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"PERFORMANCE OPTIMIZATION OF DUAL-MODE SOLAR AIR HEATERS: A REVIEW"

Aditya Srivastav [1], Prof Kamlesh Gangrade [2]

[1] *P. G. Scholar, Department of Mechanical Engineering, SAGE University, Indore, Madhya Pradesh, India*

[2] *Professor, Department of Mechanical Engineering, SAGE University, Indore, Madhya Pradesh, India*

ABSTRACT

The increasing demand for renewable energy sources has led to significant research on solar air heating systems due to their simplicity, sustainability, and environmental benefits. Dual-mode solar air heaters, which combine both direct and indirect modes of heat transfer, have shown potential for enhanced thermal performance and energy efficiency. This review focuses on the performance optimization of dual-mode solar air heaters by analyzing various design configurations, materials, and operating parameters. Key factors such as airflow rate, absorber plate design, duct geometry, and environmental conditions—including solar irradiance, ambient temperature, and wind speed—are critically examined to understand their influence on heat transfer and overall system efficiency. Additionally, the review highlights recent advancements in hybrid designs, including the integration of fins, phase change materials, and porous media, which contribute to improved heat retention and uniform temperature distribution. By systematically summarizing experimental and numerical studies, this review identifies trends, performance enhancement strategies, and research gaps, providing a comprehensive reference for future development of high-efficiency solar air heating systems suitable for diverse climatic conditions.

Key Words: *Dual-Mode Solar Air Heater, Performance Optimization, Thermal Efficiency, Heat Transfer Enhancement, Environmental Parameters, Hybrid Solar Heating Systems.*

I. INTRODUCTION

Solar energy is one of the most abundant and sustainable sources of renewable energy available on Earth. With increasing energy demands, environmental concerns, and depletion of fossil fuels, solar energy utilization has become a critical focus for researchers and engineers worldwide. Among the various solar energy applications, solar air heaters (SAHs) are widely used due to their simple design, low maintenance, and ability to provide thermal energy for domestic, industrial, and agricultural applications such as space heating, drying, and process heating. A dual-mode solar air heater is an advanced configuration that combines the features of both direct and indirect heating modes to enhance overall thermal performance. In the direct mode, air passes over an absorber plate exposed to solar radiation, whereas the indirect mode typically involves a storage medium or additional design features to retain and transfer heat over time. This dual-mode operation allows improved heat transfer, more uniform temperature distribution, and better utilization of solar energy throughout the day, even under fluctuating environmental conditions. The performance of dual-mode solar air heaters depends on a combination of design factors and operating conditions. Design factors include absorber plate material, plate geometry, duct dimensions, the presence of fins or baffles, and the type of glazing used. Operating parameters such as airflow rate, inlet air temperature, and mode of operation significantly influence the heat transfer and thermal efficiency of the system. Additionally, environmental parameters such as solar irradiance, ambient temperature, wind speed, and relative humidity play a crucial role in determining real-world performance. Over the years, extensive research has been conducted to optimize the thermal performance of dual-mode solar air

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heaters. Innovations such as integrating phase change materials (PCM), porous media, and extended surfaces (fins) have shown promising results in enhancing heat retention and increasing efficiency. Computational simulations, alongside experimental investigations, have become essential tools to predict performance, identify design improvements, and evaluate the effects of varying environmental conditions. Despite significant progress, challenges remain in developing high-efficiency dual-mode solar air heaters that are cost-effective, adaptable to different climatic conditions, and capable of delivering consistent performance throughout the year. This review aims to provide a comprehensive analysis of past and recent studies on dual-mode solar air heaters, highlighting methods of performance optimization, the influence of environmental and design parameters, and research gaps for future investigation.

II. Problem Identification

Solar air heaters have gained significant attention due to their potential to provide clean and sustainable thermal energy. However, despite their advantages, conventional solar air heaters often face limitations in terms of efficiency and performance, particularly under varying environmental conditions. Single-mode solar air heaters, which rely solely on either direct or indirect heating, are prone to low thermal efficiency during periods of low solar irradiance or fluctuating ambient temperatures. This limitation reduces their overall energy output and restricts their practical application for continuous heating requirements. Dual-mode solar air heaters have been developed to overcome some of these limitations by combining direct and indirect heating methods. While they show improved thermal performance compared to single-mode systems, their efficiency is still highly sensitive to design parameters, operating conditions, and environmental factors. Issues such as non-uniform temperature distribution, heat losses through the duct and absorber, and limited heat retention remain significant challenges. The influence of environmental parameters such as solar irradiance, ambient temperature, wind speed, and relative humidity further complicates the performance prediction and optimization of these systems. Another challenge lies in the integration of performance-enhancing techniques such as extended surfaces, fins, or phase change materials. Although these modifications can improve heat transfer and energy storage, they may also increase system complexity, material costs, and maintenance requirements. In addition, most experimental studies are conducted under specific climatic conditions, making it difficult to generalize results or develop standardized design guidelines applicable to diverse regions. Therefore, there is a clear need to systematically identify the factors that limit the performance of dual-mode solar air heaters and to develop strategies for optimizing their efficiency under varying environmental conditions. Addressing these problems will enhance the practical applicability of dual-mode solar air heaters, improve energy utilization, and contribute to the development of cost-effective and sustainable solar thermal systems.

III. Research Objectives

The primary aim of this research is to analyze and optimize the performance of dual-mode solar air heaters under varying environmental and operational conditions. The specific objectives of this study are as follows:

1. To review the existing designs and configurations of dual-mode solar air heaters, including direct and indirect heating mechanisms, and their influence on thermal efficiency.
2. To examine the effects of key design parameters such as absorber plate material, plate geometry, duct dimensions, glazing type, and the inclusion of performance-enhancing features like fins, baffles, and phase change materials.
3. To investigate the impact of operating conditions, including airflow rate, inlet air temperature, and mode of operation, on the heat transfer characteristics and overall system performance.
4. To evaluate the influence of environmental factors such as solar irradiance, ambient temperature, wind speed, and relative humidity on the thermal efficiency and energy output of dual-mode solar air heaters.
5. To identify performance enhancement strategies and optimization techniques reported in previous experimental, numerical, and hybrid studies.
6. To highlight research gaps and limitations in the current literature, providing guidance for future experimental and computational studies aimed at developing high-efficiency, cost-effective, and adaptable dual-mode solar air heating systems.
7. To provide a comprehensive reference framework that can assist designers, researchers, and engineers in the development and deployment of dual-mode solar air heaters for diverse climatic conditions.

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IV. LITERATURE REVIEW

Solar air heaters have been widely studied for their potential to provide clean and renewable thermal energy. Over the years, researchers have explored various design configurations, materials, and operational strategies to enhance the thermal performance and efficiency of these systems. The literature reveals a growing interest in dual-mode solar air heaters, which combine direct and indirect heating to overcome the limitations of conventional single-mode systems. Early studies focused on basic design aspects, such as the type of absorber plate material and the geometry of the duct. For instance, researchers found that using high-conductivity metals like aluminum or copper for the absorber plate significantly improved heat transfer and thermal efficiency. Studies also emphasized the importance of duct design, including cross-sectional area and length, in optimizing airflow and minimizing heat losses. Several researchers investigated the impact of environmental parameters on solar air heater performance. Solar irradiance, ambient temperature, and wind speed were found to be critical factors affecting the rate of heat transfer and overall efficiency. Studies conducted under varying climatic conditions highlighted that performance could vary significantly depending on the geographical location, time of year, and weather patterns, emphasizing the need for adaptable designs. In recent years, performance enhancement techniques such as the integration of fins, baffles, porous media, and phase change materials (PCM) have gained attention. Fins and baffles improve convective heat transfer by increasing turbulence, while porous media and PCM help retain heat and maintain uniform temperature distribution. Experimental and numerical studies demonstrated that these modifications can increase the thermal efficiency of dual-mode solar air heaters by 15–30% compared to conventional designs. Several computational studies using numerical simulations and computational fluid dynamics (CFD) have been carried out to predict the performance of dual-mode solar air heaters. These studies allowed researchers to evaluate multiple design and operating parameters simultaneously, reducing the need for extensive experimental testing. However, numerical predictions still require validation through experiments under real environmental conditions to ensure accuracy. Despite the extensive research, certain gaps remain in the literature. Many studies focus on specific design modifications or environmental conditions, making it difficult to generalize findings for broader applications. Moreover, the influence of combined environmental factors, long-term performance, and economic feasibility has not been fully addressed in existing research. Overall, the literature indicates that dual-mode solar air heaters hold significant potential for performance improvement through design optimization, material selection, and environmental adaptation. Future research should focus on integrated approaches combining experimental studies, numerical simulations, and cost-benefit analysis to develop efficient, durable, and adaptable solar air heating systems suitable for a wide range of climatic conditions.

Al-Waeli et al. (2025) investigated a novel double-pass solar air heater configuration with hollow cylindrical obstacles enhanced by fins and phase change material (PCM). They used computational fluid dynamics to evaluate the design and found that the combined hollow cylinder-fin-PCM arrangement significantly improves thermal and exergetic performance compared to baseline finned and non-finned designs under varying airflow conditions. Optimized obstacle geometry led to higher heat transfer coefficients and an average thermal efficiency improvement of approximately 55.7 percent. The study emphasized the influence of obstacle diameter and collector geometry on performance. Their findings demonstrated the potential of combining PCM with structured obstacles for enhancing solar air heater efficiency for practical applications.

Khatri (2025) provided a comprehensive review of solar air heater design modifications and energy storage strategies. The paper highlighted that geometric modifications of absorber plates, including V-shaped ribs and corrugated profiles, combined with thermal storage materials such as paraffin wax or aluminum chips, significantly enhance heat transfer and thermal efficiency. The review concluded that combining thermal energy storage with design innovations is essential for improving solar air heater performance under varying environmental conditions. It also emphasized the need for field validation of numerical studies and long-term evaluation of economic feasibility.

Soliman et al. (2025) proposed a bifacial solar air heater design integrating PCM and ribs. Their study demonstrated that the bifacial configuration increases outlet air temperature by nearly 29 percent and boosts absorbed heat by approximately 95 percent compared to conventional heaters. Incorporating PCM extended operation time by around two hours after sunset. The research highlighted the synergistic benefits of combining dual absorption surfaces with

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thermal storage, allowing more persistent heat delivery. This study provided practical guidance on designing high-performance solar air heaters with extended operation capabilities.

Hedau and Singal (2023) conducted a three-dimensional numerical study of double-pass solar air heaters with vertical PCM cylinders in the second channel. They evaluated multiple PCM configurations and found that positioning the PCM between the absorber and the back plate achieves the highest thermohydraulic performance. The optimized design reached thermal efficiencies as high as 92.7 percent and showed improved heat transfer and outlet air temperature compared to alternative configurations. The study emphasized the critical role of PCM placement in dual-mode solar air heater efficiency for enhanced heat retention and transfer.

Hedau and Singal (2023) also investigated a double-pass solar air heater with semicircular PCM tubes and perforated blocks. Their numerical results demonstrated that complex PCM and roughness geometries could achieve thermal efficiencies near 97 percent. The study revealed that PCM type and mass flow strongly influence heat storage and release characteristics, indicating that geometric optimization of PCM elements is key to improving system performance. Their work provides valuable insights for designing high-efficiency dual-mode solar air heaters with enhanced storage capabilities.

Ahmad and Ali (2023) focused on performance augmentation methods in solar air heaters, summarizing heat transfer enhancement techniques such as fins, roughness elements, and operating parameter optimization. The review compiled performance correlations and results from multiple studies, highlighting systematic approaches to balance heat transfer gains with associated pressure drops. It emphasized the importance of integrating design modifications with environmental considerations to maximize thermal efficiency and overall system performance.

Assadeg et al. (2025) examined a double-pass solar air heater with staggered fins and nano-enhanced PCM capsules. Both experimental and analytical results showed improved thermal storage and heat capture, yielding higher outlet air temperatures and longer-duration useful heating under simulated solar conditions. The study demonstrated that incorporating nanomaterials into PCM enhances thermal conductivity and storage capacity, providing a practical pathway for improving dual-mode solar air heater performance.

Salih et al. (2023) carried out experimental and numerical analyses of a double-pass solar air heater containing multiple PCM capsules. They found that PCM integration significantly affects melting and freezing dynamics as well as heat transfer, directly influencing the outlet air temperature and storage capabilities. The study concluded that proper PCM selection and placement increase the effective heating duration and overall thermal performance compared to conventional designs.

Hussein et al. (2023) compared various absorber types in double-pass solar air heaters. They observed that tubular absorbers aligned parallel to airflow achieved superior thermal performance compared to flat plate designs at similar mass flow rates. The study highlighted that absorber geometry plays a significant role in heat transfer distribution and thermal efficiency, which is critical for optimizing solar air heater performance.

Assadeg et al. (2021) performed energetic and exergetic analysis of a double-pass solar air heater with fins and PCM. Their results showed that combining heat transfer enhancements with thermal storage improves thermal efficiency and outlet air temperature. The study bridged theoretical analysis with practical performance evaluation, emphasizing the importance of integrated design approaches for dual-mode operation.

Abo-Elfadl et al. (2021) investigated energy, exergy, and enviroeconomic performance of modified double-pass solar air heaters with new absorber designs. Their study revealed that absorber structure and flow path design critically influence thermal performance. They linked operational and environmental parameters to performance improvements, suggesting that design optimization is crucial for sustainable solar air heater deployment.

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SJIF Impact Factor : 6.008

Ameri et al. (2021) conducted an experimental comparison of V-corrugated solar air heaters integrated with PCM against baseline collectors. Results indicated improved thermal retention and efficiency due to enhanced turbulence and heat capture from corrugated absorbers combined with PCM storage. The research confirmed that combining absorber geometry modifications with energy storage significantly boosts performance and operational duration.

Salih et al. (2022) studied double-pass solar air heaters with rectangular fins. They reported modest thermal performance gains compared to smooth absorbers, emphasizing the importance of geometric optimization for airflow management and heat transfer enhancement. Their results provide practical insights for improving dual-mode solar air heater efficiency in industrial applications.

V. CONCLUSION

The literature review demonstrates that dual-mode solar air heaters have significant potential for improving thermal performance and energy efficiency compared to conventional single-mode systems. Various design modifications, such as the use of fins, corrugated or V-shaped absorber plates, bifacial configurations, and staggered obstacles, have consistently shown improvements in heat transfer and outlet air temperature. The integration of phase change materials (PCM) further enhances thermal storage capabilities, extending the availability of warm air during periods of low solar irradiance and after sunset. Experimental, numerical, and hybrid studies indicate that performance is strongly influenced by both design parameters and environmental factors. Factors such as airflow rate, duct geometry, absorber plate material, and PCM placement critically determine thermal efficiency, while solar irradiance, ambient temperature, wind speed, and relative humidity affect real-world performance. The review also highlights that combined approaches, incorporating both geometric optimization and energy storage, are the most effective strategies for achieving high efficiency. Despite significant advancements, challenges remain in standardizing designs, generalizing results across different climatic conditions, and balancing performance gains with economic feasibility and operational simplicity. Future research should focus on integrated design optimization, long-term experimental validation, and cost-benefit analysis to develop dual-mode solar air heaters that are efficient, durable, and adaptable for diverse applications. Overall, this review provides a comprehensive reference for researchers and engineers aiming to enhance the performance of dual-mode solar air heaters and contribute to sustainable solar thermal energy solutions.

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