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**Experimental investigation of optimum fin
configurations for performance enhancement of solar
air heaters**

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Praise be to Allah, Lord of the Worlds

Dedication

This humble endeavor is dedicated, above all, to my dearest parents. Next to God's grace, it is through their endless sacrifices, prayers, and boundless material and emotional support that I have reached this stage of success. They have been the light guiding my academic journey and the true inspiration that kept me moving forward through every challenge.

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El Hadj Omar

Dedication

This achievement was not born in a single moment, but is the result of years of effort, support, and unwavering belief. Today, as I reap the rewards of my hard work, I know with certainty that behind this success stand hearts that believed in me before I fully believed in myself.

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To my brothers and sisters, who shared this journey with love and encouragement and were part of every detail along the way. To my friends and everyone who stood by me with sincere words or genuine support, this achievement carries a part of you. I pray that my parents are always blessed with health and happiness, and that we are all granted success in what lies ahead.

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الملخص

أجريت هذه الدراسة التجريبية في جامعة قاصدي مرباح ورقلة (الجزائر) بهدف تحسين الأداء الحراري لسخان هواء شمسي ذي صفيحة ماصة مستوية يعمل بالحمل الحراري الطبيعي، وذلك من خلال تحسين تشكيلات الزعانف ودمج مادة متغيرة الطور . تم فحص نموذج تجريبي مائل بزاوية 33° بشكل دقيق عبر ثماني وضعيات مختلفة: صفيحة ماصة بدون زعانف، وزعانف أسطوانية، وزعانف مثلثية موجهة نحو الأسفل أو نحو الأعلى بزوايا ميل مختلفة (75° ، 60° ، 45° ، و 30°)، مع استخدام شمع البارافين كوسط لتخزين الطاقة الحرارية الكامنة أظهرت النتائج التجريبية أن استخدام الزعانف المائلة يلعب دوراً محورياً في تعزيز انتقال الحرارة من خلال إحداث اضطراب في الطبقة الحدية الحرارية وزيادة شدة الاضطراب داخل مجرى الهواء. ونتيجة لذلك، حققت الزعانف المثلثية الموجهة نحو الأسفل بزاوية ميل 30° أعلى كفاءة حرارية لحظية بلغت حوالي 65%، تلتها الوضعية ذات الميل 75° نحو الأسفل بكفاءة تقارب 60%. في المقابل، وفرت الوضعية ذات الميل 45° نحو الأسفل أفضل توازن بين الأداء والاستقرار، من خلال الحفاظ على سرعة هواء خارجة مستقرة ولمدة أطول علاوة على ذلك، أثبتت البيانات التجريبية أن دمج شمع البارافين مكن من استمرار تزويد الهواء الساخن بفارق حراري ملحوظ لعدة ساعات بعد غروب الشمس، مما يؤكد أن الجمع بين هندسة الزعانف المحسنة وتقنية تخزين الحرارة الكامنة يمثل حلاً مستداماً وعالي الكفاءة لتعزيز الأداء الحراري وإطالة فترة تشغيل سخانات الهواء الشمسية.

الكلمات المفتاحية:

سخان الهواء الشمسي، الزعانف المثلثية، المادة متغيرة الطور ، الحمل الحراري الطبيعي، الكفاءة الحرارية، ورقلة

Abstract

This experimental study was conducted at Kasdi Merbah University in Ouargla (Algeria) to enhance the thermal performance of a flat-plate solar air heater (SAH) operating under natural convection, by optimizing fin configurations and integrating a phase change material (PCM). An experimental prototype, tilted at an angle of 33° , was thoroughly investigated across eight distinct configurations: a finless absorber plate, cylindrical fins, and triangular fins oriented either downward or upward at various inclination angles (75° , 60° , 45° , and 30°), utilizing paraffin wax as a latent heat thermal energy storage medium. The experimental results indicated that the deployment of inclined fins plays a pivotal role in augmenting heat transfer by disrupting the thermal boundary layer and inducing higher turbulence intensity within the air duct; consequently, the downward-oriented triangular fins at a 30° inclination angle yielded the highest peak instantaneous thermal efficiency of approximately 65%, followed by the 75° downward configuration at around 60%, whereas the 45° downward configuration offered the optimum compromise by providing a stable and extended output air velocity. Furthermore, the empirical data demonstrated that the integration of paraffin wax effectively sustained the delivery of heated air at a significant temperature differential for several hours after sunset, thereby confirming that coupling optimized fin geometries with latent heat storage represents a sustainable and highly efficient approach to maximizing the thermal performance and extending the operating period of solar air heaters.

Keywords: Solar air heater, Triangular fins, Phase change material (PCM), Natural convection, Thermal efficiency, Ouargla.

Nomenclature

Symbol	Description	Unit
A_c	Collector area	m ²
C_p	Specific heat	J/kg.K
$\dot{m}$	Mass flow rate	kg/s
T_{in}	Inlet temperature	°C
T_{out}	Outlet temperature	°C
η	Thermal efficiency	%

Contents

Acknowledgments	i
Dedication	ii
Dedication	iii
Abstract	v
Contents	vii
List of Figures	viii
General Introduction	1
I Overview of Renewable Energy and Solar Air Heater	2
I.1 Introduction	2
I.2 Renewable Energy Sources	2
I.2.1 Solar Energy	2
I.2.2 Wind Energy	3
I.2.3 Hydropower	3
I.2.4 Biomass Energy	3
I.2.5 Wave Energy	3
I.2.6 Ocean Thermal Energy (OTEC)	3
I.2.7 Geothermal Energy	3
I.3 Solar Energy:	4
I.3.1 Definition of Solar Energy	4
I.3.2 Types of Solar Energy	4
I.3.3 Solar Resource in Algeria	5
I.3.4 Solar Potential in Algeria	6
I.4 Solar air heaters	6
I.4.1 Definition of (SAH)	6
I.4.2 Classification of Solar Air Heaters	7
I.4.3 Components of a Solar Air Heater (SAH)	11
I.4.4 Technical Advantages and Operational Challenges of Solar Air Heaters (SAHs)	12
I.4.5 Phase Change Materials (PCMs)	13
I.4.6 State of the Art	13
I.4.7 Literature Review on Solar Air Heaters (SAH)	15
General Conclusion	37

List of Figures

I.1	Renewable Energy Sources	4
I.2	Annual average of global solar irradiation received on a surface inclined at the site's latitude.	6
I.3	Schematic diagram of a typical flat plate solar air heater	7
I.4	Classifications of SAHs (Ghritlahre et al., 2019).	10
I.5	Classification of Phase Change Materials.	13
I.6	Network visualization of author keywords on "Solar air heater" developed with VOSviewer	14
I.7	Co-occurrence and links of the keyword "solar air heater". The most frequently used terms are associated with the diameter of the spots (nodes) and the font size.	15

General Introduction

General Introduction

Over the past few decades, the world has witnessed an accelerating transition toward clean, sustainable, and low-carbon energy systems. This shift is a direct response to the escalating environmental challenges posed by climate change and the continuous depletion of fossil fuel reserves. Consequently, the adoption of renewable energy has become a strategic imperative for achieving sustainable development and ensuring long-term energy security. Within this framework, solar energy occupies a prominent position owing to its abundance, widespread geographical distribution, and minimal environmental footprint compared to conventional energy sources. Solar thermal systems are considered among the most vital technologies utilized to harness solar radiation for low-to-medium-temperature thermal applications, such as space heating, agricultural drying, and various industrial processes. Among these systems, the Solar Air Heater (SAH) emerges as a highly efficient, cost-effective solution characterized by its structural simplicity, ease of fabrication, and low maintenance requirements. Furthermore, it offers significant operational flexibility and can be seamlessly integrated into diverse practical applications. The fundamental working principle of the solar air heater relies on the absorption of solar radiation by an absorber plate, which subsequently transfers the acquired thermal energy to the air flowing through the duct.

Despite the significant advancements in the design of solar air heaters (SAHs), poor convective heat transfer between the absorber plate and the air stream remains a primary bottleneck limiting the system's overall thermal efficiency. Under standard operating conditions, the thermal efficiency of conventional flat-plate solar air heaters typically ranges between 20% and 40%[1]. To address this limitation, numerous studies have proposed various geometric modifications, such as integrating fins or corrugated surfaces to expand the heat transfer area, as well as incorporating turbulators to induce a transition from laminar to turbulent flow. These modifications enhance heat transfer rates and consequently improve the system's thermal performance. However, these solutions introduce a secondary challenge: enhancing the convective heat transfer coefficient frequently results in a substantial increase in pressure drop within the air duct. This, in turn, demands higher mechanical pumping power to maintain the airflow and ensure the efficient, continuous operation of the system. Consequently, the core problem addressed by this study is evaluating the feasibility of developing a solar air heater prototype that effectively enhances heat transfer while maintaining the desired airflow velocity and minimizing pressure drop within the duct, thereby optimizing both thermal efficiency and overall system performance.

This study was conducted at the Faculty of Mathematics and Matter Sciences, Kasdi Merbah University, Ouargla, a region characterized by high solar potential (Latitude: 32.37° N, Longitude: 3.77° E). The research aims to achieve the following objectives:

- Enhance the thermal efficiency of the solar air heater by optimizing its structural design and operational performance.

- Augment the heat transfer rate between the absorber plate and the flowing air through the integration of geometrically optimized fins.
- Ensure continuous operational reliability during nocturnal hours or periods of intermittent solar radiation by incorporating a suitable thermal energy storage medium.

This study serves as a scientific reference aimed at enhancing and developing the thermal performance of solar air collectors, and it is structured into three interconnected chapters.

Chapter I comprises the theoretical framework and literature review, presenting the fundamental concepts of renewable energy with a specific focus on solar energy potential in Algeria. Additionally, it reviews solar air collector technologies and their diverse applications, alongside evaluating relevant previous studies to contextualize the current research within the broader scientific discourse. **Chapter II** details the methodology and experimental setup. It provides a comprehensive description of the utilized apparatus, the geometric modifications introduced to enhance thermal performance, the measurement instrumentation, data acquisition techniques, and the evaluation procedures established to ensure the accuracy and reliability of the results. **Chapter III** is dedicated to the presentation and discussion of the results. It involves the analysis of the gathered experimental data and assesses the impact of the engineered geometric enhancements on the thermal performance of the solar air collector, thereby demonstrating the efficacy of these modifications in improving overall system efficiency.

Chapter I

Overview of Renewable Energy and Solar Air Heater Systems

Chapter I

Overview of Renewable Energy and Solar Air Heater

I.1 Introduction

This chapter constitutes the theoretical foundation of the study by providing an integrated conceptual framework that links clean energy technologies with their thermal applications within the Algerian context. It begins by reviewing the nine primary sources of renewable energy, with a specific focus on solar energy in both its photovoltaic and thermal forms. The research then transitions to evaluating the immense solar irradiance potential of Algeria across its three distinct regions (the coastal zone, the highlands, and the Sahara). Subsequently, it delves into the core specialization by analyzing Solar Air Heater (SAH) systems in terms of their operating principles, structural components, and geometric classifications based on absorber plate designs or airflow passage configurations. Furthermore, the chapter highlights the technical trade-off between the advantages of these heaters and their thermodynamic challenges, which are primarily associated with the poor thermal properties of air and the accompanying pressure drop penalty. In this regard, phase change materials (PCMs) are presented as a promising solution for latent heat storage to overcome the intermittent nature of solar radiation. Finally, the chapter concludes with a comprehensive literature review that traces historical and recent research efforts dedicated to enhancing thermal and hydraulic performance, culminating in the deployment of artificial intelligence techniques.

I.2 Renewable Energy Sources

Renewable energy sources are defined as forms of energy derived from continuous, naturally replenishing environmental flows that do not deplete on a human timescale, provided they are utilized and managed sustainably. These sources include several primary types as illustrated in the (Figure I.1), among which are:[2]

I.2.1 Solar Energy

Solar energy is the primary source of most renewable energy forms, as it originates from the electromagnetic radiation emitted by the Sun. It is generally classified into solar thermal energy and solar photovoltaic energy.

I.2.2 Wind Energy

Wind energy arises from pressure and temperature differences in the atmosphere, primarily caused by the uneven heating of the Earth's surface by the Sun. This energy is harnessed using wind turbines that convert the kinetic energy of moving air into mechanical energy and subsequently into electrical energy.

I.2.3 Hydropower

Hydropower relies on the exploitation of the potential or kinetic energy of flowing water in rivers or water stored behind dams. This energy is converted into electricity using hydraulic turbines. It encompasses both large-scale dam-based systems and small-scale distributed hydropower installations.

I.2.4 Biomass Energy

Biomass energy is derived from organic plant or animal materials that store solar energy through the process of photosynthesis. Biomass can be converted into thermal energy, electricity, or biofuels through processes such as direct combustion, pyrolysis, fermentation, or anaerobic digestion.

I.2.5 Wave Energy

Wave energy originates from the transfer of energy from wind to the surface of seas and oceans, resulting in waves that carry mechanical energy. This energy can be converted into electricity using specialized devices designed to capture energy from water motion.

I.2.6 Ocean Thermal Energy (OTEC)

Ocean Thermal Energy Conversion (OTEC) is based on exploiting the temperature difference between warm surface waters and cold deep waters in oceans to drive a thermodynamic cycle for electricity generation. This technology requires relatively stable thermal gradients, typically found in tropical regions.

I.2.7 Geothermal Energy

Geothermal energy is derived from the heat stored within the Earth's interior, either from underground hot water reservoirs or from hot dry rocks. It can be used for electricity generation, direct heating applications, and ground-source heat pump systems.

RENEWABLE ENERGY SOURCES IN THE WORLD

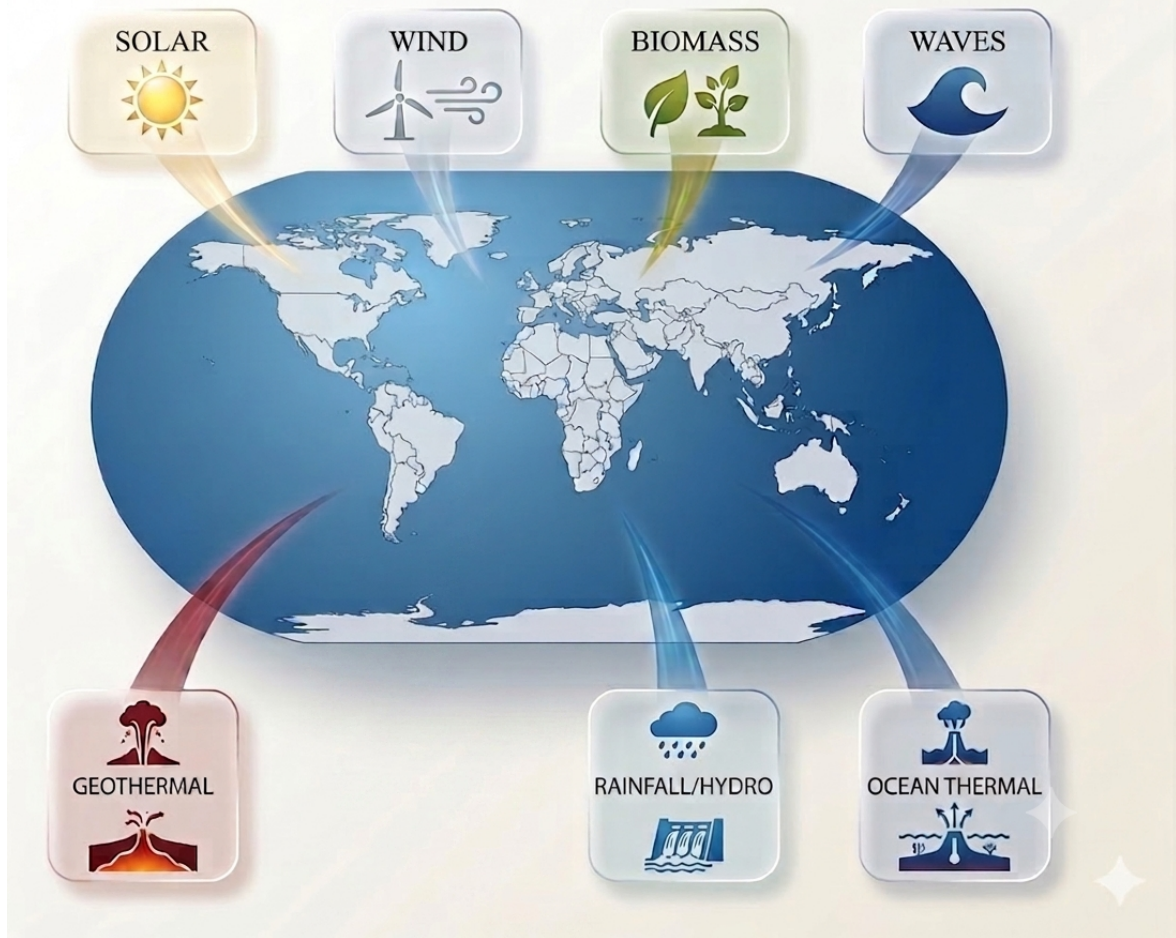


Figure I.1: Renewable Energy Sources [2]

I.3 Solar Energy:

I.3.1 Definition of Solar Energy

Solar energy is defined as the radiant energy emitted by the sun, which can be captured and converted into electrical or thermal energy using advanced conversion technologies. It is considered one of the most abundant and clean renewable energy sources globally, due to its low carbon emissions and its versatility for applications across residential, industrial, and commercial sectors. Utilization of solar energy relies on converting solar radiation into usable forms, whether for electricity generation or for producing heat for water heating, space heating, or driving industrial processes.[3]

I.3.2 Types of Solar Energy

Solar energy exploitation technologies are mainly divided into two categories: photovoltaic (PV) solar energy and solar thermal energy. Each differs in terms of conversion mechanisms and practical applications.[4]

Photovoltaic Solar Energy (PV):

Photovoltaic solar energy involves directly converting sunlight into electricity using solar cells made of semiconductor materials. This technology is widely used for electricity generation in homes, commercial facilities, and large-scale power plants. Photovoltaic systems have significantly evolved through technologies such as multi-junction solar cells and sun-tracking systems, which have improved conversion efficiency and reduced production costs.

Solar Thermal Energy (STE)

Solar thermal energy involves converting solar radiation into heat energy, which is used in various applications such as water heating, space heating, and electricity generation. This technology can be classified into:

a. Low- and Medium-Temperature Systems These include flat-plate solar collectors, commonly used for water heating and building heating in residential and commercial settings.

b. Concentrated Solar Power (CSP) Systems These are used to achieve high temperatures that enable electricity generation. Key technologies include parabolic troughs, solar towers, and dish/engine systems.

I.3.3 Solar Resource in Algeria

The solar resource is defined as the aggregate of quantitative data characterizing the temporal evolution of available solar irradiance at a specific geographic site over a predetermined period. Global solar irradiation incident on a surface tilted at an angle equal to the site's latitude and oriented southward is commonly adopted as the primary reference indicator for assessing solar energy potential. (Figure I.2) illustrates the spatial distribution of the annual average of this irradiation, thereby facilitating a comprehensive evaluation of the available solar energy potential on a large scale[5].

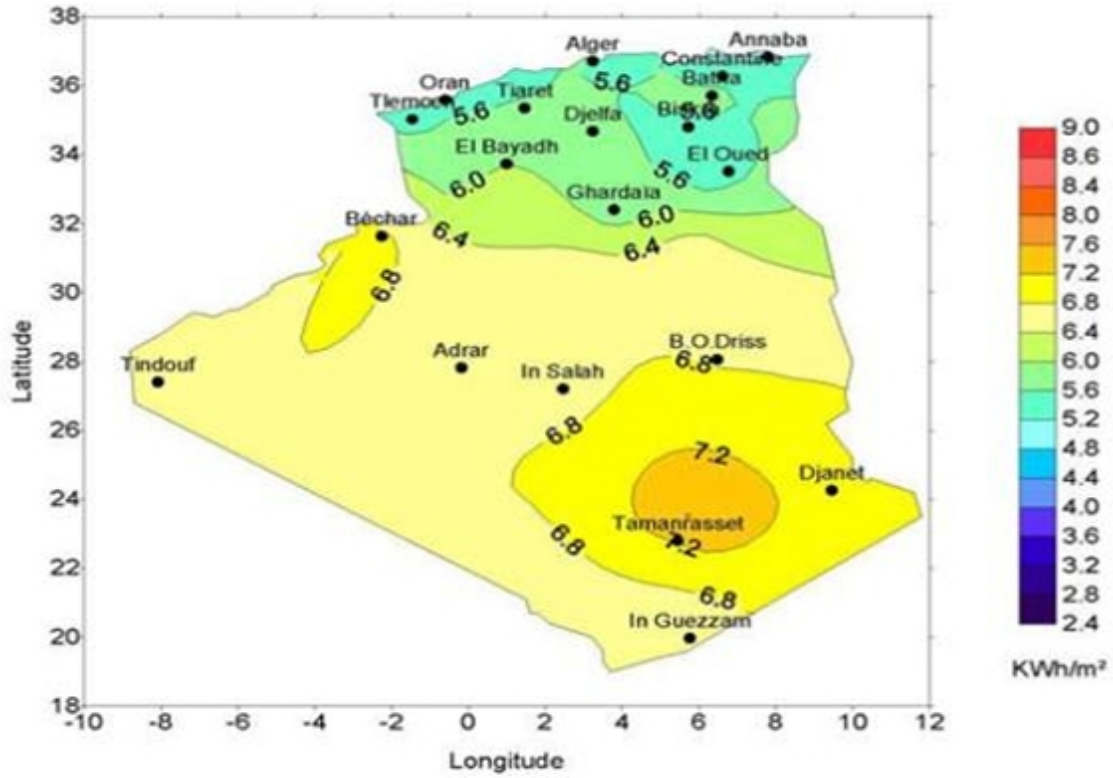


Figure I.2: Annual average of global solar irradiation received on a surface inclined at the site's latitude.[6]

I.3.4 Solar Potential in Algeria

Algeria possesses a significant energy resource. It receives annually an energy of approximately 2200 kWh/ m²/ year as an average value, considering the three regions of Algeria.

Table I.1: Solar potential in Algeria.[7]

Regions	Coastal regions	High Plateaus	Sahara
Area (%)	4	10	86
Average duration Of sunshine (Hours/year)	2650	3000	3500
Average energy received (KWh/ m ² /year)	1700	1900	2650

I.4 Solar air heaters

I.4.1 Definition of (SAH)

Solar Air Heaters (SAHs) are recognized as one of the most widely utilized solar thermal systems, functioning by converting solar radiation into thermal energy for air heating, as illustrated in the (Figure I.3). Owing to their simplistic design, robust durability, and low maintenance requirements, SAHs have become suitable for a diverse range

of applications across residential and industrial sectors. These include the preheating of process air in industrial operations, the drying of agricultural products, the space heating of residential and commercial buildings, as well as applications in ventilation and dehumidification within the food and agricultural industries[8].

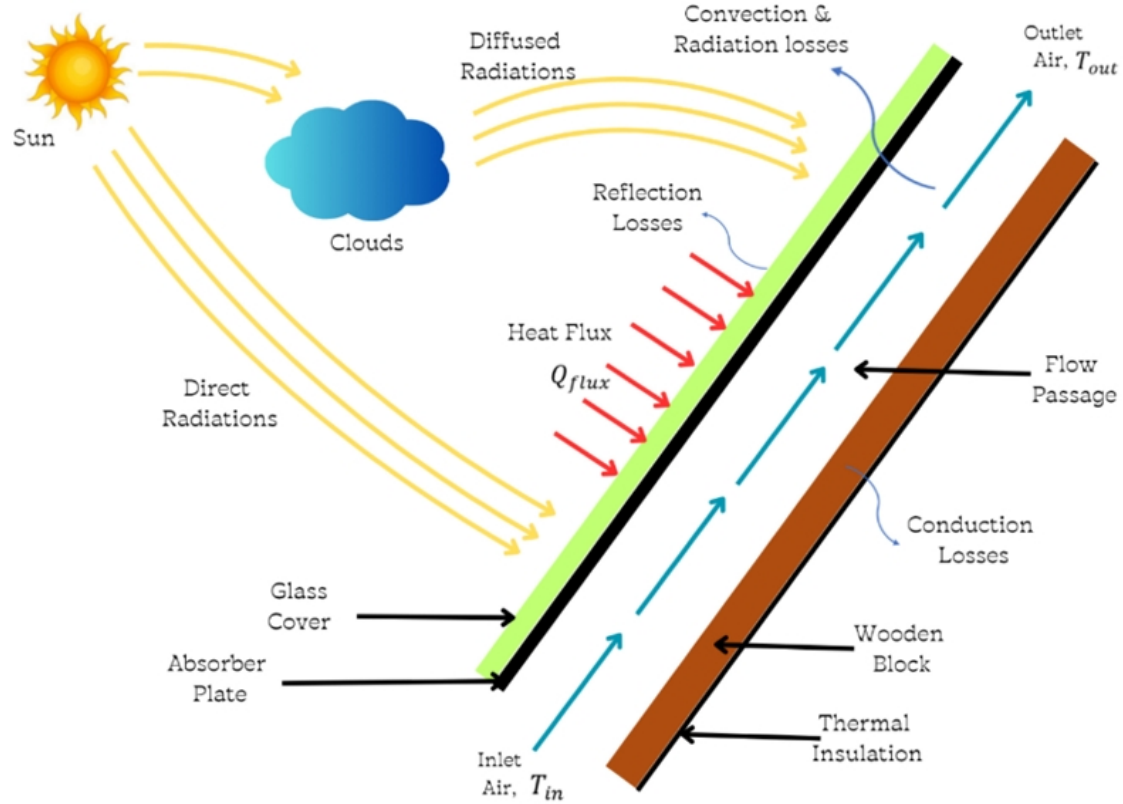


Figure I.3: Schematic diagram of a typical flat plate solar air heater[9]

I.4.2 Classification of Solar Air Heaters

Solar air heaters (*SAHs*) represent thermal systems that combine structural simplicity with high operational effectiveness. Their geometric and operational designs vary significantly depending on the targeted performance criteria, such as maximizing thermal efficiency, mitigating thermal losses, or satisfying specific application requirements. Consequently, researchers classify these collectors into several primary categories as illustrated in (Figure I.3) governed by their design configurations, flow path aerodynamics, absorber surface topographies, and functional operations.[10]

A. Classification Based on Collector Glazing Configuration

The transparent cover plays a pivotal role in trapping thermal energy and mitigating convective and radiative losses to the ambient environment. Based on this configuration, collectors are categorized into:

- **Unglazed / Bare Plate Collectors:** These systems lack a transparent cover, exposing the absorber plate directly to the ambient air. This category is predominantly utilized in very low-temperature applications where convective thermal

losses induced by ambient wind have a negligible scientific impact on overall system efficiency.

- **Single-Glazed Collectors:** A single glass or polymer cover is integrated above the absorber plate to establish a stagnant air gap. This traps long-wave radiation (the greenhouse effect) and suppresses free convective heat losses.
- **Double/Multi-Glazed Collectors:** These incorporate two or more transparent covers separated by insulating air gaps. This design is widely deployed in severe cold climates to minimize the overall heat loss coefficient (U_L) to the lowest possible threshold, despite a marginal reduction in the total transmittivity of solar radiation..

B. Classification Based on Absorber Material and Structure

The physical and thermophysical properties of the material utilized in the absorber plate dictate the heat transfer rate to the working fluid. They are classified into:

- **Metallic Absorbers:** The most engineering-dominant type, fabricated from high thermal conductivity (k) metals such as copper and aluminum. These are typically coated with selective layers to optimize absorptivity while minimizing emissivity.
- **Non-Metallic Absorbers:** These encompass advanced polymeric or composite materials, offering high economic feasibility, lightweight characteristics, and excellent resistance to corrosion and chemicals, despite their lower thermal conductivity compared to metals.
- **Matrix / Porous Absorbers:** Composed of mesh structures or packed porous beds through which the fluid permeates. This structural design significantly enhances the total volumetric heat transfer area and improves the volumetric efficiency of the collector.

C. Classification Based on the Geometry of the Absorbing Surface

Modifying the topology and geometry of the absorber surface is the most prominent hydrodynamic technique used to induce boundary layer turbulence. This breaks up the laminar flow regime and augments the convective heat transfer coefficient (h_c). Notable configurations include:

- **Slat-Type Surfaces:** Composed of segmented or staggered slats arranged to guide the airflow through tortuous paths, thereby continuously disrupting and reforming the thermal boundary layer.
- **Porous Media Absorbers:** The fluid passes through a metallic sponge or matrix, ensuring intimate and direct thermal contact between the air molecules and the heated internal matrix microstructures.
- **Finned and Obstacle-Augmented Absorbers:** These feature integrated extended surfaces (longitudinal, split, or distinct geometries such as triangular or cylindrical fins) or artificial roughness/vortex generators. These modifications significantly increase the heat transfer surface area and promote local flow turbulence, thereby substantially elevating the collector's thermal performance.

D. Classification Based on Absorber Flow Pattern

The geometric routing of the fluid relative to the absorber plate varies considerably, directly influencing the magnitude of top thermal losses through the glazing:

- **Over-Flow Collectors:** The air flows exclusively through the channel bounded by the transparent cover and the upper surface of the absorber plate. This pattern exhibits higher top thermal losses due to the direct contact of the heated air with the glazing.
- **Under-Flow Collectors:** The fluid flows through the lower duct beneath the absorber plate, while the gap between the glazing and the absorber remains stagnant. This regime effectively suppresses top convective heat losses.
- **Double-Sided Flow Collectors:** The airflow splits to pass through both upper and lower channels simultaneously. This doubles the effective heat transfer surface area extracted from the absorber plate and lowers the absorber surface temperature, consequently decreasing radiative losses.

E. Classification Based on the Number of Flow Passes

This classification relates to the residence time of the fluid inside the collector and the frequency of its interaction with the heated surfaces:

- **Single-Pass Collectors:** The air enters from one end of the collector, traverses the flow channel a single time, and exits directly from the opposing end with a defined thermal gain.
- **Double-Flow Collectors:** These feature parallel channels where the air flows simultaneously and independently (parallel feeding) to accommodate higher mass flow rates.
- **Double-Pass Collectors:** The fluid is directed to flow through one channel (e.g., the upper duct), and upon reaching the collector boundary, its flow path is inverted by 180° to return through the adjacent channel (e.g., the lower duct). This prolongs the residence time and elevates the temperature differential (ΔT).
- **Multi / Triple-Pass Collectors:** Advanced geometric designs where the air sequentially traverses three separate pathways. This yields the highest possible thermal gradient and highly effective heat removal factors, albeit at the expense of a higher pressure drop (ΔP) that demands greater fan/pumping power.

F. Hybrid Systems and Multi-Fluid Collectors

These systems transcend the conventional paradigm of single-medium heat transfer, aiming to maximize the total exploitation of incident solar radiation and achieve co-generation:

- **Air-Based Collectors:** Rely on air as the sole heat transfer fluid.
- **Water-Based Collectors:** Conventional solar thermal collectors utilizing water as the thermodynamic working fluid.

- **Water–Air Hybrid Collectors:** Advanced configurations featuring independent, concurrent channels for both water and air within a single collector structure, offering high operational flexibility to meet diverse thermal loads simultaneously.
- **Photovoltaic Thermal Hybrid (PV/T) Systems:** Integrate photovoltaic cells with a thermal air or water cooling mechanism. This ensures a reduction in PV cell operating temperatures to maintain higher electrical efficiency, while concurrently harvesting the resulting waste heat as useful hot air.

G.Functional Classification Based on Operational Applications

The design constraints of the collector and its internal geometry are governed by the thermodynamic requirements of the target application, including:

- **Drying Applications (Crops and Agricultural Products):** Require stable airflow rates and strictly regulated, moderate temperatures to prevent the thermal degradation of vital biomass materials (e.g., indirect solar food drying).
- **Industrial Preheating Processes:** The collector is utilized to heat ambient air as a preliminary stage before introducing it into boilers or large-scale industrial furnaces, thereby yielding substantial fossil fuel savings.
- **Space Heating (Architectural Environments):** Winter air conditioning applications for residential or industrial buildings, where indoor air is recirculated through the solar collector to increase its internal energy.
- **Cooling Applications:** The generated hot air is utilized as a thermal energy source to drive absorption chillers or desiccant cooling systems.

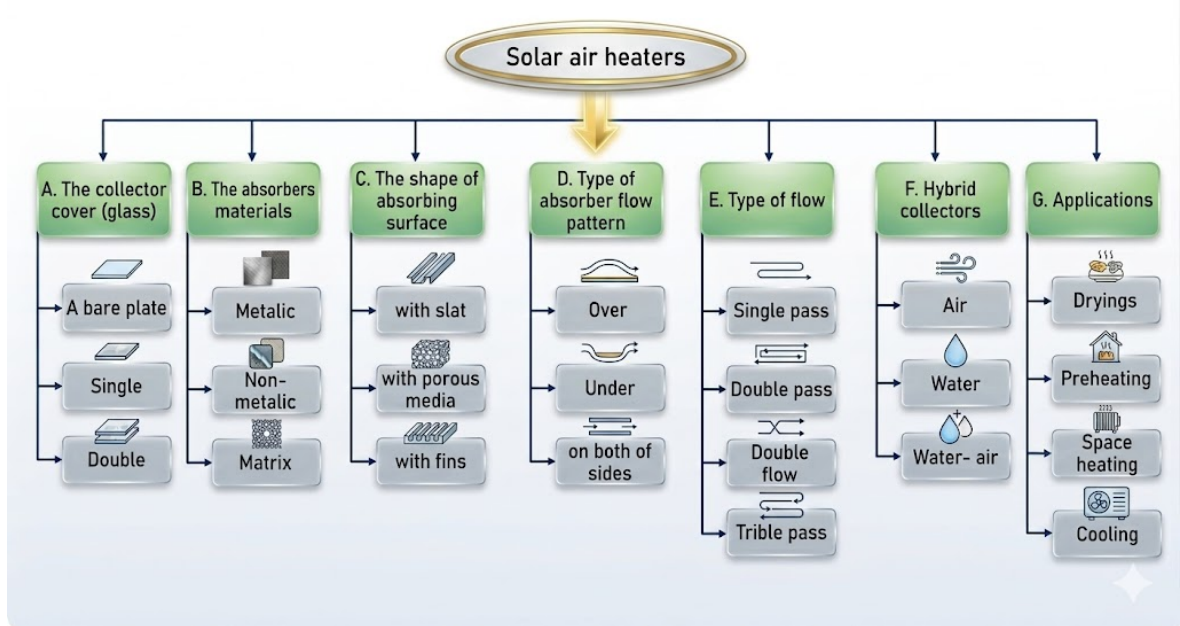


Figure I.4: Classifications of SAHs (Ghritlahre et al., 2019).[10]

I.4.3 Components of a Solar Air Heater (SAH)

A solar air heater primarily consists of the following elements, arranged from the exterior to the interior[11]:

Heat Transfer Fluid (Air)

In this type of collector, atmospheric air serves as the medium responsible for transporting thermal energy.

- **Characteristics:**Air is characterized by low density and low specific heat capacity, necessitating a large contact surface area and optimized flow velocities to ensure efficient heat exchange.

Absorber Plate

The absorber is the fundamental component responsible for converting radiative energy into thermal energy; it is considered the "heart" of the device.

- **Academic Design:**In solar air heaters, the absorber is often equipped with fins (ailettes) or designed with a corrugated profile to increase flow turbulence and enhance the heat transfer surface area between the plate and the air.
- **Coating:**The absorber is treated with a selective surface specifically engineered to exhibit maximal solar absorptivity while maintaining minimal thermal emissivity, thereby optimizing heat retention and reducing radiative losses.

Flow Channel (Air Duct)

The physical space through which air flows to extract heat from the absorber.

- **Configurations:**Depending on the engineering design aimed at maximizing thermal efficiency, the flow can be categorized as over-absorber, under-absorber, or double-pass (flowing on both sides).

Thermal Insulation

Material placed at the base and sides of the collector to minimize thermal leakage to the surroundings.

- **Material:**Utilizes materials with extremely low thermal conductivity, such as rock wool or polyurethane foam.

Enclosure (Casing/Frame)

A rigid structural frame that integrates all components and protects them from environmental factors (moisture, wind). It ensures a hermetic seal to prevent air leakage, which can significantly degrade performance.

I.4.4 Technical Advantages and Operational Challenges of Solar Air Heaters (SAHs)

Solar Air Heaters (SAHs) represent a promising solution within renewable energy frameworks. They possess distinct technical and economic characteristics that define their thermal performance and application scope, as categorized below:

Advantages and Positive Attributes

SAHs offer several competitive advantages that enhance their viability as sustainable heating systems[12]:

- **Economic Feasibility:**These systems are characterized by lower capital and operational costs compared to solar water heaters, primarily due to the absence of high-pressure piping and the need for anti-freeze agents.
- **Design Simplicity and Maintenance:**SAHs feature streamlined engineering designs that facilitate ease of fabrication, installation, and maintenance. Furthermore, they are inherently resistant to issues such as corrosion or leakage, which are prevalent in liquid-based heat transfer systems.
- **Application Versatility:**They demonstrate high efficacy in agricultural crop drying, space heating for buildings, and industrial processes requiring pre-heated air, such as the textile and paper industries.
- **Environmental Sustainability:**By significantly reducing reliance on fossil fuels and eliminating carbon emissions during operation, these systems align with global sustainable development goals.
- **Performance Optimization:**Recent technological advancements specifically the integration of artificial roughness and extended surfaces (fins) have succeeded in disrupting the thermal boundary layer, thereby substantially enhancing heat transfer rates and overall thermal efficiency.

Technical Challenges and Constraints

Despite their advantages, SAHs face fundamental thermodynamic challenges that impact their operational [13]:

- **Inferior Thermophysical Properties of Air:**The low thermal conductivity and low specific heat capacity of air pose significant hurdles, resulting in poor heat transfer coefficients between the absorber plate and the working fluid.
- **Pressure Drop:**The implementation of performance enhancers (such as baffles or fins) induces high turbulence, which consequently leads to a significant pressure drop. This necessitates higher fan power consumption, potentially offsetting the net energy gains.
- **Thermal Losses:**SAHs are prone to substantial heat dissipation through the glazing and side walls via convection and radiation, particularly in cold climatic conditions.

- **Intermittency and Instability:** System performance is strictly dependent on instantaneous solar irradiance, rendering it ineffective during nocturnal hours or overcast conditions unless integrated with Thermal Energy Storage (TES) systems using Phase Change Materials (PCMs).
- **Low Exergy Efficiency:** Research indicates high rates of exergy destruction within these systems due to significant temperature gradients and inherent irreversibilities in the heat transfer process.

I.4.5 Phase Change Materials (PCMs)

Phase Change Materials (PCMs) serve as pivotal elements in thermal energy storage technology, utilizing the storage and release of latent heat during the melting and solidification processes while maintaining a nearly constant temperature. This characteristic grants them high energy storage density and exceptional thermal management capabilities in solar energy applications, buildings, and greenhouses. These materials are distinguished by their vast diversity and operational flexibility across a wide range of temperatures. Technically, PCMs are categorized into three primary groups: organic compounds (such as paraffin waxes, which are cost-effective despite their low thermal conductivity), inorganic compounds (such as hydrated salts, which offer higher storage density and conductivity but face challenges like supercooling and phase segregation), and eutectics. A detailed classification of these groups, tailored to the thermal requirements of specific applications, is illustrated in (Figure I.3)[14].

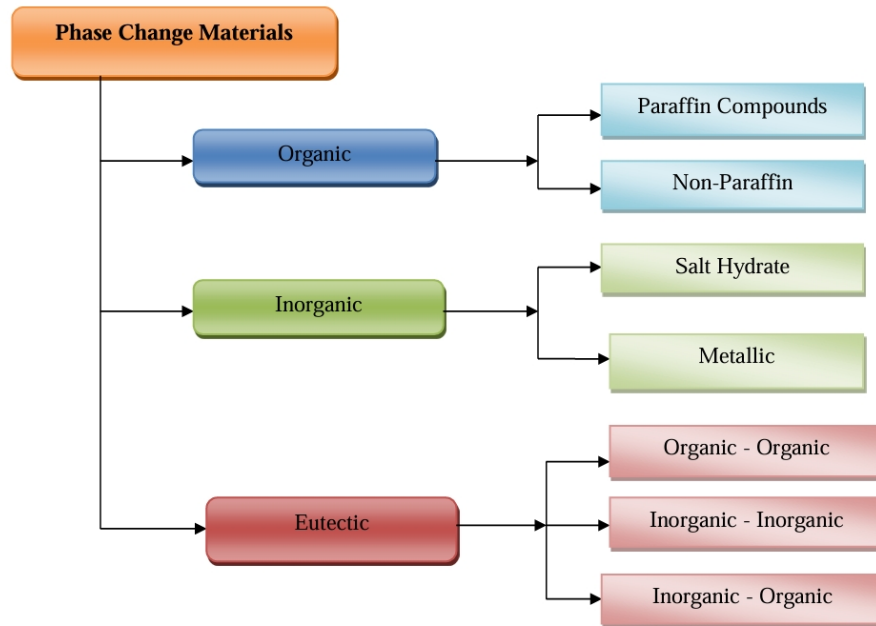


Figure I.5: Classification of Phase Change Materials.[14]

I.4.6 State of the Art

The performance parameters of a Solar Air Heater (SAH) vary considerably with the uniformity of velocity and temperature distributions within the solar collector. Therefore,

optimizing the operating conditions and design of SAHs is of great importance for enhancing heat transfer performance. Furthermore, one of the most challenging aspects in the study of a new Solar Air Heater design, or even in the refurbishment of an existing SAH system, is achieving a configuration that ensures a uniform distribution of heat and airflow. Consequently, parametric investigations generally require a large number of experiments to identify the optimal design. However, such experimental studies are time-consuming and economically inefficient.

To facilitate the identification of research gaps in the literature, a visualization of scientific publications related to Solar Air Heaters was carried out. The authors of this thesis conducted an extensive bibliometric analysis based on 978 documents, including original research articles, review papers, book chapters, and conference proceedings. These documents were collected by searching the term “solar air heater” in the Scopus database, with the latest access on April 20, 2026. One of the major advantages of this type of analysis is its ability to identify the most relevant methodologies employed by researchers within a specific [15].

In this bibliometric study, data analysis was performed using the open-source software VOSviewer (Version 1.6.16) (see Figure I.6). This software enables the generation and visualization of bibliometric networks representing relationships among various elements of scientific publications. In the present analysis, the relationships between elements were expressed in terms of co-occurrence links[16].

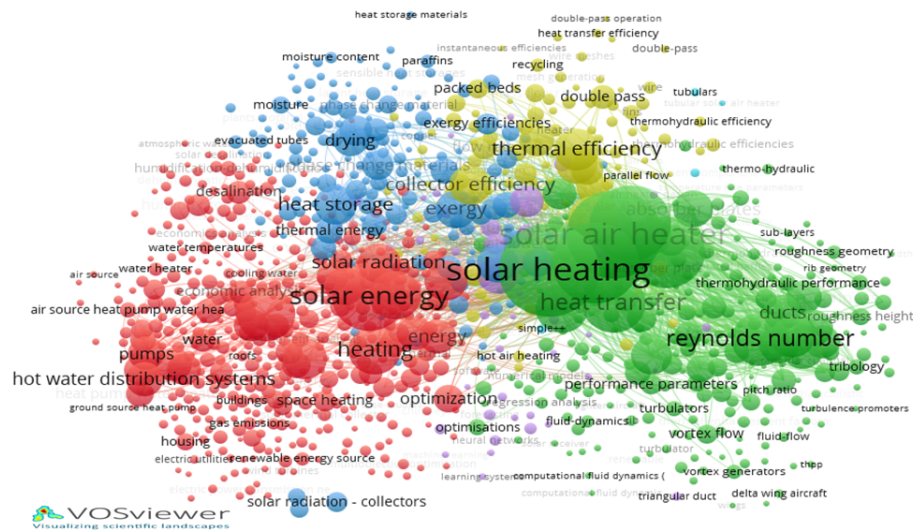
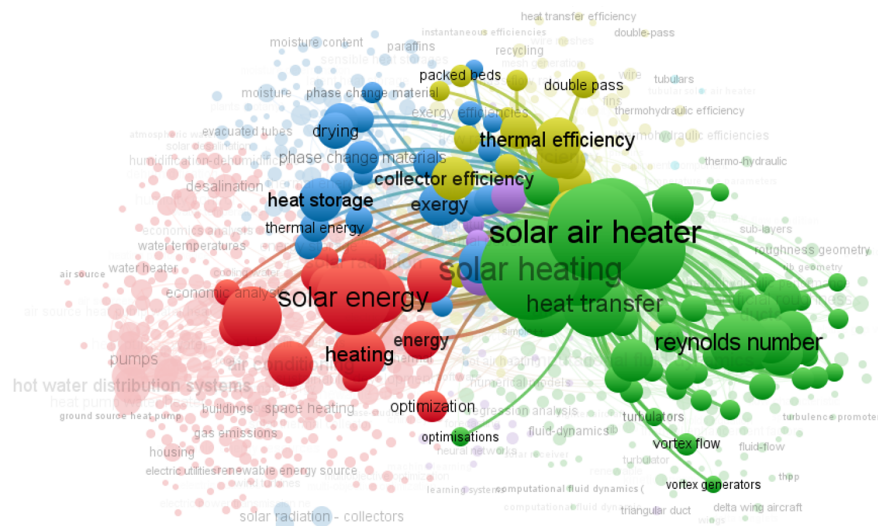


Figure I.6: Network visualization of author keywords on "Solar air heater" developed with VOSviewer[16]

As shown in Figure I.7, keywords are displayed in a network visualization where each keyword is represented by a colored node. The size of each node is proportional to its weight, expressed either by the number of occurrences or by the strength of the link. Consequently, the most frequently used terms appear in larger and bolder fonts and are represented by larger nodes (e.g., solar air heaters), whereas less frequently used terms appear as smaller nodes (e.g., solar energy). The colors correspond to the clusters to which the different elements belong, while the distance between two nodes is proportional to the degree of relationship between the corresponding keywords. Analysis of the obtained results revealed the presence of five major clusters[16]

- **Cluster 1:** Solar air heaters, heat transfer, and efficiency.
- **Cluster 2:** Heat transfer, heat exchange, thermal performance, heat and mass transfer, and thermal conductivity.
- **Cluster 3:** Phase change, temperature distribution, thermal performance, and exergy.
- **Cluster 4:** Forced convection, natural convection, turbulent flow, and Reynolds number.
- **Cluster 5:** Numerical simulation, computational fluid dynamics (CFD), optimization, and solar energy applications as shown in Figure I.7.



I.4.7 Literature Review on Solar Air Heaters (SAH)

successfully extended the duration of thermal utility beyond sunset by integrating spherical capsules containing latent heat storage materials. From an analytical and modeling perspective, numerical analyses by Gupta and Kaushik (2009) revealed the superiority of absorber surfaces with artificial roughness over smooth plates[19]. Additionally, Velmurugan and Kalaivanan (2015) concluded that multi-pass collectors provide higher efficiency due to the increased residence time of air within the system. More recently, the deployment of artificial intelligence (AI) has emerged as a robust tool for prediction and optimization, as evidenced by the study of Ghritlahre and Prasad (2017), which utilized Artificial Neural Networks (ANN)[20].

Chapter II

Experimental setup

Chapter III

Results and Discussions

General Conclusion

General Conclusion

This experimental investigation focused on enhancing the thermal performance of solar air heaters (SAHs) through the optimization of fin configurations and the integration of phase change materials (PCMs). Conducted in Ouargla, Algeria a region characterized by high solar energy potential the study evaluated eight experimental configurations to compare the effects of various fin orientations and geometries. The primary findings of this research are summarized as follows:

1. **Baseline Performance:** The conventional flat-plate solar air heater (without modifications) exhibited limited thermal efficiency, ranging between 17% and 50%, which is attributed to weak convective heat transfer between the absorber plate and the airflow.
2. **Impact of Fins and PCM Integration:** The incorporation of cylindrical and triangular fins, combined with the integration of paraffin wax as a thermal energy storage medium, led to a substantial improvement in heat transfer rates. This synergetic approach significantly increased the outlet air temperatures and extended the operating duration after sunset through the latent heat release mechanism.
3. **Optimal Fin Configuration:** Among the six fin configurations tested, the downward-oriented triangular fins at a 30° inclination angle achieved the highest thermal efficiency, peaking at approximately 65%. Meanwhile, the 45° downward configuration provided the most stable and sustained aerodynamic performance, maintaining an outlet air velocity of around 1.5 m/s during peak hours (10:30–16:30). The 75° downward configuration recorded the maximum instantaneous outlet velocity, reaching 2.0 m/s.
4. **Thermal Stability:** The integration of the PCM effectively mitigated temperature fluctuations during periods of declining solar irradiance. This ensured operational continuity and a sustained supply of heated air until 20:00, thereby addressing the inherent intermittency challenge of solar thermal systems.
5. **Comparative Efficiency Ranking:** The downward-oriented fin configurations consistently outperformed the upward-oriented ones. The 30° downward model achieved the highest overall efficiency, followed sequentially by the 75° downward and 45° downward configurations.

This study demonstrates that the synergetic combination of optimally oriented fins and phase change materials constitutes a viable and highly effective strategy for significantly improving the thermal efficiency and operational reliability of solar air heaters. These findings provide valuable design guidelines for engineers and researchers aiming to

develop high-performance, cost-effective solar air heating systems suitable for applications such as space heating, agricultural drying, and industrial pre-heating processes. Future work may explore alternative fin geometries, different types of PCMs, and the application of artificial intelligence (AI) techniques for performance prediction and optimization.

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