg]
S	Source term in the energy equation
T	Time [s]
DO	Discrete Ordinates Radiation Model
S2S	Surface-to-Surface Radiation Model
PVT	Photovoltaic Thermal (hybrid) system
EVA	Ethylene-Vinyl Acetate (PV encapsulant layer)
HDPE	High-Density Polyethylene (PCM containment material)
VO_C	Open circuit voltage [V]
I_SC	Short circuit current [A]
DC	Direct Current
AC	Alternating Current
Reynolds Number (Re)	Dimensionless number representing flow regime
Ra (Rayleigh Number)	Dimensionless number for natural convection

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General Introduction

General Introduction

With the increasing global demand for energy and the urgent need to reduce environmental impact, photovoltaic (PV) technology has become a major solution for clean and sustainable electricity generation. PV systems are appreciated for their modular design, scalability, and ability to convert solar energy directly into electricity without pollution or noise.

Despite these benefits, PV modules face performance challenges in hot climates. In regions like southern Algeria, where solar radiation is intense and temperatures often exceed 40°C, PV panels can overheat. This rise in temperature lowers their electrical efficiency and accelerates material aging, which shortens the lifespan of the system.

To address this issue, different cooling methods have been studied. Among passive techniques, phase change materials (PCMs) are considered promising because they can absorb excess heat during melting and release it during solidification. This process helps keep PV panels at more stable temperatures, especially during peak sunlight hours, without using extra energy.

This research investigates the effect of integrating PCM into PV systems under the real climatic conditions of El-Oued, Algeria. A two-dimensional numerical model was developed using ANSYS Fluent to simulate heat transfer and phase change. The goal is to analyze how PCM helps reduce surface temperature and improve the overall energy performance of the PV module.

This thesis is organized into three main chapters that guide the reader through the research process, from the background and problem to the simulation results and analysis:

- **Chapter I: Overview of the Study**

Introduces the research context, explains the impact of high temperature on PV performance, and presents the study's objectives. It also highlights the motivation for using PCM and the role of numerical simulation in evaluating its effect.

- **Chapter II: Photovoltaic Technology and Cooling Techniques**

Reviews the basic operation of PV systems, discusses how temperature affects their efficiency, and presents different cooling techniques. Special focus is given to passive methods such as PCM. The chapter also summarizes previous experimental and numerical studies and introduces ANSYS Fluent as the simulation tool used in this work.

- **Chapter III: Numerical Simulation and Result Analysis**

Describes the simulation methodology and presents the results. It includes the system setup, materials, geometry, governing equations, and boundary conditions used in the model. The chapter then analyzes the effect of PCM integration on temperature distribution, melting behavior, and PV performance.

- **Conclusion**

Summarizes the main findings of the study and proposes recommendations for future research and real-world applications in hot climate areas.

Chapter I: Overview of the Study

I.1. Introduction:

The accelerating global shift towards sustainable energy solutions is a direct response to escalating environmental degradation, the finite nature of fossil fuel reserves, and the pressing demand for secure, long-term energy alternatives. Among the spectrum of renewable technologies, photovoltaic (PV) systems have emerged as a cornerstone in the global energy transition. These systems harness solar radiation and convert it directly into electrical energy via the photovoltaic effect, employing semiconductor materials most notably silicon.

However, while PV technology offers numerous advantages modularity, low operating cost, environmental friendliness it is not without limitations. One of the critical challenges impeding the optimal performance of PV modules is their sensitivity to temperature rise. In hot climate regions such as North Africa, and particularly in Algeria, PV panels often operate under elevated ambient temperatures that exceed 40°C during summer. This thermal environment, although rich in solar irradiance, paradoxically degrades the efficiency of PV modules, making it difficult to harness the full potential of solar energy in such regions [1].

This paradox of “abundant sunlight but declining efficiency” forms the crux of the thermal challenge in PV applications, especially in desert or semi-arid environments. It necessitates innovative thermal management strategies to stabilize panel temperature and maintain consistent electrical output.

I.2.Problem Statement:

The thermal sensitivity of photovoltaic cells is a well-documented phenomenon that directly influences their electrical performance. Crystalline silicon PV modules, which dominate the commercial market, typically suffer an efficiency loss ranging from 0.4% to 0.5% per degree Celsius above the reference temperature of 25°C, as defined in standard testing conditions (STC) [2].

This thermal degradation is not merely a technical inconvenience it represents a significant economic and operational obstacle. Elevated temperatures not only reduce the instantaneous power output of PV systems, but also accelerate the aging of panel materials, potentially shortening their operational lifespan [3]. Consequently, in hot climate zones, where solar investment is most logical, system owners may paradoxically face diminished returns.

Thus, the core problem addressed in this thesis revolves around the urgent need to mitigate the adverse effects of high temperature on PV modules, particularly through solutions that are cost-effective, passive, and easily integrable into existing systems. Tackling this challenge is essential to unlocking the full potential of solar energy in thermally harsh environments and improving the long-term reliability and profitability of solar technologies [4].

I.3. Study Aim:

This research seeks to provide a scientifically grounded and practically viable solution to the thermal limitations faced by PV systems in hot climates. Specifically, the aim is to investigate the integration of Phase Change Materials (PCMs) as a passive thermal management strategy. PCMs are capable of absorbing excess heat through latent heat storage during phase transition (from solid to liquid), and subsequently releasing it as they cool and resolidify [5]. This thermal buffering capability allows PCMs to stabilize the operating temperature of PV modules during peak solar irradiance periods.

By embedding a PCM layer such as RT28HC paraffin wax at the rear side of a PV panel, this study hypothesizes that the surface temperature of the module can be significantly reduced, thereby maintaining electrical efficiency within acceptable limits throughout the day.

The research methodology relies on the use of ANSYS Fluent, a computational fluid dynamics (CFD) software, to simulate the thermal behavior of a PV module with and without PCM. The numerical model is designed to reflect realistic climatic conditions, such as those of El-Oued, Algeria. Through detailed simulations and comparative analysis, this thesis aims to quantify the thermal performance improvements and energy efficiency gains resulting from PCM integration, ultimately validating its feasibility for real-world applications in hot regions [6].

I.4. Background

I.4.1 Importance of Photovoltaic Energy in Renewable Systems

Photovoltaic (PV) energy has emerged as one of the most promising renewable energy sources due to its environmental sustainability, wide availability, and rapidly declining costs [7]. It directly converts solar radiation into electricity without generating greenhouse gases, noise, or waste, making it an ideal solution for both urban and rural electrification. PV systems are modular, easily scalable, and can be deployed in a variety of configurations ranging from small rooftop systems to large solar farms. According to the International Renewable Energy Agency (IRENA), the global installed capacity of solar PV exceeded 940 GW in 2022, with projections pointing to continuous growth due to policy support and technological advancements [8].

I.4.2 Challenges in PV Performance under High Temperature

Despite their advantages, PV systems suffer from a major drawback—temperature sensitivity. The efficiency of crystalline silicon PV cells declines as their surface temperature increases, typically by 0.4%–0.5% per °C rise above 25°C, the standard testing temperature. In hot and arid regions such as the MENA region, especially in Algeria, ambient temperatures frequently exceed 40°C, pushing PV modules to operate under extreme thermal stress. This results in reduced energy output, accelerated material degradation, and ultimately a decrease in the economic viability of solar investments [9].

I.4.3 Need for Cooling Technologies

To overcome the problem of thermal degradation, researchers have explored various cooling strategies. These include both active methods—such as water spraying, liquid circulation, and forced air cooling and passive methods, including heat sinks and phase change materials (PCMs). While active systems can significantly reduce PV surface temperature, they are often impractical in remote or off-grid applications due to their power requirements and maintenance complexity. In contrast, passive cooling solutions are more cost-effective, reliable, and sustainable for long-term operation [10].

I.4.4 PCM as a Passive Cooling Technique

Phase Change Materials (PCMs) provide a viable passive thermal management solution. These materials absorb latent heat during melting and release it upon solidification, thus maintaining a nearly constant temperature. When integrated into the backside of PV modules, PCMs can delay the rise in temperature during periods of high irradiance, thereby improving energy yield. Paraffin-based PCMs, in particular, are widely used due to their chemical stability [11], affordability, and appropriate melting range for PV applications. Studies have shown that PCM integration can reduce module temperature by up to 6°C, resulting in a significant increase in power output [12].

I.4.5 Role of Numerical Simulation in Thermal Analysis

Numerical modeling has become a cornerstone in evaluating and optimizing thermal management strategies for PV systems. Through simulation, researchers can study heat transfer, fluid dynamics, and phase change behaviors under various environmental conditions and design configurations without the need for costly prototypes. Computational Fluid

Dynamics (CFD) tools enable detailed time-dependent simulations that provide insights into temperature distribution and material performance. Such simulations are particularly beneficial in early-stage design and parametric analysis of PV-PCM systems [13].

I.4.6 Brief on ANSYS Fluent and Modeling Approach

ANSYS Fluent is a widely adopted CFD platform that provides robust tools for simulating heat and mass transfer, radiation, and phase change phenomena. It employs finite volume methods to solve governing equations for conservation of mass, momentum, and energy. In this study, a two-dimensional transient model was developed in ANSYS Fluent to analyze the thermal behavior of a PV module with and without PCM under realistic boundary conditions. The enthalpy-porosity technique was used to model the melting and solidification of the PCM, providing accurate insights into its effect on PV surface temperature and overall performance [14].

I.5 Objectives

The main objective of this study is to evaluate the feasibility and effectiveness of integrating phase change materials (PCMs) as a passive cooling strategy to enhance the thermal and electrical performance of photovoltaic (PV) panels operating under high-temperature conditions. This approach aims to minimize temperature-induced efficiency losses through reliable and physically grounded numerical simulations using Computational Fluid Dynamics (CFD) tools.

To meet this objective, the research focuses on the following specific goals:

- Design a simplified two-dimensional (2D) numerical model of a PV module, incorporating all major layers, including the glass cover, EVA sheets, silicon cells, backsheet, and a rear PCM layer.
- Select a suitable PCM (RT28HC paraffin wax) based on its thermal properties, melting range, and compatibility with PV operating temperatures.
- Conduct transient simulations using ANSYS Fluent to model heat conduction and phase change processes under realistic solar irradiation.
- Analyze and compare the thermal response of the PV module with and without PCM integration, with emphasis on surface temperature evolution, liquid fraction behavior, and the corresponding impact on energy efficiency.

Chapter II: Photovoltaic Technology and Cooling Techniques

II.1 Introduction

Photovoltaic (PV) systems offer a reliable and sustainable method for generating electricity by converting sunlight directly into energy. However, their performance is strongly affected by environmental factors especially high temperatures. Prolonged exposure to sunlight causes PV modules to heat up, which leads to lower efficiency and faster wear of their components.

To address this challenge, it is essential to understand the fundamental structure and operation of PV cells, as well as the thermal factors that affect their output. Implementing appropriate cooling strategies plays a vital role in maintaining optimal performance. These strategies range from active methods, such as forced air or liquid cooling, to passive solutions like heat sinks and phase change materials (PCMs), which regulate temperature without external energy input.

This chapter offers a detailed overview of PV system components and working principles, analyzes the effect of temperature on PV performance, and reviews a variety of cooling approaches. Particular focus is given to passive thermal management techniques especially the integration of PCMs as a means to enhance the reliability and efficiency of PV systems in high temperature environments.

II.2. Photovoltaic Systems Overview

Photovoltaic (PV) systems are energy conversion systems that utilize semiconductor-based devices, known as solar cells, to convert sunlight directly into electrical energy through the photovoltaic effect. This section provides an overview of the fundamental working mechanism of PV cells and a brief classification of the main PV cell types.

II.2.1. solar panel

A solar panel is a flat technological device, typically measuring around 1 m², designed to capture solar radiation and convert it into usable energy. Depending on the type, it can either transform sunlight into heat for domestic water heating (via thermal collectors) or into electricity using photovoltaic (PV) cells made of semiconductor materials. Some panels even combine both thermal and electrical technologies. These systems are commonly installed on rooftops or mounted on the ground for optimal solar exposure [15].

II.2.1.1 Composition of a Photovoltaic Panel

A standard PV panel consists of several integrated components:

- **Photovoltaic cells** encapsulated in **EVA** (ethylene-vinyl acetate),
- A **transparent glass** cover facing the sun,
- A **Tedlar** polymer backsheet,
- An **aluminum frame** for structural support,
- And internal electrical wiring for system connection.

These layers work collectively to protect the cells, transmit light, and ensure mechanical durability and electrical output [16]

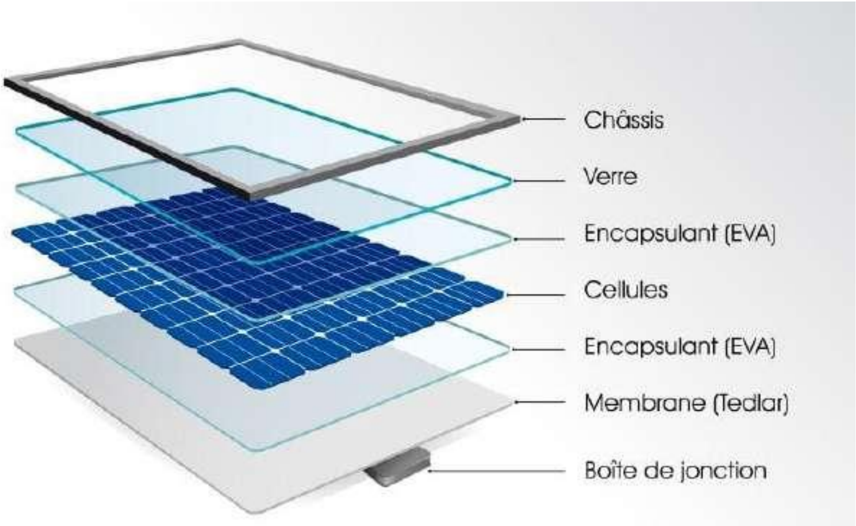


Figure II.1: Composition of a PV Pane l16]]

II.2.2 The Photovoltaic Cell

A photovoltaic cell is a semiconductor-based electronic device that generates electrical voltage when exposed to solar radiation—a process known as the **photovoltaic effect**. These cells are typically composed of a **p-n junction** using silicon. When light photons are absorbed, **electron-hole pairs** are created, allowing the flow of electric current in a direct current (DC) form. The voltage output from a typical cell ranges from **0.3 to 0.7 volts**, depending on material purity, temperature, and aging effects [17].

II.2.3 Operating Principle of a Photovoltaic Cell

The photovoltaic effect used in solar cells makes it possible to directly convert the light energy of solar rays into electricity through the production and transport in a semiconductor material of positive and negative electrical charges under the effect of light. This material has two parts, one with an excess of electrons and the other with a deficit of electrons, called respectively n-doped and p-doped. When the first is brought into contact with the second, the excess electrons in the n material diffuse into the p material. The initially n-doped area becomes positively charged, and the initially p-doped area negatively charged. An electric field is therefore created between them which tends to repel the electrons in the n zone and the holes towards the p zone. A junction (called p-n) has been formed. By adding metal contacts on the n and p zones, a diode is obtained.

The electrons only flow from the p zone to the n zone and vice versa for the holes. This is due to the use of semiconductors. When the junction is illuminated, photons with energy equal to or greater than the width of the forbidden band communicate their energy to the atoms, each one passing an electron from the valence band into the conduction band and also leaving a hole capable of moving, thus generating an electron-hole pair. If a charge is placed at the terminals of the cell, the electrons of the n zone join the holes of the p zone via the external connection, giving rise to a potential difference: the electric current flows [18].

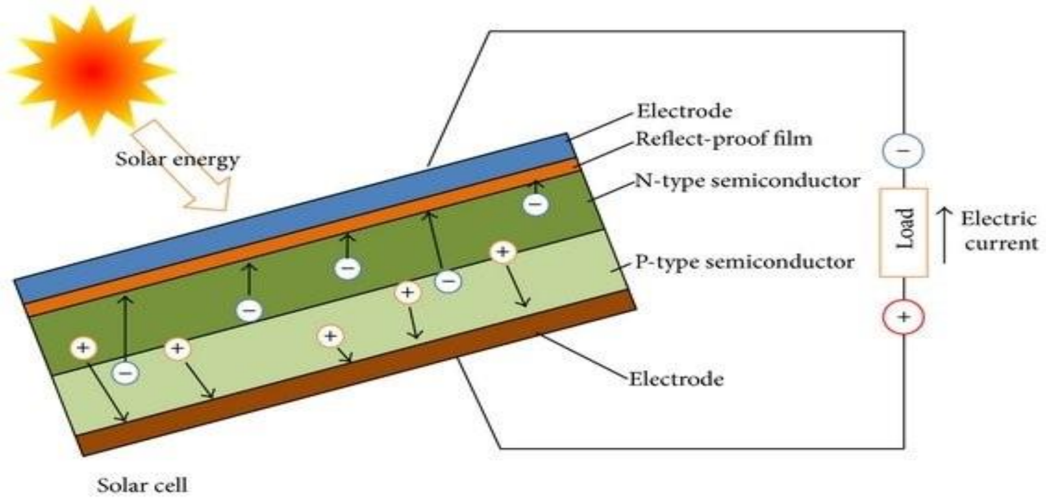


Figure II.2: Operating Principle of a PV Cell [18].

II.2.4 Photovoltaic Cell Technologies

Monocrystalline Silicon:

Monocrystalline PV cells are made from a single, continuous crystal structure. They offer the highest efficiency, typically ranging from 18% to 21%, and up to 24% for advanced technologies like bifacial PERC cells. They are known for their longevity, space efficiency, and performance under low-light conditions .

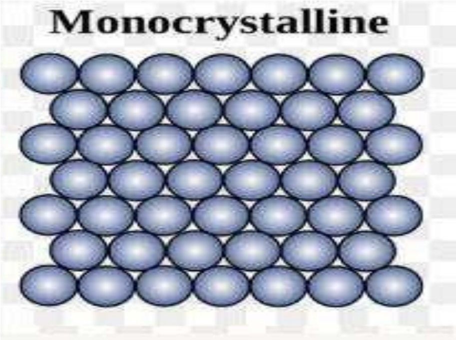


Figure II.3: Monocrystalline PV Panel [16].

Amorphous Silicon:

Amorphous PV cells are created by depositing thin silicon layers onto various substrates like **glass**, **steel**, or **plastic**. Although their efficiency is relatively low (~10%), they perform well in diffused light and are more flexible and cost-effective. These panels are ideal for small-scale or portable applications [16].

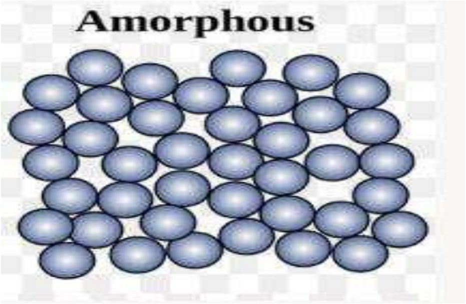


Figure II.4 Amorphous PV [16].

Hybrid (Perovskite-Based) Technologies

Hybrid PV panels use **perovskite compounds**, often composed of **calcium titanate** mixed with **lead or tin halides**, as the light-absorbing layer. These next-generation cells can achieve efficiencies of **up to 28%** and are the focus of intensive research due to their low-cost fabrication and high potential. Large-scale deployment is still under development [16].

II. 2.5 The Photovoltaic System

Although fundamental in the chain that represents a system, the photovoltaic module alone cannot do much: to meet a defined need, it must in fact be closely associated with a complete system corresponding to a very specific application.

A photovoltaic system will therefore consist of the generator described above generally associated with one or more of the following elements: - an orientation or tracking system (rarely encountered in our latitudes) - electronic management (storage, current shaping, energy transfer), - storage to compensate for the random nature of the solar source, - a DC/AC converter - a charge in low voltage direct current or standard alternating current The most commonly used PV systems are of three types:

-PV systems with electrical storage (electrochemical accumulator battery).

These supply user devices: 0either directly in direct current or in alternating current via a direct current - alternating current converter (inverter).

-Direct-coupled systems without a battery (also called “running with the sun”) the user devices are connected either directly to the solar generator or, possibly, via a direct current - direct current converter (impedance adapter).

For systems without batteries, it is possible to use a form of storage that is not electrochemical in nature.

-Systems connected to the local network via an inverter controlled at the network frequency, the network serving as storage. The study of photovoltaic systems comes down to the study of load adaptation. We will seek to optimize the system to have the best system adaptation efficiency (ratio of the electrical energy supplied to use to the electrical energy that could have been provided by the generator always operating at its maximum power point). [17].

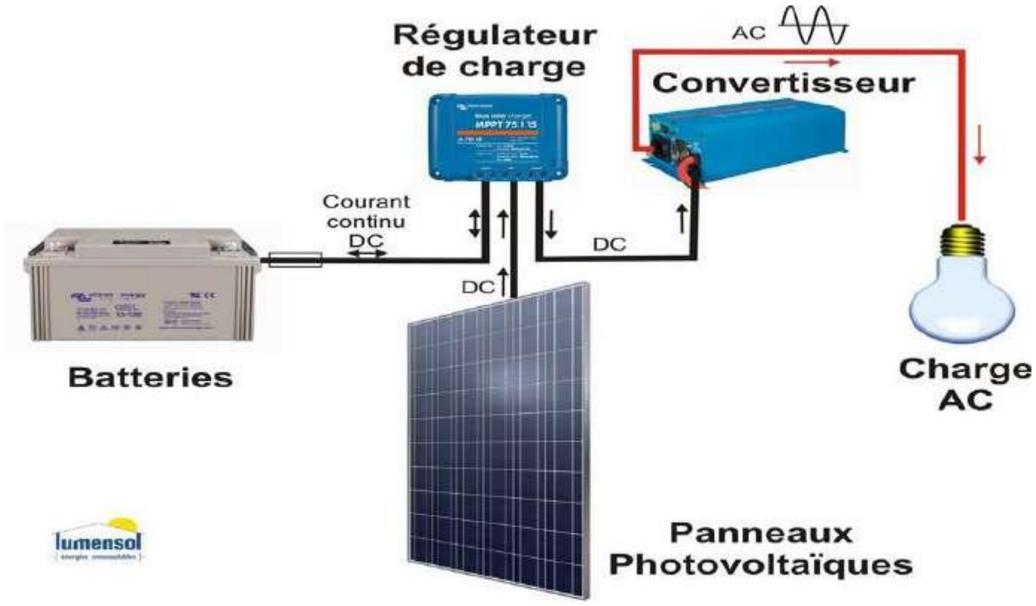


Figure II.5 Photovoltaic system (Solar Technology) [17].

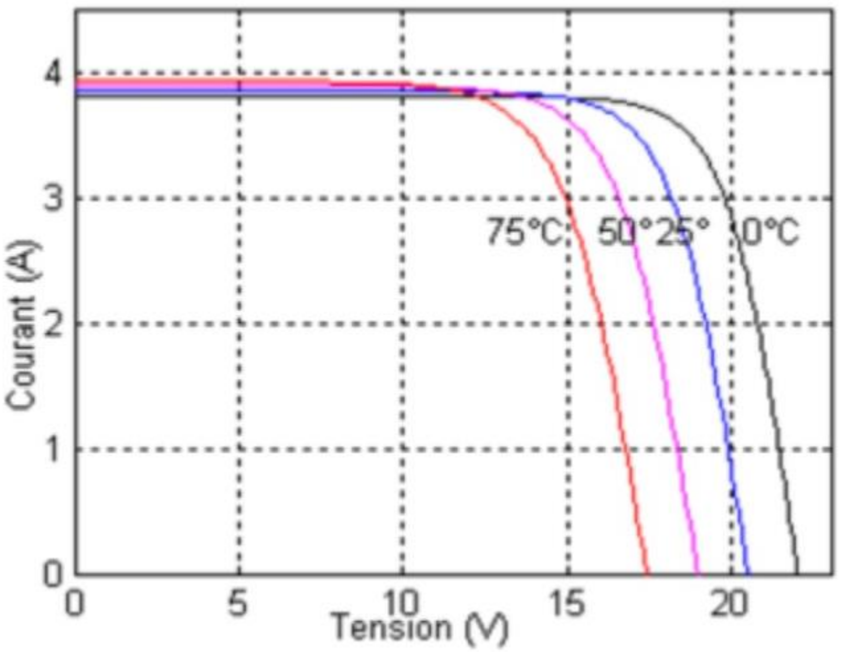
Table I.1 Advantages and disadvantages of different types of PV [17].

Type	Polycrystalline silicon	Polycrystalline silicon	Amorphe
Lifetime	**35 years**	**35 years**	**<10 years**
Advantages	**good performance in direct sunlight**	**Good performance in direct sunlight (less than monocrystalline but more than amorphous.**	**Flexibility, lower price than crystalline lenses, good performance in diffuse**
Inconvenient	**Poor performance in diffuse sunlight (cloudy weather, etc.) high price**	**Poor performance in diffuse sunlight (cloudy weather, etc.) high price**	**Poor performance in full sun**

II.3. Effect of temperature on efficiency

Temperature has a significant influence on the behavior of photovoltaic (PV) cells, and consequently, on their overall efficiency. This influence is primarily observed as a decrease in the output voltage, accompanied by a slight increase in current [19]. As temperature rises, the energy gap (band gap) of the semiconductor material narrows, leading to an increase in charge carrier concentration, which slightly enhances current. However, this is not sufficient to compensate for the voltage drop, resulting in an overall reduction in power output.

According to experimental data, each 1°C rise in cell temperature can cause a loss of approximately 0.5% in efficiency, relative to the cell's maximum rated efficiency [19]. This emphasizes the critical importance of implementing effective ventilation systems behind PV panels to facilitate heat dissipation.



Figures II.6 Influence de la température sur la caractéristique [20].

As illustrated in Figure II.2 the impact of temperature on PV performance is clearly visible: with increasing temperature, the open-circuit voltage (Voc) drops significantly, while the short-circuit current (Isc) shows only a minor increase. This temperature dependence should be carefully considered during the design and installation of PV systems, especially in regions with hot climates [19].

II.4. Cooling Techniques for PV Panels

Photovoltaic (PV) panels are extensively used for solar energy conversion; however, their efficiency is significantly impacted by elevated operating temperatures. Research indicates that for every 1°C rise above 25°C, the power output of silicon-based PV cells decreases by approximately 0.3% to 0.5% . This performance decline is attributed to the semiconductor properties of silicon, where higher temperatures lead to a reduction in bandgap energy and an increase in electron-hole recombination rates. To counteract these thermal losses, various cooling techniques have been developed, which can be broadly categorized into passive, active, and hybrid cooling methods.

Passive cooling techniques dissipate heat naturally through convection, radiation, and phase change materials (PCM), while active cooling methods utilize mechanical components such as fans and water circulation to enhance heat dissipation. Hybrid cooling systems combine both approaches to optimize thermal regulation [21].

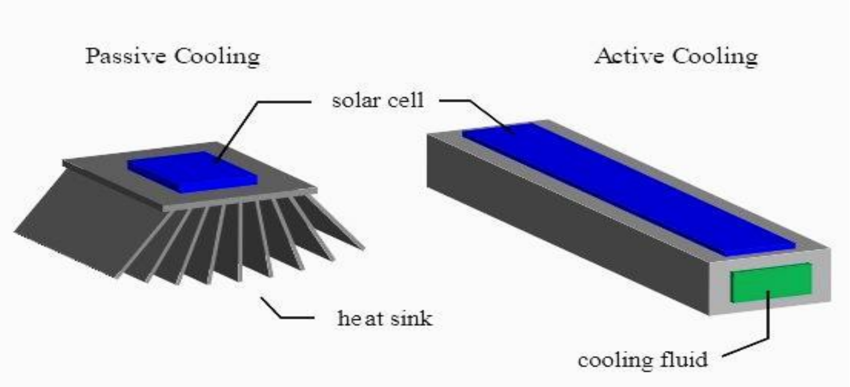


Figure II.7: Passive and active cooling techniques [21].

II.4.1 Passive Cooling Techniques

Passive cooling methods are widely utilized due to their simplicity, cost-effectiveness, and lack of external energy consumption. These methods rely on natural heat dissipation mechanisms such as conduction, convection, and radiation to regulate the temperature of photovoltaic (PV) panels. The two most commonly employed passive cooling techniques are heat sinks and phase change materials (PCMs). Heat sinks enhance heat dissipation by increasing surface area, while PCMs absorb and store excess heat through phase transitions, ensuring stable operating temperatures. These techniques are particularly beneficial in energy-efficient applications requiring minimal maintenance, such as solar panels in remote locations or off-grid systems. However, their cooling effectiveness may be limited under extreme environmental conditions, necessitating hybrid approaches for enhanced performance [21].

II.4.1.1 Heat Sink Cooling

Heat sinks function by enhancing the surface area available for thermal dissipation, facilitating heat transfer from the PV panel to the surrounding air. As heat is conducted through the sink, natural or forced convection aids in removing excess heat, thereby lowering the panel's operating temperature. The efficiency of heat sinks depends on material composition, structural design, and airflow conditions. Typically, aluminum and copper are used due to their high thermal conductivity. Studies indicate that heat sinks can reduce PV panel temperatures by up to 10°C, leading to an efficiency improvement of approximately 5% [22].

To further enhance heat dissipation, advanced heat sink designs such as finned or ribbed structures have been developed. These modifications optimize airflow dynamics, increasing convective heat transfer. Additionally, high-emissivity coatings are being explored to maximize radiative cooling effects. In extreme conditions, hybrid heat sinks incorporating small-scale fans or thermoelectric cooling modules have been proposed to improve thermal regulation while maintaining energy efficiency.

Despite their advantages, heat sinks exhibit performance limitations in low-wind environments, where natural convection is insufficient. Moreover, the additional structural weight may pose design constraints for lightweight PV modules. Therefore, integrating heat sinks with other cooling strategies, such as phase change materials (PCMs) or forced air cooling, can further enhance their efficiency [22].

II.4.2 Active Cooling Techniques

Active cooling methods rely on external energy sources to operate, providing superior temperature regulation compared to passive techniques. These methods are particularly effective in hot climates and high solar-intensity regions, where passive cooling alone may be insufficient.

The two primary types of active cooling are fluid-based cooling and air-based cooling. Fluid-based cooling utilizes liquids such as water, nanofluids, or organic coolants to absorb and transfer heat efficiently. In contrast, air-based cooling employs fans, blowers, or evaporative cooling techniques to enhance airflow and dissipate heat.

For enhanced performance, hybrid cooling systems integrate both fluid and air-based methods, offering improved thermal management. These systems are widely applied in electronics cooling, industrial processes, and solar panel temperature regulation. However, despite their effectiveness, active cooling techniques present challenges such as higher energy consumption, increased system complexity, and maintenance issues, including corrosion in fluid-based systems and dust accumulation in air-based cooling systems [23].

II.4.2.1 Fluid-Based Cooling

This method involves circulating a cooling fluid (such as water or nanofluids) through pipes or channels attached to the PV panels. Water-based cooling is highly effective, with studies reporting temperature reductions of up to 20°C and efficiency improvements of 15-20%. Nanofluids, which are engineered by suspending nanoparticles (e.g., aluminum oxide or silicon dioxide) in a base fluid, have shown even greater potential due to their enhanced thermal conductivity. However, fluid-based systems require pumps and additional infrastructure, increasing their complexity and cost [24]..

Various fluid-based cooling methods have been developed to enhance the thermal management of solar panels, thereby reducing their temperature and improving efficiency. Among these techniques, spray cooling involves directly spraying water onto the panel's surface, facilitating evaporative heat dissipation. This method is widely recognized for its simplicity and effectiveness in lowering surface temperature. Another approach, tube cooling, employs water circulation through thermally conductive pipes—typically made of copper, aluminum, or heat-resistant plastic—attached to the panel’s backside to optimize heat transfer. Furthermore, nanofluid cooling enhances conventional water cooling by incorporating nanoparticles such as aluminum oxide (Al_2O_3) or copper oxide (CuO), significantly increasing thermal conductivity and heat dissipation efficiency. Additionally, immersion cooling involves partially submerging solar cells in dielectric cooling fluids, such as mineral oils or fluorinated liquids, which efficiently absorb heat while ensuring electrical insulation. Collectively, these cooling strategies contribute to effective temperature regulation, leading to improved photovoltaic panel performance and extended operational lifespan, making them essential for optimizing solar energy systems [25].

Fluid-based cooling provides highly efficient heat dissipation and can be integrated with PV/T systems, significantly increasing energy output. However, it requires a continuous water supply, and there is a risk of pipe corrosion and scaling. Additionally, the pumping system adds operational costs [26].

II.4.3 Air-Based Cooling

Air cooling systems use fans or blowers to force air over the surface or beneath the PV panels. While less effective than fluid-based cooling, air-based systems are simpler and more cost-effective. They can reduce panel temperatures by 10–15°C, resulting in efficiency gains of 8–12%.

Natural Ventilation utilizes wind-driven airflow to carry away excess heat. In Ducted Air Cooling, air is forced through channels behind the PV panel for enhanced heat extraction. A more advanced approach, Hybrid Air-Water Cooling, combines air movement with water misting to improve cooling efficiency.

Air-based cooling does not require water, making it ideal for arid climates, and has lower maintenance needs than liquid cooling. However, it is less effective than water cooling and depends on wind conditions. Additionally, it requires sufficient space for air circulation [27].

II.4.4 Hybrid Cooling Systems

Hybrid cooling systems integrate multiple cooling techniques to optimize thermal management and enhance the efficiency of photovoltaic (PV) panels. Given that PV modules experience efficiency degradation at elevated temperatures, implementing hybrid cooling strategies can mitigate thermal losses and improve energy output. Various hybrid cooling systems combine passive and active cooling techniques, particularly focusing on Phase Change Materials (PCMs) in conjunction with other cooling methods [28].

II.4.4.1 PCM and Water Cooling

Phase Change Materials (PCMs) absorb excess heat from PV panels during peak solar radiation periods by undergoing a phase transition. However, their ability to release stored heat efficiently is limited, leading to thermal saturation. By integrating PCMs with water cooling, the stored heat is effectively dissipated, ensuring better thermal regulation. Studies indicate that such a system can reduce PV surface temperatures by 10–25°C, leading to an efficiency improvement of 8–15% [29].

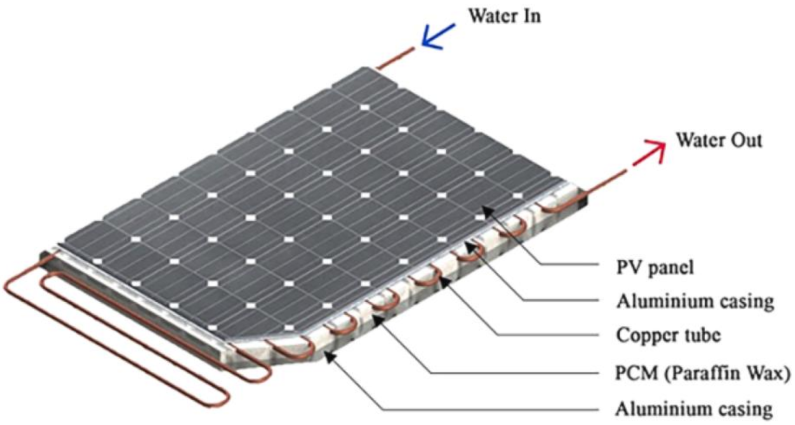


Figure II.8 Diagram of a water-based hybrid PVT/PCM system [29].

II.4.4.2 Heat Sinks with Forced Air Cooling

Heat sinks made of highly conductive materials, such as aluminum or copper, enhance heat dissipation by increasing the surface area available for heat transfer. When combined with forced air cooling using fans, the system accelerates convective heat removal, preventing excessive heat accumulation in PV panels. This hybrid approach effectively maintains lower operating temperatures without excessive energy consumption [30].

II.4.4.3 Nano fluids in Water Circulation

Nano fluids containing nanoparticles with high thermal conductivity—offer superior heat transfer characteristics when used in water-based cooling systems. By circulating nano fluids within a cooling loop beneath PV panels, heat extraction efficiency significantly improves. Studies have demonstrated that using Nano fluids can enhance thermal conductivity by up to 30%, thereby reducing module temperatures and increasing overall energy yield [30].

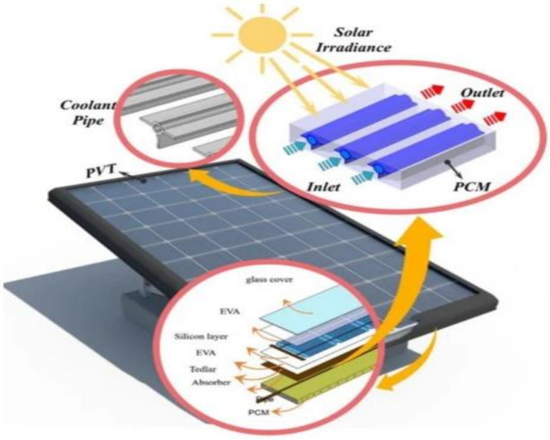


Figure II.9: Schematic of the system with PCM flow pipe and nano-fluid [30].

II.5. Phase Change Materials (PCM)

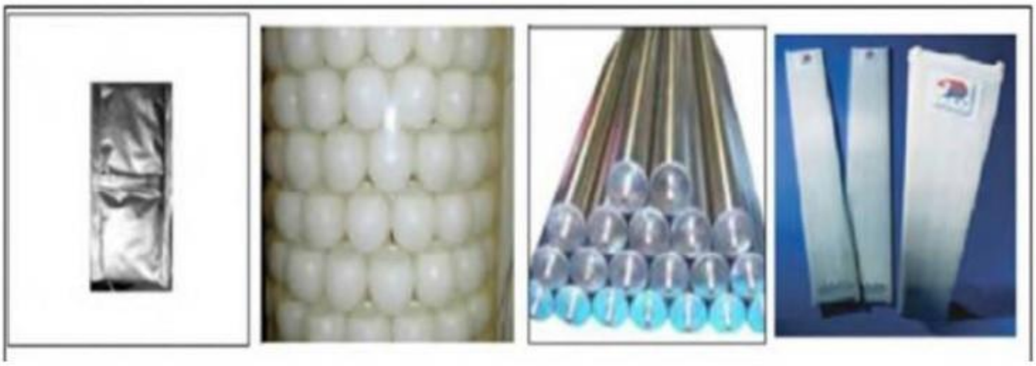
II. 5.1 Definition

Phase Change Materials (PCMs) are latent heat storage materials that absorb and release thermal energy during phase transitions (typically solid to liquid). When incorporated into PV systems, PCMs absorb excess heat during peak solar radiation hours, preventing temperature spikes, and later release the stored energy when ambient temperatures drop. Research findings indicate that PCM-based cooling can lower PV module temperatures by 8–12°C, resulting in an efficiency gain of 6–10%, depending on environmental conditions and the PCM's melting point [31].

Various PCM types are utilized based on their thermal properties and stability:

- **Paraffin waxes and salt hydrates**: Cost-effective with high latent heat capacity but may suffer from phase separation and low thermal conductivity.
- **Fatty acids and organic-inorganic composites**: Environmentally stable and durable, but require advanced encapsulation techniques to prevent leakage.
- **Metallic or nanoparticle-enhanced PCMs**: Improve thermal conductivity, ensuring faster heat absorption and dissipation.

While PCMs offer significant thermal regulation benefits, their low intrinsic thermal conductivity limits heat dissipation efficiency unless combined with conductive additives such as metal foams or nanoparticles. Additionally, long-term stability issues, including phase separation and material degradation, must be addressed to ensure consistent performance [31].



Figures II.10:Some phase change materials: pouches, spheres, tubes, plates [31].

II.5.2. Classification of phase change materials :

Un grand nombre de substances chimiques peuvent être identifiées comme matériaux à changement de phase (MCP) du point de vue de leurs températures de fusion et de leurs chaleurs latentes de fusion. Cependant, en dehors du critère essentiel du point de fusion situé dans la plage de température de fonctionnement souhaitée, la majorité de ces substances ne répondent pas aux autres exigences nécessaires pour être des supports appropriés au stockage de chaleur. Ces substances diffèrent par leurs propriétés thermo-physiques telles que la température de fusion, la chaleur latente de fusion, la conductivité thermique et la masse volumique[32].

On peut classer les MCP couramment utilisés en trois grandes catégories :

- Les composés organiques : paraffines, corps non-paraffinés et polyalcools,
- Les composés inorganiques : hydrates salins, sels, métaux et alliages,
- Les eutectiques composés de substances inorganiques et/ou organiques.

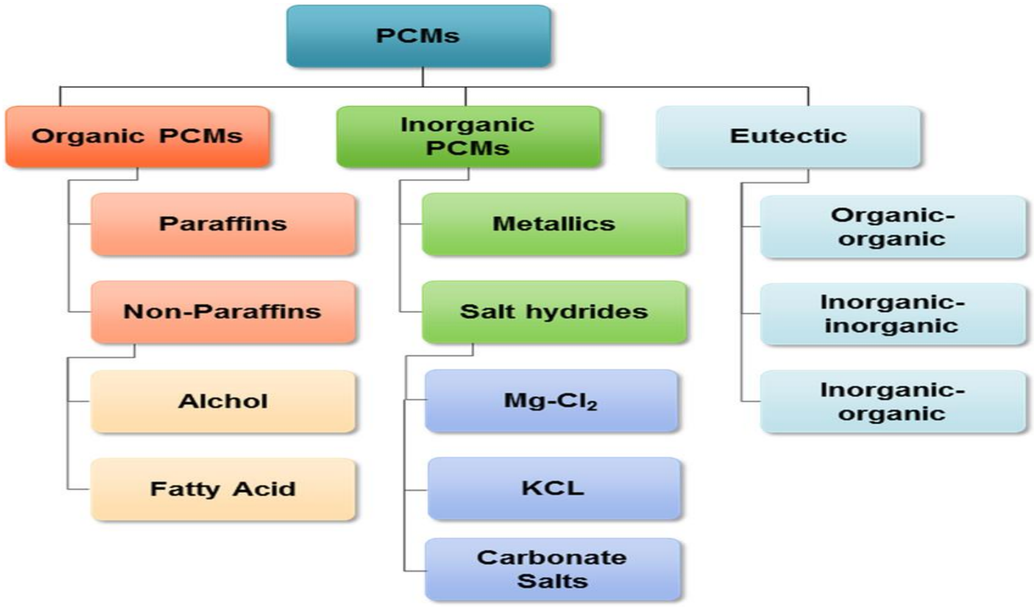


Figure II.11: Classification of phase change materials [32].

II.5.2.1 Organic PCMs:

Organic materials or substances have a temperature or temperature range between 0°C and 150°C. The most commonly used are mainly based on paraffin, fatty acids, and sugar alcohols. However, they present certain disadvantages compared to the advantages of inorganic PCMs: they have lower thermal conductivity in both solid and liquid states, lower latent heat of fusion, and they are flammable [33].

On the other hand, they offer major advantages: they are available over a wide range of temperatures, compatible with conventional construction materials, chemically stable, and do not require the use of nucleating agents. Additionally, they are mostly non-reactive and recyclable. [33].

II.5.2.2 Inorganic PCMs:

Inorganic materials or substances have a melting temperature or range between -100°C and +1000°C. The most commonly used inorganic PCMs are: water (melting point 0°C), salt aqueous solutions (melting point below 0°C), hydrated salts (melting point between 5°C and

130°C), salt mixtures, and metal alloys (melting point above 150°C).They offer several advantages: High latent heat of fusion, High thermal conductivity, Sharp melting point (i.e., narrow melting range),Non-flammable nature, Affordable investment cost, Generally widely available in the market[34].

However, the major issues encountered when using inorganic PCMs are related to phase segregation, corrosion, and supercoiling, which often require the addition of nucleating agents to ensure reliability and consistent performance [35].

II.5.2.3 Eutectic PCMs:

Eutectic PCMs are substances composed of a combination of two or more pure PCMs. Generally, they are mixtures of organic and inorganic PCMs (organic-organic, organic-inorganic, or inorganic-inorganic).They present two main advantages: They have a sharp melting point, similar to pure substances. They exhibit slightly higher volumetric latent heat compared to pure organic compounds. However, two main disadvantages are associated with eutectic PCMs: Limited data are available regarding their thermal properties. They are rarely used in industrial-scale systems [36].

II.5.4 Properties of PCM Materials

Composite PCMs exhibit a unique combination of properties that make them ideal for thermal management applications. These properties can be categorized into **thermal**, **mechanical**, **chemical**, and **physical** characteristics, each of which plays a critical role in determining the performance and suitability of these materials for specific applications [37].

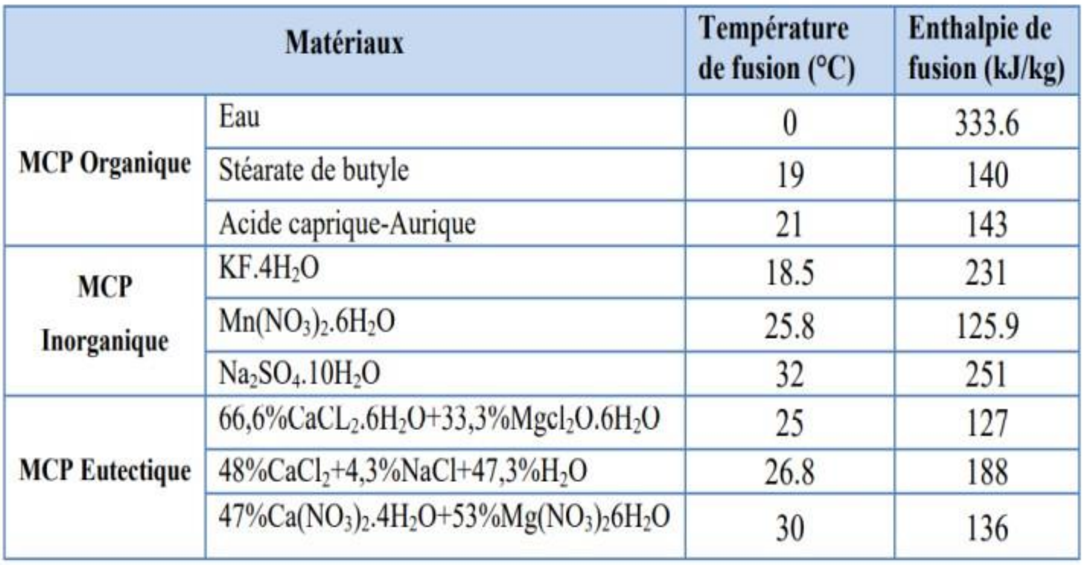
II.5.4.1 Thermal Properties

The thermal performance of composite PCMs is central to their function as energy storage materials. The following features define their ability to absorb, store, and release heat effectively:

- **High latent heat capacity:** PCMs can absorb or release large amounts of heat during melting/freezing.
- **Adjustable melting point:** PCMs can be selected or engineered to change phase at specific temperatures (e.g., 25°C, 55°C).

- **Low thermal conductivity (pure PCMs):** Often improved using additives like graphite or metal particles.
- **Good thermal stability:** Some PCMs can endure repeated melting/solidifying without performance loss.

Table II.1 presents the thermal properties of some PCMs [37].



Matériaux		**Température de fusion (°C)**	**Enthalpie de fusion (kJ/kg)**
MCP Organique	Eau	0	333.6
	Stéarate de butyle	19	140
	Acide caprique-Aurique	21	143
MCP Inorganique	$KF.4H_2O$	18.5	231
	$Mn(NO_3)_2.6H_2O$	25.8	125.9
	$Na_2SO_4.10H_2O$	32	251
MCP Eutectique	$66,6\%CaCL_2.6H_2O+33,3\%Mgcl_2O.6H_2O$	25	127
	$48\%CaCl_2+4,3\%NaCl+47,3\%H_2O$	26.8	188
	$47\%Ca(NO_3)_2.4H_2O+53\%Mg(NO_3)_2 6H_2O$	30	136

II.5.4.2 Mechanical Properties

Mechanical characteristics influence how easily the PCM can be integrated into devices and structures while maintaining reliability and durability [38].

Shape Stability:

- The supporting matrix (like polymers) prevents leakage during melting.
- Example: HDPE maintains the PCM's shape.

Flexibility:

- Some composite PCMs are flexible and can be molded into different shapes.
- Useful in wearable devices or curved electronics.

Mechanical Strength:

- Adding materials like carbon fibers or metal foams increases strength and durability.

- Suitable for demanding applications like automotive or aerospace.

II.5.4.3 Chemical Properties

The chemical properties of composite PCMs influence their compatibility with other materials and their long-term performance [38].

- **Non-corrosive (especially organics):** Safe for use with sensitive equipment or electronics.
- **Chemical stability:** Resistant to oxidation or decomposition over time.
- **Low vapor pressure:** Prevents evaporation or gas buildup.

II.5.4.4 Physical Properties

The physic al properties of PCMs determine their ease of use and integration into various applications [38].

- **Density:** Affects the volume needed for energy storage.
- **Volume change:** Some PCMs expand or contract during phase change—must be managed in design.
- **Compatibility:** Must be compatible with container and environment.

II.5.5 Applications of PCMs in Thermal Management

Phase Change Materials (PCMs) have found extensive applications in thermal management due to their ability to absorb and release large amounts of latent heat during phase transitions. This unique property makes them particularly useful in maintaining temperature stability, enhancing energy efficiency, and reducing thermal stress in a wide range of systems [39].

In the building sector, PCMs are integrated into walls, ceilings, and floors to improve thermal insulation and reduce heating and cooling loads. This leads to increased energy savings and improved indoor comfort, particularly in climates with significant temperature fluctuations.

In electronics and telecommunications, PCMs help dissipate heat from sensitive components such as CPUs, batteries, and data centers, thus extending device lifespan and ensuring stable operation under variable thermal loads.

Solar energy systems, especially photovoltaic (PV) modules, benefit significantly from PCM integration. PCMs are used to regulate module temperature, reduce overheating, and thereby maintain electrical efficiency. These materials are often embedded beneath the PV panel or in specially designed heat sinks.

In the automotive and aerospace industries, PCMs are used for thermal regulation of batteries, cabin environments, and structural components exposed to rapid temperature changes. Their passive thermal control capabilities are especially advantageous where space and power are limited.

In textiles and wearable technologies, PCMs are incorporated into fabrics to provide thermal comfort by absorbing excess body heat and releasing it when needed, which is valuable in sportswear, protective clothing, and medical applications.

Overall, the versatility of PCMs in thermal management continues to drive innovation across multiple sectors, making them a vital component in the development of energy-efficient and temperature-stable systems [39].

II.6. Previous Studies on PCM Cooling

II.6.1. Experimental Studies

Experimental investigations have consistently demonstrated the potential of PCMs to lower the operating temperature of PV modules and improve their power output.

- **Hasan et al. (2010)** conducted an experimental study where paraffin wax was attached to the back of PV panels. The system achieved a temperature reduction of up to 10°**C**, resulting in a 3–5% increase in electrical efficiency [40].

  Result: The system achieved a temperature reduction of up to 10°C, resulting in a 3–5% increase in electrical efficiency.

- **Ling et al. (2013)** examined a PV panel integrated with PCM and fins. They found that adding fins enhanced the heat transfer from the panel to the PCM, which significantly improved the PCM melting rate and maintained lower panel temperatures over a longer duration [41].

Result: Adding fins enhanced heat transfer and accelerated PCM melting, maintaining lower panel temperatures for a longer duration.

- **Chandrasekara Pillai et al. (2014)** tested organic PCMs such as coconut oil and palm wax and showed that natural PCMs are not only effective in cooling but are also environmentally friendly alternatives [42].

Result: These natural PCMs proved to be effective cooling agents and environmentally friendly, offering comparable thermal performance to commercial PCMs .

- **Soares et al. (2015)** investigated a PV-PCM system using microencapsulated PCM. Their results showed better temperature control and cycle stability over several charge/discharge cycles [43].

Result: The system exhibited superior temperature control and improved cycle stability across multiple melting and solidification processes .

- In a desert climate study, **Mahdi et al. (2018)** applied PCMs in PV panels under high solar radiation. They observed significant thermal regulation, especially during midday hours, which improved overall system stability [44].

Result: The PCM layer effectively reduced midday peak temperatures and stabilized output performance, especially in extreme heat .

II.6.2. Numerical Studies

Numerical modeling plays a crucial role in understanding the thermal behavior of PV/PCM systems and allows researchers to simulate a wide range of design parameters that are often challenging to study experimentally.

- **Elbahjaoui et al. (2020)** performed a 3D CFD simulation using ANSYS Fluent, analyzing the effects of PCM thickness, thermal conductivity, and natural convection. Their findings showed that increasing PCM thickness beyond an optimal value yields diminishing thermal returns [45].

Result: They found that increasing PCM thickness improves cooling up to a limit, beyond which thermal benefits saturate .

- **Khouya et al. (2019)** simulated a PV/PCM system using finite element modeling and found that the placement and distribution of PCM modules significantly affect cooling efficiency and phase change duration [46].

Result: The study showed that PCM placement and modular design significantly influence both cooling efficiency and phase change duration .

- **Yousefi et al. (2021)** explored the use of nanoparticle-enhanced PCM (nano-PCM) for PV cooling in a numerical study. By integrating Al_2O_3 nanoparticles into paraffin wax, they improved thermal conductivity and reduced PV temperature more effectively than conventional PCM [47].

Result: The addition of nanoparticles boosted thermal conductivity, leading to better temperature regulation and more rapid phase transitions compared to conventional PCM .

- **Krauter and Preiss (2012)** developed a transient heat transfer model for PCM-cooled PV panels and verified their model using experimental data, showing good agreement and highlighting the importance of PCM selection based on local climate conditions [48].

Result: The model showed strong agreement with measurements and confirmed the importance of climate-adapted PCM selection for optimal performance .

These studies collectively highlight the following:

- PCMs can significantly reduce PV surface temperature, particularly during peak sun hours.

- Material selection (paraffin, fatty acids, hydrated salts) and encapsulation methods influence thermal performance.

- The use of thermal conductivity enhancers (e.g., graphite, fins, nanoparticles) improves heat dissipation and melting uniformity.

- Numerical tools like ANSYS Fluent and COMSOL Multiphysics enable detailed analysis and system optimization.

II.7. ANSYS Fluent in PV Thermal Modeling

ANSYS Fluent is one of the most powerful and widely used computational fluid dynamics (CFD) tools for simulating heat transfer and fluid flow in complex systems. In the context of photovoltaic (PV) thermal modeling, Fluent offers valuable capabilities for understanding and optimizing the thermal performance of PV modules, particularly when enhanced by cooling techniques such as phase change materials (PCMs) [49].

Strengths

1. **High Accuracy in Solving Heat Transfer Equations**

ANSYS Fluent provides precise solutions to the energy equation, allowing for accurate prediction of temperature distribution within PV modules and attached PCM layers.

2. **Coupled Fluid Flow and Heat Transfer Modeling**

The software enables simultaneous modeling of conduction, convection, and radiation**,** which is crucial for realistic simulation of PV/PCM systems, especially under natural outdoor conditions.

3. **Customizable Material Properties**

Fluent allows the definition of temperature-dependent thermal properties such as specific heat, thermal conductivity, and latent heat, which is essential when modeling PCM phase transitions**.**

4. **Advanced Meshing and Solver Control**

Users can generate structured or unstructured meshes to optimize the accuracy and convergence of their models, particularly in regions with steep thermal gradients (e.g., near the PV/PCM interface).

5. **User-Defined Functions (UDFs)**

Fluent supports the implementation of custom functions to define complex behaviors (e.g., PCM melting kinetics, enthalpy-temperature relationships), offering flexibility for advanced research applications.

6. **Validation Against Experimental Data**

Numerous studies have successfully validated ANSYS Fluent models with experimental results, demonstrating its reliability and robustness in PV thermal analysis.

Limitations

1. **Computational Cost**

High-fidelity simulations, especially in 3D and with transient conditions (e.g., hourly solar radiation), require significant **computational power and time**, which may limit practical use for large systems or long simulation periods.

2. **Complex Setup for Phase Change Materials**

Accurately modeling PCM requires careful handling of **enthalpy-porosity methods** or user-defined melting/solidification models, which can be challenging for beginners.

3. **Limited Built-In PCM Libraries**

Fluent does not provide a predefined library of PCM materials, so researchers must input thermal properties manually, increasing the chance of error if reliable data is not available.

4. **Steep Learning Curve**

Mastering the full capabilities of Fluent, including mesh refinement, solver settings, and UDF integration, requires **advanced CFD knowledge and training**.

5. **Simplified Solar Radiation Modeling**

While Fluent can simulate radiation, modeling **real-time solar irradiance** and its effects on PV panels requires integration with external weather or solar position data, which adds complexity.

In conclusion, ANSYS Fluent is a powerful tool for simulating the thermal behavior of PV-PCM systems. Its ability to capture complex heat transfer mechanisms makes it invaluable in academic and industrial research. However, it demands careful setup, computational resources, and expertise to ensure accurate and reliable results [50].

II.8. Research Gap and Justification

Despite the extensive research conducted on photovoltaic (PV) cooling systems, there remain significant gaps that justify further investigation—particularly in the application of phase change materials (PCMs) for passive thermal regulation.

While numerous experimental and numerical studies have explored the use of PCMs to reduce PV module temperature and enhance electrical efficiency, most of these works focus on limited climatic conditions, short-term performance, or specific PCM types (e.g., paraffin). Few studies provide comprehensive analysis under realistic, dynamic outdoor conditions or assess long-term thermal cycling stability of PCM-integrated systems.

Additionally, many previous models assume ideal thermal contact between the PV panel and the PCM layer, which may not reflect actual field conditions. There is also limited exploration of optimization strategies for PCM selection (e.g., latent heat capacity, melting point) tailored to specific geographic locations and seasonal variations.

Moreover, while ANSYS Fluent has been widely used to model PV/PCM systems, some studies overlook important parameters such as natural convection within the PCM, ambient temperature fluctuations, and degradation effects over time.

Therefore, this study aims to address these gaps by:

- Numerically investigating the effect of PCM cooling on PV module performance using a validated CFD model in ANSYS Fluent.
- Evaluating the thermal behavior under realistic boundary conditions.
- Selecting PCM materials based on thermophysical properties suitable for hot climates, such as those in the Saharan region.
- Providing insights into design guidelines for more efficient, passive PV cooling systems without relying on active components.

By filling these research gaps, the work contributes to the development of sustainable, cost-effective solutions for enhancing solar panel efficiency in high-temperature environments, which is particularly relevant in regions like southern Algeria.

II.9. Conclusion

This chapter has provided a comprehensive review of the current state of research and technologies related to photovoltaic (PV) systems and their thermal management. It began by outlining the fundamental working principles of PV modules and highlighted the critical impact of temperature on their electrical efficiency, particularly under high solar irradiation.

Various cooling techniques were discussed, with a focus on the distinction between **active** and **passive** systems. Among the passive methods, Phase Change Materials (PCM) emerged as a promising and energy-efficient approach to reduce PV panel temperature and improve performance without additional energy input.

The chapter then explored the definition, thermal behavior, and classification of PCMs, as well as the selection criteria necessary for their effective integration into PV systems. Composite PCMs, in particular, were emphasized for their enhanced thermal, mechanical, and chemical properties, which enable stable and efficient operation under dynamic thermal conditions.

A detailed examination of previous experimental and numerical studies revealed the growing body of work focusing on PCM-enhanced PV modules. However, these studies often remain limited in scope, either by geographic climate constraints or simplified modeling assumptions.

Furthermore, **ANSYS Fluent** was reviewed as a key computational tool for simulating PV thermal behavior. While it offers strong capabilities in simulating complex heat transfer processes, challenges such as mesh sensitivity, computational cost, and the assumption of ideal thermal contact persist.

Finally, the identified **research gaps** highlight the need for improved modeling of PCM-based cooling systems under realistic boundary conditions and long-term performance considerations. These gaps form the basis and justification for the present study, which aims to develop a validated CFD model using ANSYS Fluent to assess the effectiveness of PCM cooling in hot climate regions.

This literature review lays the groundwork for the following chapters, which detail the methodology, numerical modeling, and results of the current research.

Chapter III: Numerical Simulation and Result Analysis

III.1. Introduction:

This chapter presents an integrated approach that combines the numerical modeling and performance analysis of a photovoltaic (PV) module enhanced with a phase change material (PCM). The main objective is to assess the thermal and electrical behavior of the PV system under realistic solar conditions using a two-dimensional transient computational model implemented in ANSYS Fluent.

The first part of the chapter (Section III.2) describes the numerical methodology, including the physical configuration of the PV-PCM system, thermophysical properties of materials, geometry and meshing, the governing heat transfer equations, as well as simulation and boundary conditions.

The second part (Sections III.3 to III.6) focuses on the results of the simulations, where two configurations are compared: a baseline PV module without PCM and a modified version with an integrated RT28HC paraffin PCM layer. The analysis includes temperature distributions, melting dynamics, efficiency evaluation, and the impact of PCM on daily energy yield.

The final sections provide a discussion of the trends observed in the numerical results and compare them with existing studies. This integrated evaluation highlights the potential of PCM integration for improving PV performance in hot climates.

III.2. Numerical Methodology and Simulation Setup

III.2.1 System Description

The system consists of a flat-plate photovoltaic panel with a PCM layer attached to its rear surface. The PCM serves as a thermal buffer, absorbing excess heat during peak solar periods and releasing it when temperatures drop. The setup mimics a typical PV installation under warm climate conditions.

- PV Panel Dimensions: 992 mm (length) × 1640 mm (width) × 40 mm (total thickness)
- PCM Configuration: The PCM is placed in full contact with the PV panel’s aluminum backsheet, forming a 20 mm thick layer encapsulated within an aluminum container. Note: A schematic diagram illustrating the PV-PCM configuration and layer distribution is provided later.

III.2.2 Material Properties

All material properties are assumed temperature-dependent. The system includes standard PV module layers (glass, EVA, silicon, backsheet) and a paraffin-based PCM (RT28HC). Thermophysical properties are sourced from experimental data and validated literature.

Complete summary of material properties is provided in Table 3.1.

Table III.1 :Thermo physical Properties of RT28HC PCM [51].

Phase Change Material	Melting Range	Latent Heat	Density (Solid)	Density (Liquid)	Thermal Conductivity	Specific Heat
RT28HC	27–29 °C	200 kJ/kg	880 kg/m³	760 kg/m³	0.2 W/m·K	2000 J/kg·K

III.2.3 Geometry and Meshing

The geometry used in this study represents a cross-sectional 2D model of a typical photovoltaic (PV) panel integrated with a phase change material (PCM) layer. The PV panel consists of five main layers: a glass cover, two layers of Ethylene-Vinyl Acetate (EVA), silicon solar cells, and a Tedlar backsheet, as illustrated in Figure III.1.

The glass layer is made of ultra-clear, low-iron glass to maximize solar energy transmission. The EVA layers serve to encapsulate and protect the silicon cells, while the Tedlar backsheet, composed of polyvinyl fluoride (PVF), provides electrical insulation and environmental protection.

The main geometric dimensions of the PV panel and its layers are summarized in **Table III.2**.

Table III.2 The dimensions of the panel and its layers [52].

Total length of photovoltaic panels	Total thickness of panels	Thickness Glass	Thickness PCM	Thickness Silicon	Thickness EVA (1 ,2)	Thickness Tedlar
360 mm	35 mm	3 mm	20 mm	0.4 mm	0.5 mm	0.1 mm

The complete 2D geometry was created using **ANSYS DesignModeler**, with all layers accurately represented according to their thicknesses. The model also includes the PCM layer placed in direct contact with the PV backsheet within a sealed aluminum enclosure.

A structured mesh was generated using ANSYS Meshing, with approximately 112,000 nodes and 112,000 elements. The mesh was refined sufficiently to capture the thermal gradients within each material layer. A mesh independence study was conducted to ensure that the results are not affected by mesh density.

The final geometry and mesh are shown in **Figures III.1 and III.2**, respectively.

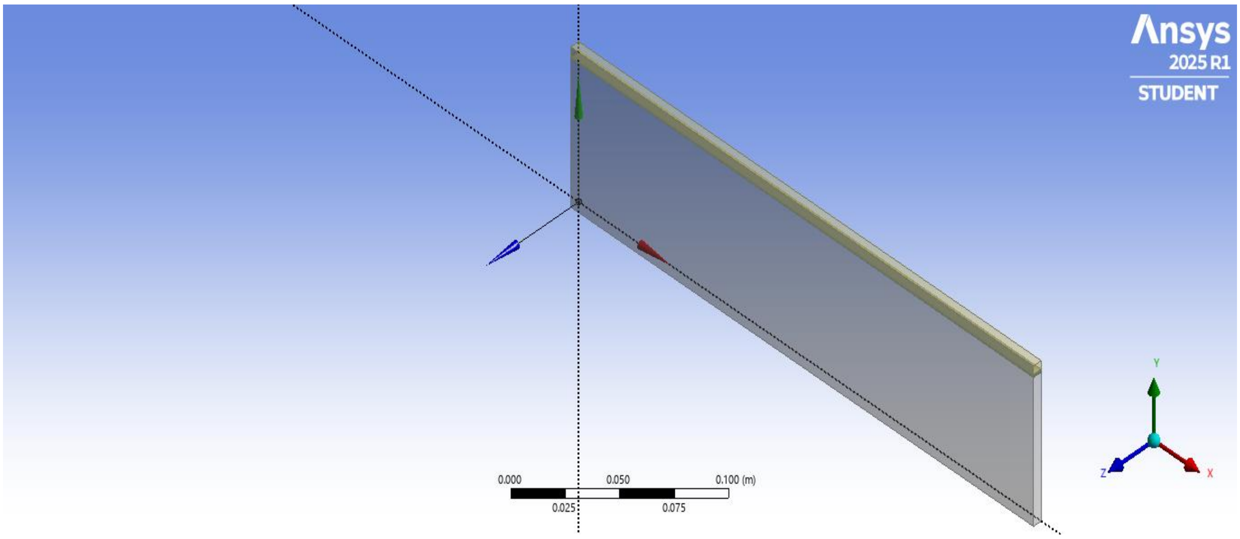


Figure III.1: Geometry of the photovoltaic panel under study.

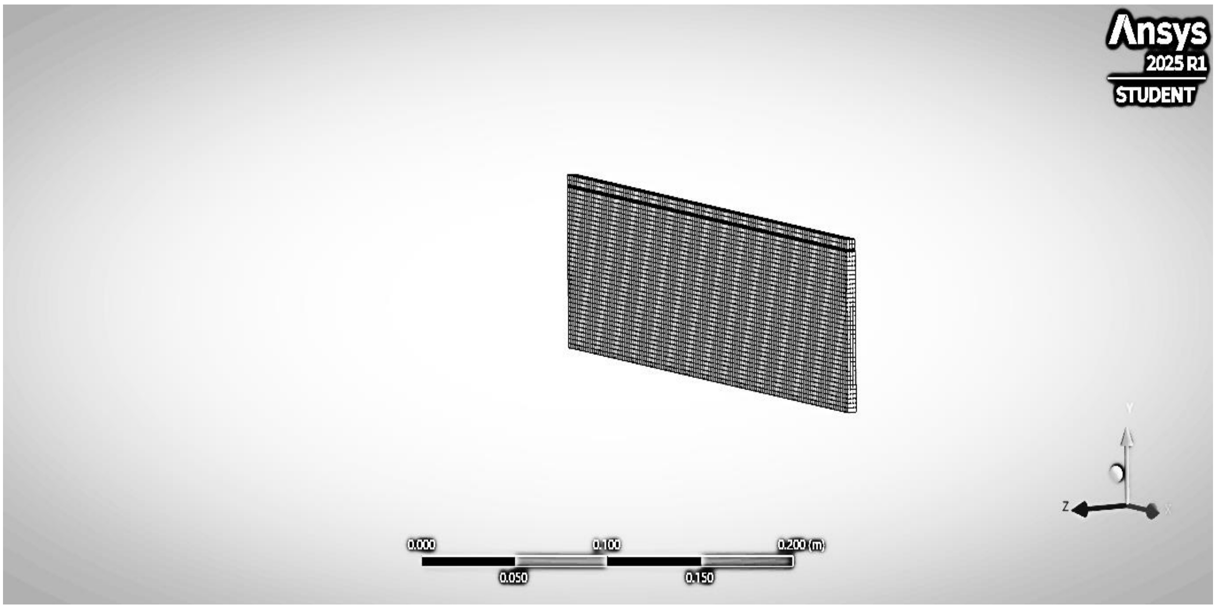


Figure. III.2: the mesh obtained.

III.2.4 Governing Equations

The numerical modeling of the PV-PCM system is based on the fundamental laws of heat transfer and phase change thermodynamics. The simulation considers three major phenomena: transient heat conduction, latent heat absorption/release during phase change, and external boundary interactions through radiation and convection [53].

III.2.4.1 Transient Heat Transfer

Heat conduction is the dominant mechanism of energy transport within the solid layers of the photovoltaic module and the PCM. This process is governed by the unsteady heat conduction equation, derived from the first law of thermodynamics applied to a differential control volume:

$$\rho\, Cp.\frac{\partial T}{\partial t} = \nabla \bullet (k\, \nabla T) + S$$

Where:

- ρ is the material density $[kg/m^3]$
- cp: is the specific heat capacity $[J/kg \bullet K]$
- T: is the local temperature $[K]$
- k : is the thermal conductivity $[W/m \bullet K]$
- S : is the internal heat generation term or energy source, representing latent heat effects in the PCM

This equation allows the simulation to capture spatio-temporal temperature variations within the composite layers of the module as a response to the applied solar heat flux and thermal boundaries[53].

III.2.4.2 Phase Change Modeling

To model the melting and solidification of the PCM, the enthalpy–porosity method is employed. This method is particularly effective in capturing the latent heat storage behavior without requiring the explicit tracking of the phase interface [54].

The total enthalpy H in the PCM domain is expressed as:

$$H = h\_sens + h\_lat = \int_{T\_ref}^{T} Cp(T)\, dT + \beta L$$

Where:

- H: Total enthalpy [J/kg]
- h_sens: Sensible heat component
- h_lat: Latent heat component
- Cp(T): Temperature-dependent specific heat capacity
- T_ref: Reference temperature [K]
- β: Liquid fraction ($0 \leq \beta \leq 1$)
- L: Latent heat of fusion [J/kg]

The phase transition occurs over a temperature range (solidus to liquidus), e.g., 27°C to 29°C for RT28HC. During this range, the material exists as a mixture of solid and liquid. and the value of β increases gradually from 0 to 1.

Additionally, natural convection inside the PCM is neglected due to the thin geometry and limited fluid motion (low Rayleigh number), making heat transfer predominantly conductive [53].

III.2.4.3 Radiation and Convection Effects

In Simulation 2 and Simulation 3, the surface-to-surface radiation model **(S2S)** was activated to simulate solar radiative heat exchange on the PV panel's front surface. This model considers gray, opaque surfaces and solves the Radiative Transfer Equation (RTE) using a surface energy balance [55].

On the rear side of the system, **natural convection** is modeled as a boundary condition:

$$q\_conv = h(T\_surface - T\_\infty)$$

Where:

-h : convective heat transfer coefficient (assumed 10 W/m²·K for natural air cooling)

-$T\_surface$: surface temperature of the panel/PCM enclosure

- T_∞: ambient air temperature (25°C)

These boundary models ensure that external thermal losses are realistically included, which is crucial for predicting the net cooling effect provided by the PCM.

III.2.5 Simulation Setup in ANSYS Fluent

In this study, two transient simulation cases were developed using **ANSYS Fluent** to analyze the thermal behavior of a photovoltaic (PV) panel under realistic solar conditions, with and without the integration of Phase Change Material (PCM).

Case 1 (Without PCM):

Solar radiation is applied to the front surface of the PV panel without any thermal regulation. This case serves as the baseline scenario to evaluate the natural temperature rise of the system.

Case 2 (With PCM):

Same as Case 1, but with adding a paraffin-based PCM layer (RT28HC) to the rear surface of the PV panel, enabling passive thermal regulation through latent heat storage.

Both simulations used a pressure-based transient solver with the energy equation enabled. The surface-to-surface (S2S) radiation model was activated to simulate solar irradiance and radiative heat transfer across the front surface. Natural convection and fluid flow were neglected due to the thin PCM layer and low Rayleigh number, making conduction the dominant mode of heat transfer.

Thermophysical properties (such as thermal conductivity, specific heat capacity, and density) for all materials (glass, EVA, silicon, Tedlar, and PCM) were taken from validated literature and were defined earlier in the simulation setup. The PCM layer was included **only in Case 2**.

Each region in the domain was assigned as a solid zone to ensure proper thermal interaction between layers.

The simulation ran for a total of **6 hours (21,600 seconds)** using a **constant time step of 10 seconds**. An energy residual threshold of 10^{-6} was used to ensure convergence and numerical stability.

Throughout the simulation, two key thermal responses were monitored:

- The **temperature distribution** on the front surface of the PV panel.
- The **liquid fraction of PCM** (in Case 2), to observe the melting progression during solar exposure.

III.2.6 Boundary Conditions and Assumptions.

The boundary conditions were carefully defined to replicate realistic thermal operating conditions for the photovoltaic (PV) system across the three simulation scenarios. These conditions govern the thermal interactions between the PV surface, the environment, and the PCM layer (if present).

a) Top Surface – Heat Input

A constant heat flux was applied to the top surface of the PV panel to simulate incident solar irradiation. No fluid flow was considered within the solid domain, and thus the velocity was set to zero (V = 0). The heat flux values differ across the simulation scenarios:

Table III.3: Heat Flux Values for the Simulation Cases.

case 1	case 2	case 3
Q = 1000 W/m²	Q=900 W/m²	Q=800 W/m²

The applied heat flux values (800, 900, and 1000 W/m²) correspond to realistic levels of solar irradiance typically observed at 08:00, 11:00, and 14:00, respectively, in hot desert climates such as El-Oued, Algeria. These values were chosen to reflect the natural increase in solar energy received by the PV surface throughout the day, allowing for a time-dependent evaluation of the system's thermal response under rising solar load.

b) Side Walls – Left and Right

The lateral surfaces of the model were assumed to be adiabatic, meaning no heat transfer occurs through these boundaries:

$q = 0$ (Insulated or zero heat flux)

This assumption is justified by the symmetry of the PV panel and the one-dimensional nature of the vertical heat flow.

c) Bottom Surface – Natural Convection (Outlet: bottom_wall)

The bottom boundary, representing the back of the PV panel or the PCM layer enclosure, was modeled as a convective surface with ambient air conditions. The following heat transfer condition was applied:

$$q = h \times (T\_surface - T\_ambient)$$

Where:

- $\mathrm{h} = 10\,\mathrm{W/m^2 \cdot K}$ (natural convection heat transfer coefficient)
- $T\_ambient = 25°C$ (ambient air temperature)

This setting enables passive heat dissipation from the system to the surrounding environment and plays a critical role in the cooling dynamics, especially in the presence of PCM.

Table III.4: Chemical properties of materials contained in the panel used [52].

Layer	Thickness	Density (kg/m^3)	Thermal conductivity	Specific heat
Glass	**3mm**	**3000**	**1.8**	**500**
EVAI	**0.5mm**	**960**	**0.35**	**2090**
PV cells	**.4mm0**	**2330**	**1480**	**677**
EVA2	**0.5mm**	**960**	**0.35**	**2090**
Tedlar	**0.1mm**	**1200**	**0.2**	**1250**

III.3. Temperature Distribution

This section presents a comparative thermal analysis of two simulated configurations of a photovoltaic (PV) module: one without any cooling enhancement, and the other incorporating a phase change material (PCM) layer on the rear surface. Both simulations were conducted using a transient, two-dimensional model in ANSYS Fluent.

To evaluate the system’s thermal response throughout the day, three representative time points were selected: 08:00, 11:00, and 14:00. These correspond to different solar irradiance levels applied in the simulation, as described previously in the boundary conditions section.

Temperature contours extracted at these times serve as a basis for comparing the thermal behavior of both configurations. The next parts of this section analyze these results in detail, beginning with the PV module without PCM, followed by the system with PCM integration.

III.3.1. PV Module Without PCM

In this configuration, the PV module is modeled with all its functional layers (glass, EVA, silicon, backsheet) but without any PCM layer or additional cooling enhancement. The system is subjected to solar radiation using the surface-to-surface radiation model available in

Fluent. Environmental conditions replicate a natural outdoor setting in the city of El-Oued, Algeria.

Heat transfer in this simulation is primarily governed by conduction through the solid layers and convection to the ambient air at the back surface, with a convective heat transfer coefficient of $h = 10\,\mathrm{W/m^2 \cdot K}$ and an ambient temperature of 25°C. As solar intensity increases throughout the day, the surface temperature of the PV module rises steadily due to the absence of any thermal buffering mechanism.

Temperature contours at the selected time steps reveal this trend:

At 08:00, the average surface temperature is 23.64°C.

At 11:00, it increases to 31.95°C.

At 14:00, it peaks at 40.11°C.

This thermal behavior is typical for PV modules operating in hot climates without active cooling, where elevated temperatures lead to reduced electrical efficiency.

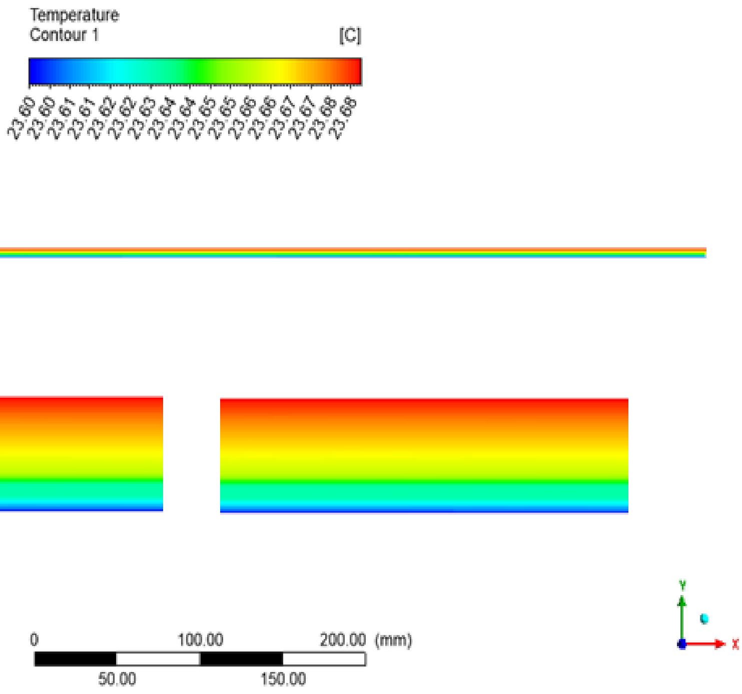


Figure III.3 Temperature contour without PCM at 08:00

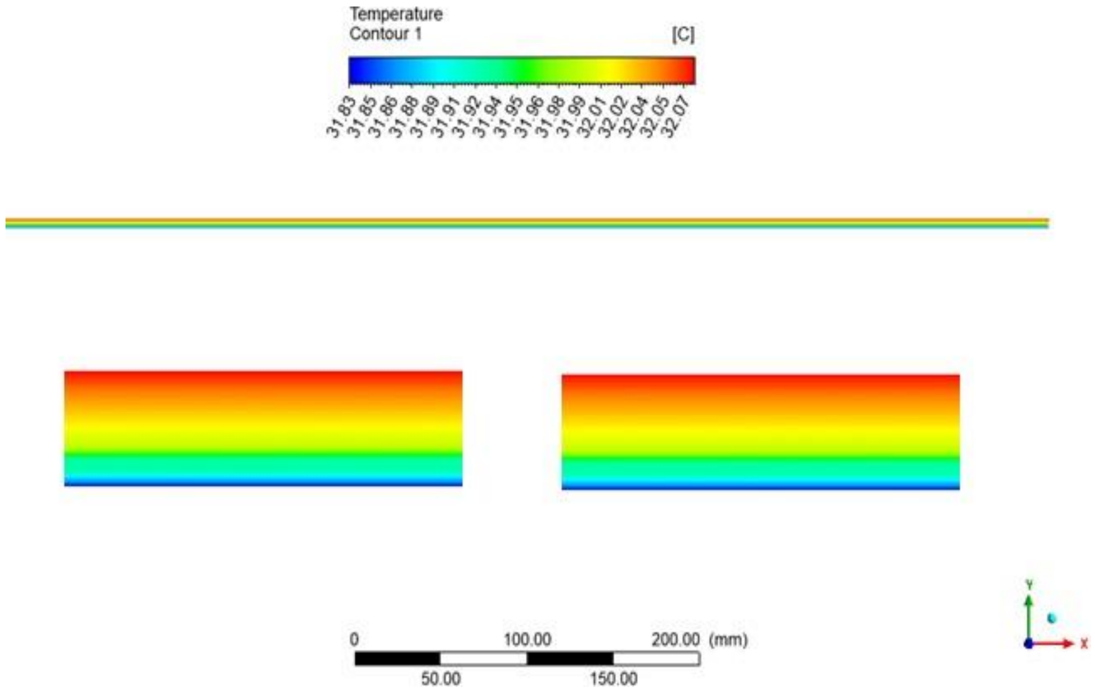
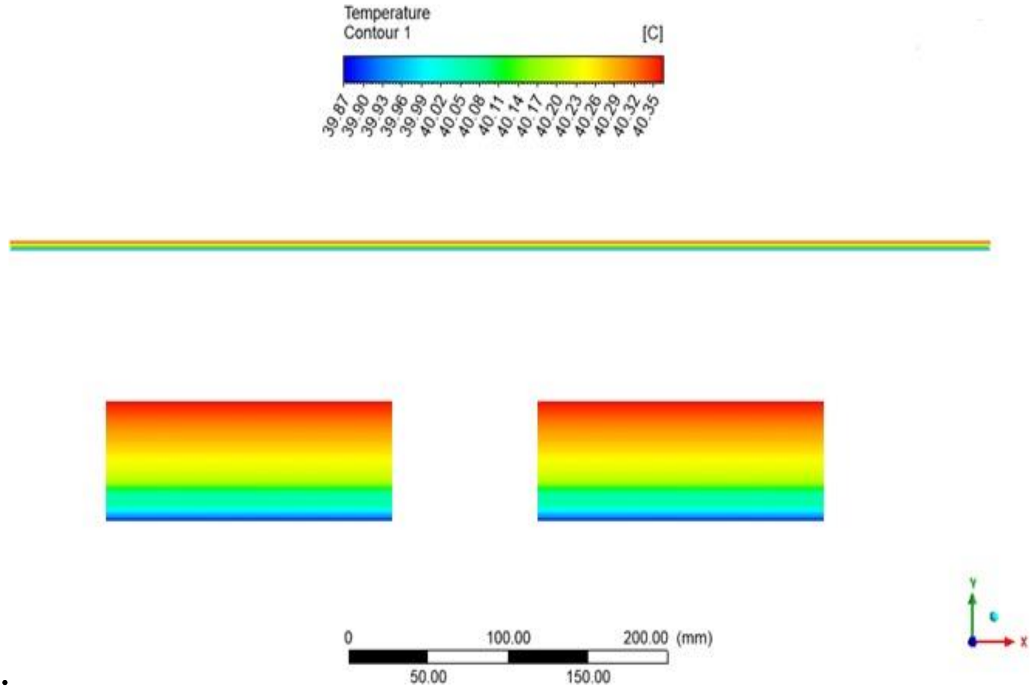


Figure III.4 Temperature contour without PCM at 11:00



5.

Figure III.5 Temperature contour without PCM at 14:00

It is observed that the temperature of the photovoltaic (PV) panel increases progressively over time when subjected to continuous solar radiation. This thermal accumulation adversely affects the overall performance of the PV system by reducing its electrical efficiency. In response to this challenge, a passive thermal regulation strategy is proposed through the integration of a phase change material (PCM) layer. The selection of the PCM was made based on both local climatic conditions and practical applicability, with the primary objective of mitigating temperature rise and enhancing the thermal stability of the PV module.

III.3.2. PV Module With PCM

This simulation introduces a paraffin-based PCM layer (RT28HC) placed at the rear of the PV module. The paraffin wax used here operates within the ambient temperature range up to 90°C, suitable for the climatic conditions of the region studied. The PCM has a melting temperature range of approximately 27°C to 29°C, making it suitable for passive thermal regulation within typical PV operating temperature ranges.

Thermal behavior at the key time steps is as follows:

- At 08:00, the PCM remains mostly solid, with temperature gradients just starting to develop within the PCM layer.
- At 11:00, the PCM begins melting, absorbing latent heat and thus limiting the temperature rise of the PV module.
- At 14:00, the PCM is partially melted, effectively reducing the peak temperature compared to the configuration without PCM.

The front surface of the module is heated by solar radiation, while the rear surface remains cooler, supporting heat flow into the PCM for efficient thermal energy storage.

The resulting temperature distribution is more uniform, with a notable reduction at the silicon and backsheet levels, demonstrating successful thermal regulation through latent heat absorption.

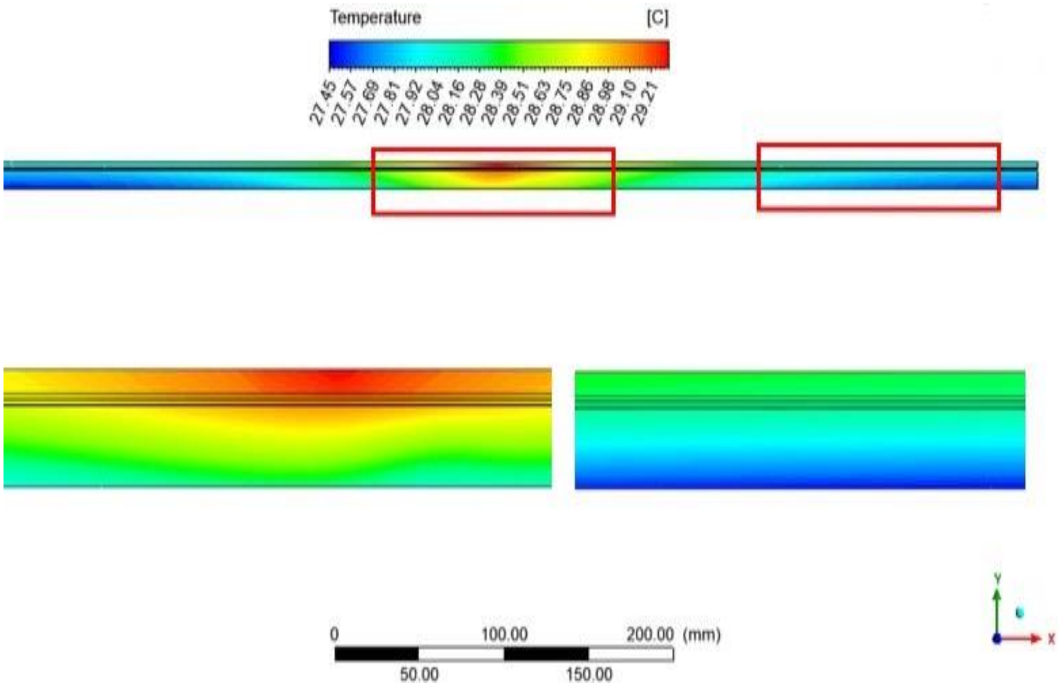


Figure III.6 Temperature contour with PCM at 08:00

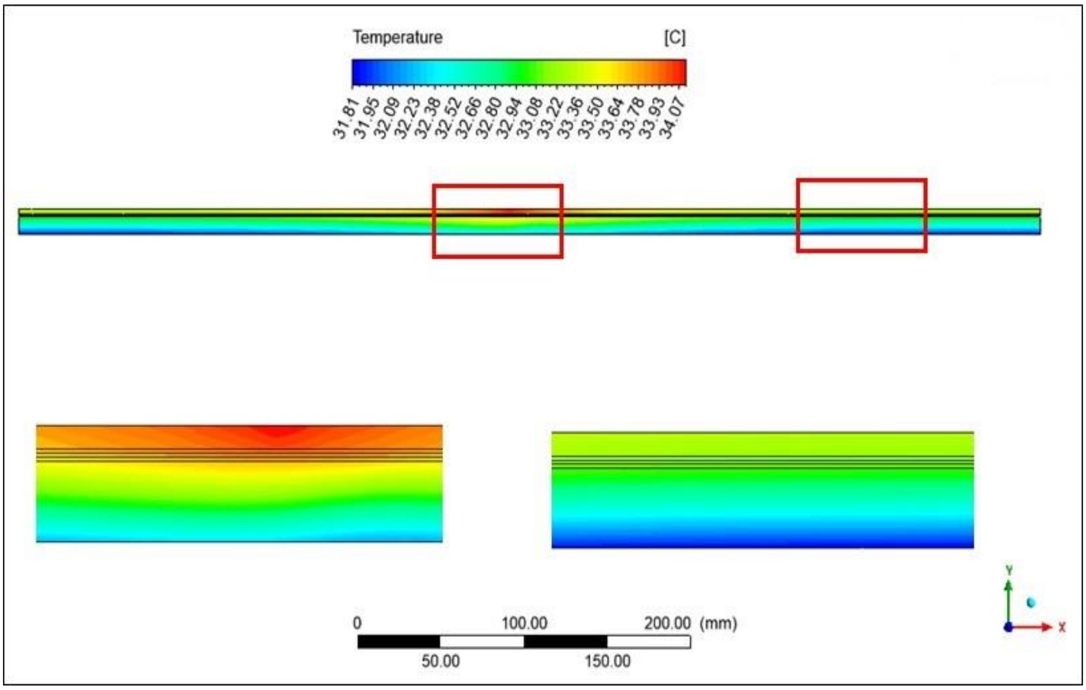


Figure III.7: Temperature contour with PCM at 11:00

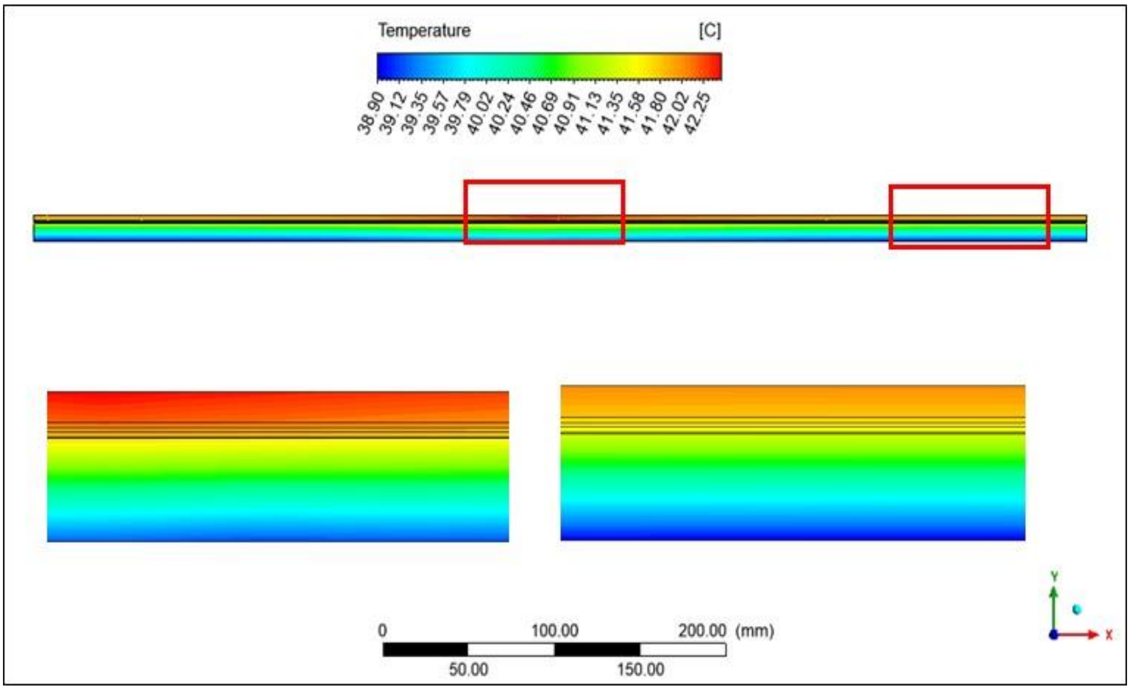


Figure III.8: Temperature contour with PCM at 14:00

The thermal simulation results revealed a clear impact of the phase change material (PCM) across the three evaluated time intervals (08:00, 11:00, and 14:00). In the early morning (08:00), the temperature difference between the two configurations was minimal, as the PCM remained in its solid state. By mid-morning (11:00), the PCM began to melt, absorbing latent heat and effectively slowing the temperature rise of the PV module. At peak solar irradiance (14:00), the temperature reduction became most pronounced, with the PCM-integrated system showing a decrease of approximately 4 to 6°C compared to the reference case. These findings confirm the PCM's effectiveness in regulating the PV module's thermal response under varying daily operating conditions.

III.4 Effect of PCM on PV Surface Temperature

The presence of a phase-change material (PCM) on the rear side of the photovoltaic (PV) module produces a clear, quantifiable moderation of the module's operating temperature. This section isolates that effect by comparing the instantaneous and time-averaged surface temperatures of the reference PV panel (without PCM) and the PCM-enhanced panel over the three representative instants examined earlier (08:00, 11:00 and 14:00).

Table III.5 Data extracted from the numerical results

Time of day	PV Temp without PCM (°C)	PV Temp with PCM (°C)	Absolute Drop ΔT (°C)	Relative drop (%)
08 : 00	**23.6**	**23.5**	**≈ 0.1**	**< 1 %**
11 : 00	**32.0**	**29.0**	**3.0**	**9 %**
14 : 00	**40.1**	**34.0**	**6.1**	**15 %**

- **Morning (08:00).** The PCM is still below its melting range; the dominant mechanism is sensible-heat absorption, and the temperature difference is negligible.
- **Late-morning (11:00).** The PCM is partially molten, absorbing latent heat; the PV surface temperature is already **~3 °C** lower than the reference case.
- **Early afternoon (14:00).** Latent-heat absorption is at its peak; the temperature reduction reaches **≈ 6 °C**, corresponding to a **15 %** decrease relative to the unclad panel.

Figure III.9 illustrates the average surface temperatures of the PV module for both configurations with and without PCM. The inclusion of PCM results in a temperature reduction of approximately 4 to 6°C, most notably during peak solar irradiance at 14:00. This reduction confirms the effectiveness of PCM as a passive thermal energy storage material, contributing to enhanced thermal stability of the PV module and potentially improved electrical performance.

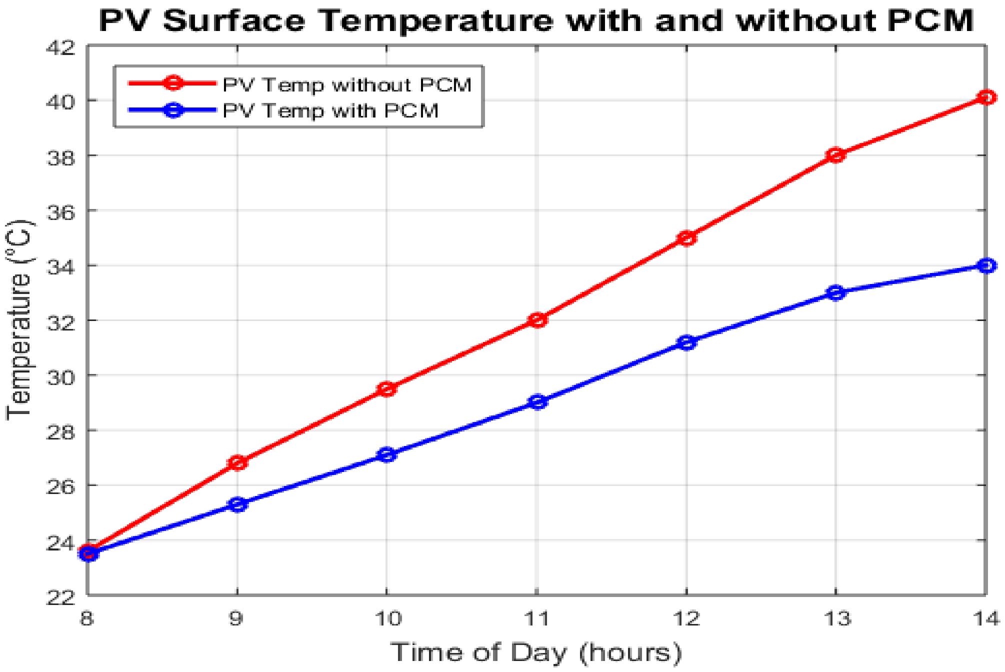


Figure III.9. PV surface temperatures with and without PCM

III.4.1 Physical Interpretation

1. **Latent-Heat Buffering.**
   Between 27 °C and 29 °C the paraffin wax absorbs latent heat, constraining the PV temperature to a narrow band until a significant liquid fraction is reached.
2. **Thermal-Mass Effect.**
   Even outside the melting interval, the PCM layer adds thermal inertia, delaying the onset of peak temperatures and smoothing temperature gradients inside the laminate.
3. **Reduced Thermal Stress.**
   Lower peak temperatures and smaller temperature swings imply smaller thermo-mechanical stresses on solder joints and encapsulation layers, potentially extending module lifetime.

III.4.2 Implications for Electrical Performance

Using the commonly adopted linear temperature coefficient for crystalline-silicon modules (≈ −0.45 % / °C), a **6 °C** reduction at 14:00 translates into an instantaneous efficiency gain of roughly **2.7 %**. Over a full day, the integrated energy yield is expected to rise by **2–4 %**, depending on local irradiance profiles.

III.5.Thermal Behavior of PCM

The internal thermal behavior of the phase change material (PCM) is a key determinant of its effectiveness as a passive cooling solution in PV applications. In this section, the simulation results of the melting process and the liquid fraction evolution of the PCM layer (RT28HC paraffin) are examined at three time intervals—08:00, 11:00, and 14:00 corresponding to different solar exposure levels.

III.5.1. Melting Profile of PCM

At the start of the simulation (08:00), the PCM is entirely in the solid phase, with a uniform temperature below its melting point (~27°C). The temperature field within the PCM layer is relatively low, and no phase transition is observed.

By 11:00, solar heating has progressed sufficiently to raise the temperature of the PV layers, initiating the melting of the PCM. The interface between the solid and liquid phases begins to form, particularly near the PV–PCM contact surface, where the heat transfer is most intense. The temperature within the PCM ranges from 27°C to 29°C, indicating active latent heat absorption.

At 14:00, the melting process is well underway, and a significant portion of the PCM has transitioned into the liquid state. The heat storage capacity of the PCM in this phase helps to maintain a more stable thermal condition in the adjacent PV layers. The phase boundary has moved deeper into the PCM layer, demonstrating effective thermal buffering.

III.5.2 Liquid Fraction Evolution

The evolution of the liquid fraction within the PCM layer is used to quantitatively track the phase change over time. The liquid fraction (β) varies between 0 (fully solid) and 1 (fully liquid).

- 08:00: β ≈ 0 across the entire PCM layer
- 11:00: Partial melting begins; β values range between 0.2 and 0.5 near the contact interface
- 14:00: Advanced melting; β values exceed 0.7 in the majority of the PCM volume

This progression confirms the effective utilization of latent heat storage during peak solar hours.

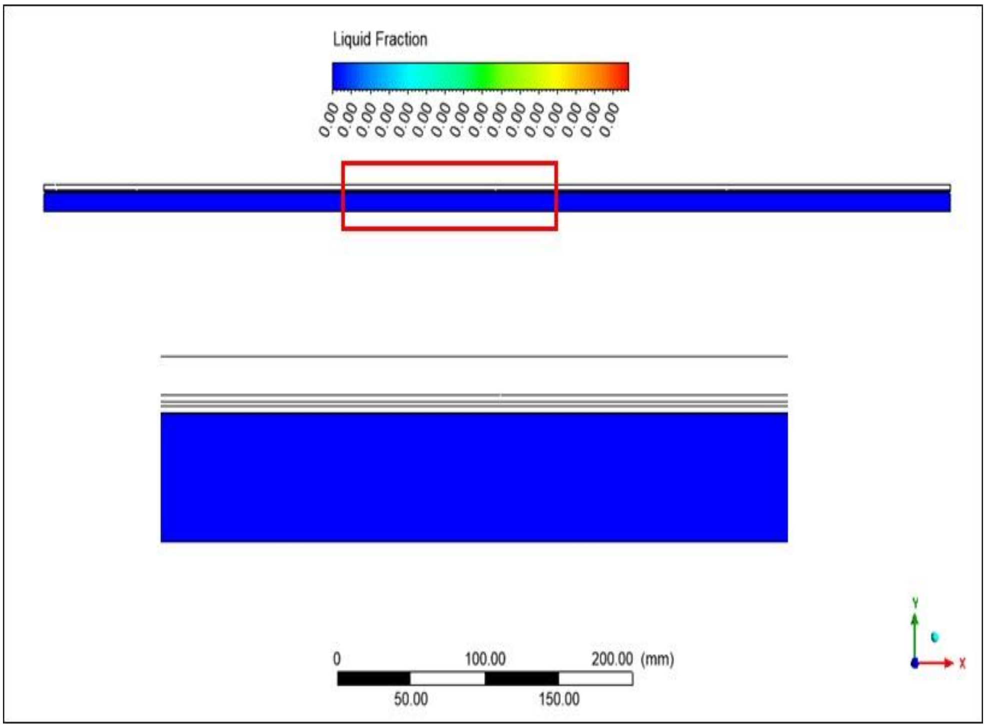


Figure III.10 Liquid fraction of «paraffin wax» at 08h00 AM

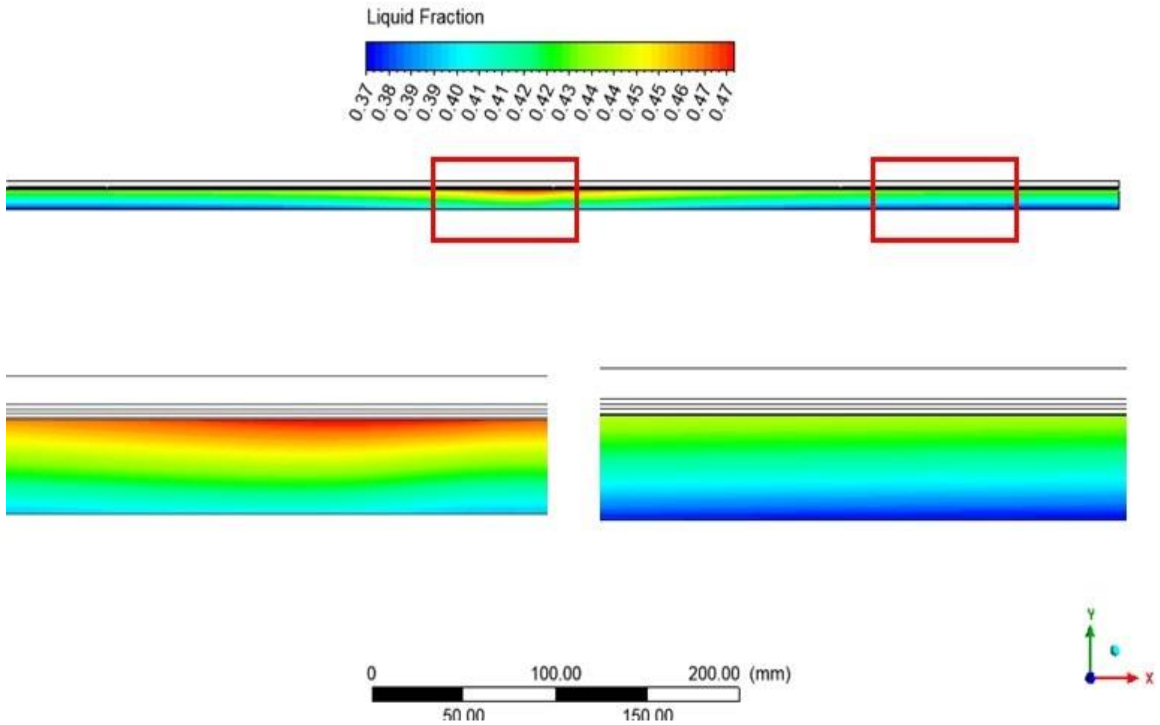


Figure III.11 Liquid fraction of « paraffin wax » at 11h00 AM.

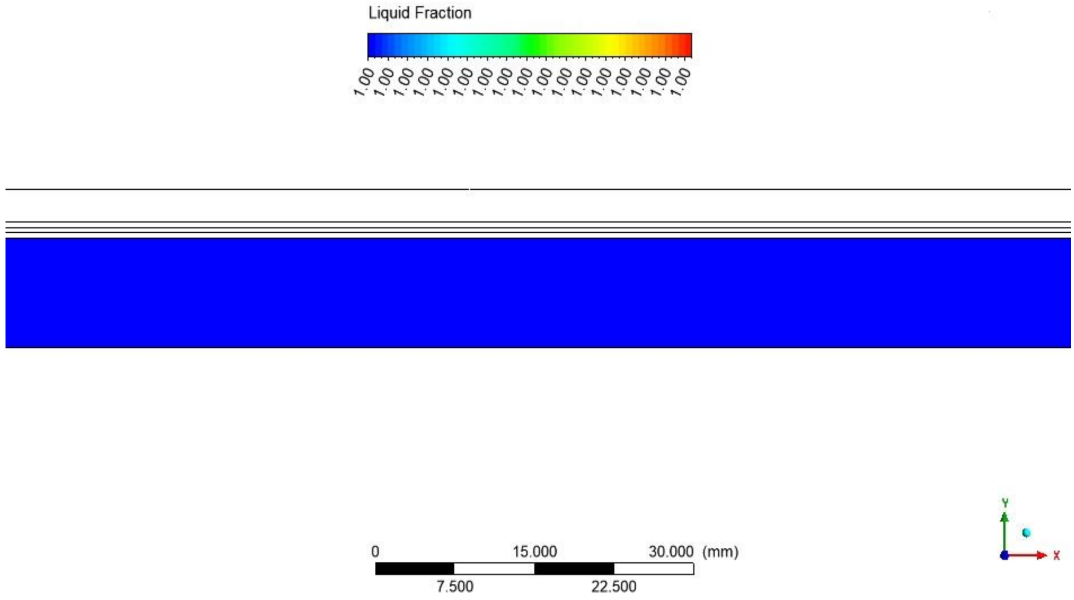


Figure III.12: Liquid fraction of « paraffin wax » at 14:00 PM

To further illustrate the melting behavior of the PCM **Figure III.13** presents the curve of the liquid fraction (β) distribution across the thickness of the paraffin wax layer at 11:00 AM. This 1D profile, extracted along a vertical line in the center of the PCM domain, shows a clear gradient in the phase-change state.

At this stage, the highest liquid fraction is observed at the PCM–PV interface (front side), where thermal energy input is greatest. The liquid fraction gradually decreases toward the rear of the PCM, confirming a directional melting process from front to back. This gradient reflects both the heat flux distribution and the thermal inertia of the material.

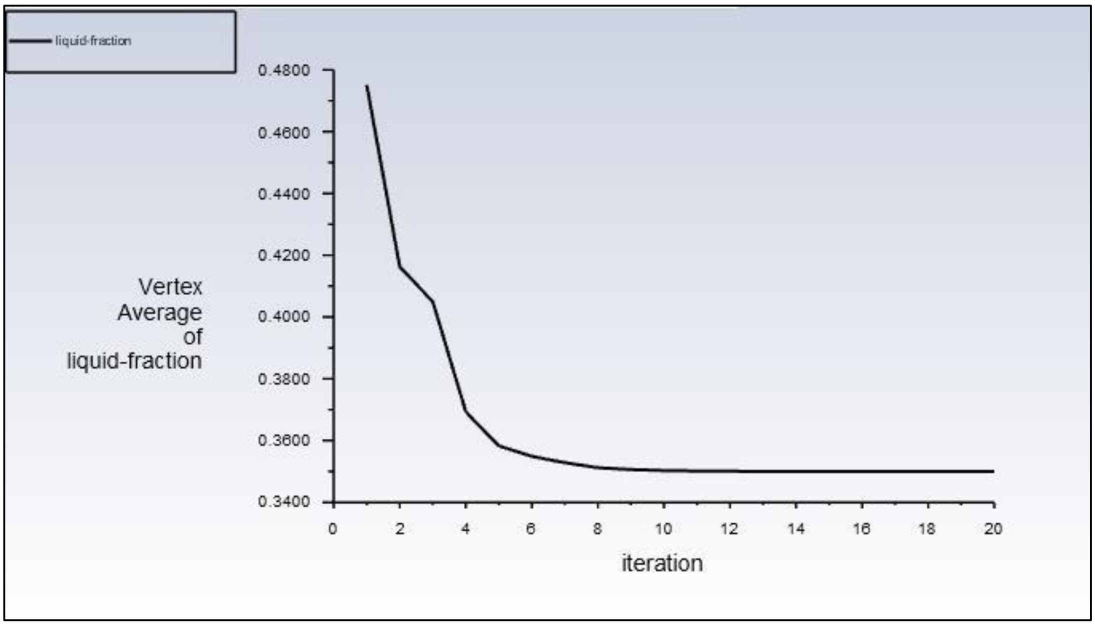


Figure III.13 Evolution curve of liquid fraction in paraffin wax at 11:00 AM

III.5.3 Interpretation

Thermal Regulation Efficiency:

1. The melting of the PCM significantly absorbs excess heat, reducing the energy reaching the rear PV layers and maintaining their temperature in a narrower operating band.
2. Layer-by-Layer Propagation:

   The melt front progresses from the interface toward the PCM's rear boundary. This behavior aligns with the direction of the heat flux and the PCM's low thermal conductivity.
3. Delayed Overheating:

   The PCM acts as a thermal buffer, delaying the temperature peak in the PV panel during high irradiance, and enhancing both performance and durability.

III.6. Impact on PV Efficiency

The electrical efficiency of photovoltaic (PV) modules, especially those made of crystalline silicon, is known to decrease with rising cell temperature. This behavior is primarily due to increased carrier recombination and reduced open-circuit voltage at higher temperatures.

III.6.1 Temperature-Efficiency Relationship

To quantify this effect, a temperature coefficient of efficiency (γ) is used, typically ranging between −0.4% and −0.5% per °C. In this study, a value of −0.45%/°C is adopted. The efficiency at any temperature T can be estimated relative to a reference efficiency η_ref of 20% at 25°C (standard test conditions).

Efficiency at temperature T is calculated using the equation:

$$\eta = \eta\_ref + \gamma \times (T\_ref - T)$$

Alternatively:

$$\Delta\eta = \gamma \times \Delta T$$

Where:

- η: Efficiency at temperature T
- η_ref: Reference efficiency = 20%
- γ: Temperature coefficient = −0.45%/°C
- ΔT: Temperature difference from reference (T_ref − T)

III.6.2 Estimated Efficiency at Peak Temperature

At 14:00, the average surface temperature of the PV module without PCM reaches 40.1°C, while the module with PCM maintains 34.0°C. Applying the formula:

Without PCM:

$$\eta = 20\% + (-0.45\%/°C \times (25 - 40.1)) = 13.2\%$$

With PCM:

$$\eta = 20\% + (-0.45\%/°C \times (25 - 34.0)) = 15.95\%$$

Efficiency gain due to PCM:

$$\Delta\eta = 15.95\% - 13.2\% = 2.75\%$$

Table III.6 PV module efficiency comparison at 14:00 with and without PCM.

Condition	Temperature (°C)	Efficiency (%)
Without PCM	**40.1**	**13.2**
With PCM	**34.0**	**15.95**

III.6.3 Daily Energy Yield Implications

Although efficiency varies throughout the day, the overall daily energy yield benefits from the cumulative temperature moderation by PCM. Based on an average surface temperature reduction of about 4.5°C, the estimated average efficiency during the day is:

Without PCM:

$\eta = 20\% + (-0.45\%/°C \times (25 - 37.5)) = 14.375\%$

With PCM:

$\eta = 20\% + (-0.45\%/°C \times (25 - 33)) = 16.4\%$

Average efficiency gain:

$\Delta\eta\_avg = 16.4\% - 14.375\% = 2.0\%$

This corresponds to a potential 2–4% increase in total daily energy production, depending on solar irradiance and module orientation.

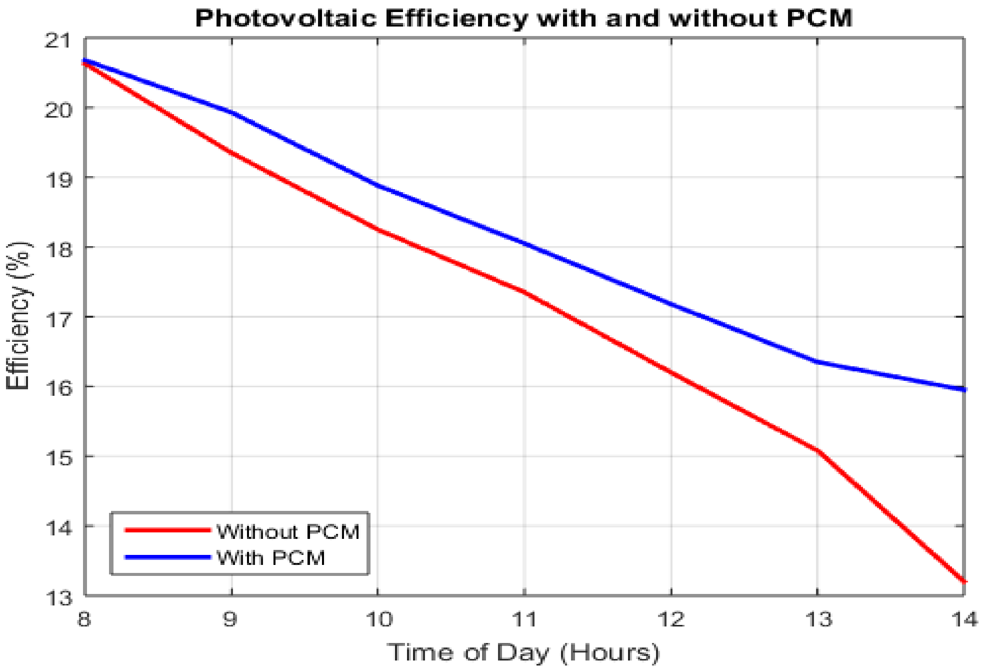


Figure III.14: Line chart of solar photovoltaic efficiency over the day

Figure III.14: presents the photovoltaic (PV) efficiency variation over the course of the day for two configurations: one with and one without phase change material (PCM) integration. As solar irradiance intensifies from morning until early afternoon, the surface temperature of the PV modules increases, leading to a progressive decline in efficiency for both cases. However, the PCM-equipped module consistently maintains higher efficiency across all recorded times.

At 08:00, ambient temperatures are relatively low, and the efficiency of both configurations is nearly identical—approximately 20.6% without PCM and 20.68% with PCM. As the day advances, the thermal divergence becomes more evident. By 14:00, the PV module without PCM drops to an efficiency of 13.2%, whereas the one with PCM retains a higher efficiency of 15.95%, reflecting a notable improvement of 2.75 percentage points due to PCM-assisted cooling.

This enhancement is attributed to the PCM's thermal buffering capability, which absorbs latent heat during melting, thereby limiting the temperature rise of the PV surface. As a result, the PV module operates closer to its optimal temperature range for a longer duration during the day. The use of PCM thus contributes to improved electrical output and enhances the thermal reliability and energy yield of the system in high-temperature environments.

III.7 Discussion

This section provides a broader interpretation of the simulation results by comparing them with existing studies and identifying the underlying trends observed throughout the numerical investigation. The objective is to position the current work within the broader context of PCM-based thermal regulation in photovoltaic systems.

III.7.1 Comparison with Literature

The results obtained in this study are in agreement with several previously published works that evaluated the thermal impact of PCM on PV performance.

Temperature reduction:

The observed temperature drop of 4–6°C aligns closely with studies such as:

- Hassabou et al. (2021): Reported a 5.5°C reduction using paraffin-based PCM on the rear of a PV panel in desert conditions.

- Kumar and Rosen (2011): Found that PCM integration can reduce peak module temperatures by up to 6°C, depending on melt temperature and PCM volume.

Efficiency improvement:

The calculated increase in electrical efficiency of 2–3% is within the typical range reported in other works:

- Sharma et al. (2009): Estimated efficiency gains between 2–4% depending on ambient temperature and solar irradiance.

These comparisons validate the simulation model used in this study and support the potential of paraffin wax (RT28HC) as an effective PCM candidate for PV cooling under hot climatic conditions.

III.7.2 Interpretation of Trends

The thermal behavior observed in the simulations highlights several important trends:
1. Time-dependent thermal regulation:

PCM cooling is most effective during periods of peak irradiance. The phase change process acts as a thermal buffer that limits the temperature rise during mid-day hours (11:00–14:00).

2. Front-to-back melting behavior:

Liquid fraction maps and temperature contours reveal that melting starts near the PV interface and propagates rearward—this indicates directional heat flow from the panel toward the PCM.

3. Stability and reliability:

The addition of PCM not only reduces thermal stress but also contributes to a more uniform temperature field, which may improve the long-term reliability of PV encapsulation materials.

III.7.3 Research Contribution

The study demonstrates the effectiveness of using a 2D transient CFD model with enthalpy–porosity PCM modeling in ANSYS Fluent. It provides:

- A realistic thermal profile of PV/PCM systems over time
- Quantitative insight into PCM melting dynamics
- Data-driven evidence of the energy efficiency improvement Thus, the work contributes both to academic understanding and practical design guidance for integrating PCM into real-world PV applications

III.8. Conclusion:

This chapter combined numerical modeling with result interpretation to assess the impact of PCM integration on the thermal and electrical performance of photovoltaic panels operating under hot climate conditions. Through a series of transient CFD simulations conducted using ANSYS Fluent, valuable insights were gained into the system's thermal behavior under realistic solar conditions in the Saharan climate.

The study demonstrated that the integration of a paraffin-based PCM (RT28HC) significantly contributes to regulating the surface temperature of the PV module, particularly during peak irradiance hours. The reduction of surface temperature by up to 6 °C, as observed at 14:00, directly translated into an estimated efficiency improvement of approximately 2.75%, thereby confirming the practical potential of PCM as a passive cooling solution.

Furthermore, the detailed thermal mapping and liquid fraction evolution revealed the internal dynamics of the PCM, including the directional melting process and the heat absorption mechanism during phase transition. These findings not only validate the numerical approach adopted in this work but also reinforce the theoretical understanding of PCM behavior in PV thermal regulation.

The comparative discussion with relevant literature confirmed the consistency of the present results with previously published data, adding academic credibility to the model and simulation methodology. Although the study was limited to a single PCM configuration and 2D modeling, the outcomes provide a reliable foundation for future optimization studies.

In conclusion, this chapter has fulfilled a key objective of the graduation project: to evaluate the thermal benefits and efficiency enhancements of using PCM in PV systems through validated, physically grounded simulation. The results form a solid basis for both academic discussion and practical implementation in renewable energy systems designed for high-temperature environments.

General Conclusion

General conclusion

This graduation project examined the use of phase change materials (PCMs) as a passive method to improve the thermal and electrical performance of photovoltaic (PV) systems in hot environments. The work included a literature review and a numerical study to evaluate how PCM can help regulate the temperature of PV panels exposed to strong solar radiation.

A two-dimensional model was developed in ANSYS Fluent to simulate the heat transfer processes in a PV module with and without PCM. The simulations showed that adding a PCM layer significantly reduces surface temperature and enhances energy efficiency during peak solar hours.

The results confirmed that PCM can act as an effective passive cooling solution. The numerical method used, especially the enthalpy–porosity approach, proved to be suitable for analyzing phase change behavior and its impact on panel temperature.

In conclusion, the study met its goal of assessing the benefits of PCM integration in PV systems. The findings offer useful guidance for future research and practical applications aimed at improving the performance of solar panels in high-temperature regions.

Based on the results obtained, the study proposes several future research directions, including:

1. 3D modeling: Expanding the model to include the third dimension for more realistic representation of PV systems, including edge effects and surrounding air interactions.

2. Exploring various PCM types and melting ranges: Studying materials with diverse properties to identify the most suitable PCM for different climates or advanced PV technologies.

3. Coupled thermal-fluid modeling: Integrating natural convection or airflow around the panel to achieve more accurate and physically consistent results.

4. Experimental validation: Conducting outdoor experiments or prototypes to strengthen the credibility of the numerical findings and uncover practical design challenges.

Addressing these future research directions would enhance the scientific and industrial value of PCM integration in solar energy systems, and contribute to the broader goal of improving energy efficiency in high-temperature environments.

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