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Advancements and Innovations in Solar Air Heater Technology: A Comprehensive Review

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Abstract

This paper reviews recent advancements in solar air heaters (SAHs), focusing on design improvements and energy storage integration. Emphasis is placed on enhanced absorber plate geometries, such as fins and corrugated surfaces, which improve heat transfer during sunshine hours. The use of phase change materials (PCMs) for thermal energy storage enables heat delivery during off-sunshine periods, enhancing system reliability. These developments have broadened the application of SAHs in areas like space heating, drying, and industrial processes. The review highlights SAHs as a promising solution for sustainable energy use and emphasizes the need for continued research in system optimization.

Keywords: Solar Air Heater (SAH) ,Thermal Energy Storage , Phase Change Materials (PCMs) ,Absorber Plate Geometry ,Heat Transfer Enhancement ,Renewable Energy Applications

1. Introduction

Solar energy serves as the fundamental source of all energy forms and plays a vital role in supporting societal infrastructure and maintaining quality of life. As energy demands grow, the shift toward renewable technologies has become increasingly important. Although several renewable energy technologies are currently in use in the 21st century, many are still under active development.Among the various solar applications, solar air heaters (SAHs) have emerged as reliable heat exchangers, particularly in thermal systems [1]. Air heating is a significant solar thermal application, commonly used in space heating, desalination, laundry operations, crop drying, and other drying processes. Relying on conventional energy sources for these purposes not only elevates operational costs but also contributes to environmental degradation. By contrast, employing solar energy for air heating minimizes both operational expenses and fossil fuel consumption [2].

This review seeks to consolidate the research conducted on SAHs and explore their potential for practical implementation and further development. The classification of SAHs is complex due to the variety of geometric designs and construction methods [3] .provided a detailed examination of diverse SAH configurations, their construction principles, and operational mechanisms for drying applications. SAHs can be broadly categorized based on their operation mode into active, passive, and hybrid types. The study [4] introduced an additional classification system that considers parameters such as tracking mechanisms, energy storage methods, surface modifications, and the number of transparent covers.n passive systems, hot air is naturally generated and directed to the point of use, typically during daylight hours. Active systems, however, incorporate heat storage materials to allow for thermal energy delivery even during non-sunshine periods. From another perspective, SAHs can also be classified based on air flow patterns into single-pass and double-pass configurations, which may or may not include thermal storage components [5,6]. In a single-pass system, air travels in one direction—either above or below the absorber plate. In contrast, a double-pass system directs air through two distinct channels, which may follow parallel or counterflow paths.SAHs generally comprise an air flow duct and an absorber plate. To enhance efficiency and minimize heat losses, these systems often utilize thermal insulation with low thermal conductivity on the sides and base. Numerous researchers have developed experimental test rigs to evaluate various modifications in SAH components. The objective of this paper is to explore the performance implications of different SAH configurations and identify directions for future development.

2. Classification of Solar Air Heaters

A solar air heater (SAH) is a device that transfers solar radiation into thermal energy to heat air. These systems are widely utilized in various applications, including crop drying, space heating, processing of marine products, and maintaining indoor thermal comfort, particularly during colder seasons. The study [7,8] conducted a detailed review of the diverse designs, construction techniques, and operational principles of SAHs specifically tailored for drying applications.In this context, an attempt is made to classify solar air heaters based on key parameters, including the presence or absence of thermal energy storage, the number of transparent covers, the use of extended surface enhancements such as fins or baffles, and the type of tracking mechanism employed to optimize solar capture. These classification criteria are illustrated in Figure 1.

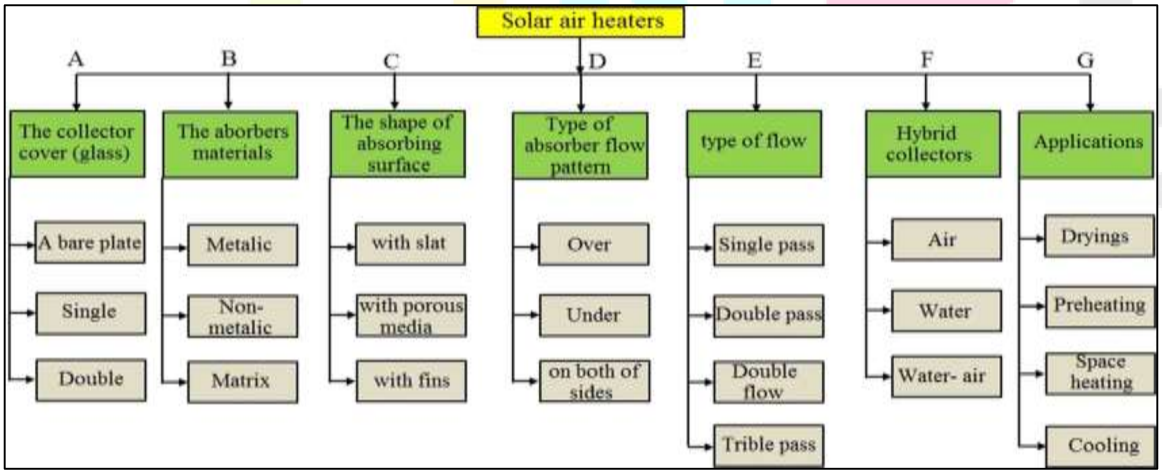


Figure1.Classification of Solar Air Heaters

3. Surface Geometry Enhancements

Enhancing the geometry of the absorber plate in thermal systems, such as solar collectors and heat exchangers, has proven to be an effective strategy for improving heat transfer performance. Various geometric modifications are employed to increase the surface area, disrupt boundary layers, and enhance fluid mixing—thereby facilitating more efficient heat transfer between the plate and the working fluid.One common enhancement involves the incorporation of extended surfaces, such as fins, which increase the contact area available for heat exchange [9-12]. Fins can be straight, wavy, pin-type, or of other complex shapes, and are particularly effective under forced convection conditions where high fluid velocities amplify their impact.Another approach is the use of internal obstacles, such as triangular, rectangular, or leaf-shaped baffles, which create turbulence in the fluid flow. This turbulence disrupts the thermal boundary layer on the absorber plate surface, enhancing convective heat transfer. These obstacles can be strategically arranged in a staggered or aligned fashion to optimize performance while managing pressure drop.

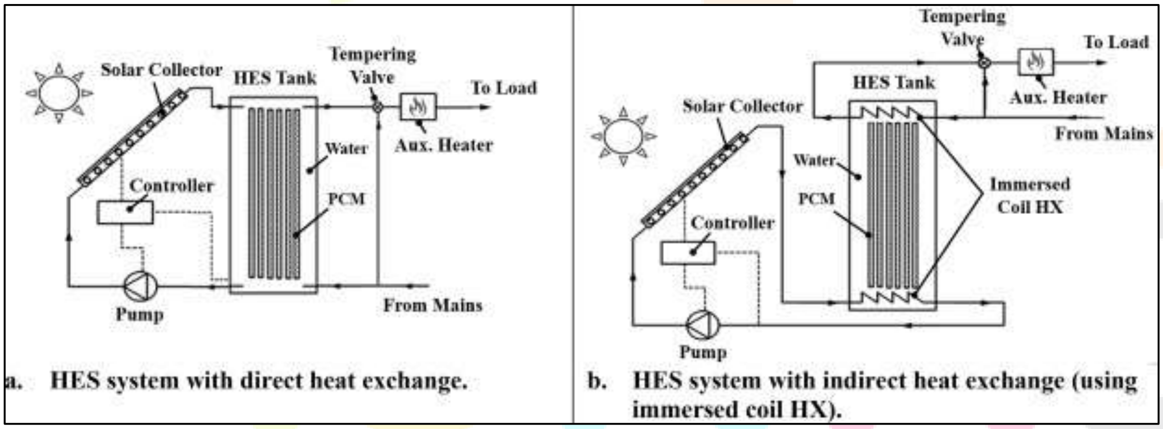
The introduction of metallic foams or porous media on the absorber surface is another technique that significantly boosts thermal performance. These materials have high surface area-to-volume ratios and promote vigorous mixing of the fluid. While they can increase pressure losses, their contribution to enhanced thermal conductivity and improved heat absorption can outweigh these drawbacks in many applications.Corrugated surfaces—featuring sinusoidal, trapezoidal, or other wave-like patterns—are also widely used. These geometries promote flow separation and reattachment, creating secondary flows that disrupt laminar layers and promote enhanced heat transfer.

These surface modifications have been investigated under both natural convection (where buoyancy drives the fluid motion) and forced convection (where external mechanisms like pumps or fans move the fluid). In both scenarios, the enhanced geometries have demonstrated considerable improvements in thermal efficiency, heat transfer coefficients, and overall system performance [13].In summary, optimizing absorber plate geometry through the use of fins, obstacles, foams, and corrugations is a proven and versatile method for increasing heat transfer rates in thermal systems, with effectiveness validated across a wide range of operational conditions.

4. Energy Storage Integration

The integration of thermal energy storage (TES) systems significantly enhances the performance and reliability of solar air heaters (SAHs) by mitigating the intermittent nature of solar radiation. Among the various TES strategies, the use of phase change materials (PCMs) has garnered considerable attention due to their ability to store and release large amounts of latent heat at nearly constant temperatures.PCMs, such as paraffin wax, fatty acids, and hydrated salts (e.g., Glauber’s salt or sodium sulfate decahydrate), are particularly well-suited for SAHs. These substances absorb thermal energy during the day when solar irradiance is high by undergoing a phase transition—typically from solid to liquid—and release this stored energy as they re-solidify when the ambient temperature drops or solar input is unavailable [14]. This mechanism allows the system to maintain a steady and extended thermal output, especially during cloudy periods or nighttime, thereby improving the overall availability and consistency of heated air.Recent advancements in hybrid thermal systems involve coupling SAHs with electrical energy sources such as resistive heaters powered by photovoltaics or grid electricity. This dual-mode system ensures reliable heat delivery regardless of solar availability, and is especially beneficial in applications requiring precise temperature control or continuous operation, such as greenhouse heating or industrial drying processes.

In parallel, mathematical modeling and simulation have become vital tools for optimizing the design and operation of PCM-enhanced SAHs. These models account for the thermophysical properties of PCMs, heat transfer characteristics, and climatic conditions to predict performance under varying scenarios. Optimization techniques are also applied to determine the ideal PCM type, melting point, mass, and placement within the solar air heater to achieve maximum thermal efficiency. Figure 2 shows Schematic of the hybrid thermal energy storage system . Moreover, research is expanding into the encapsulation of PCMs in metal or polymer shells to improve thermal conductivity and prevent leakage, as well as the development of composite PCMs—blends of phase change materials with high-conductivity additives like graphite or metal foams. The integration of phase change materials and hybrid energy systems into solar air heaters offers a robust solution for overcoming solar intermittency, increasing energy autonomy, and improving thermal management. Ongoing research and development efforts continue to refine these systems for greater efficiency, reliability, and scalability [15].Figure 3 represents Phase Change Materials (PCM) for Solar Energy Usages and Storage.



a. HES system with direct heat exchange.

b. HES system with indirect heat exchange (using immersed coil HX).

Figure 2 Schematic of the hybrid thermal energy storage system

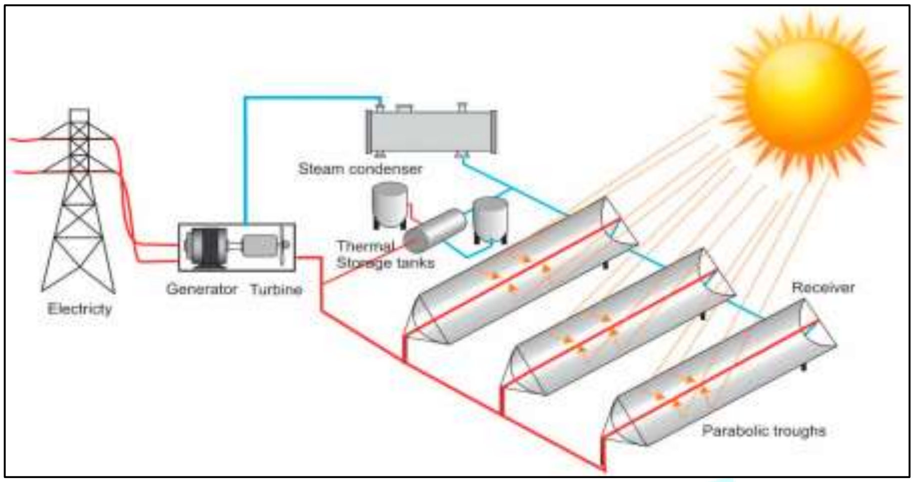


Figure 3 Phase Change Materials (PCM) for Solar Energy Usages and Storage

5. Hybrid PV/T Solar Air Heaters

Photovoltaic (PV) solar panels typically convert only about 5–20% of incident solar energy into electricity, with the remaining energy mostly lost as heat. To utilize this thermal energy and enhance overall efficiency, hybrid photovoltaic/thermal (PV/T) systems are employed. A PV/T collector simultaneously generates both electricity and thermal energy. Figure 4 shows Schematic diagram of PV/T collector .It usually comprises a PV module coupled with an absorber plate mounted on its back. The absorber plate serves two main functions: it cools the PV cells—thereby improving their electrical output, since electrical efficiency drops by approximately 0.4% for every 1 °C rise in cell temperature above the standard 25 °C under irradiance of 1000 W/m²—and it captures the thermal energy that would otherwise dissipate into the environment.

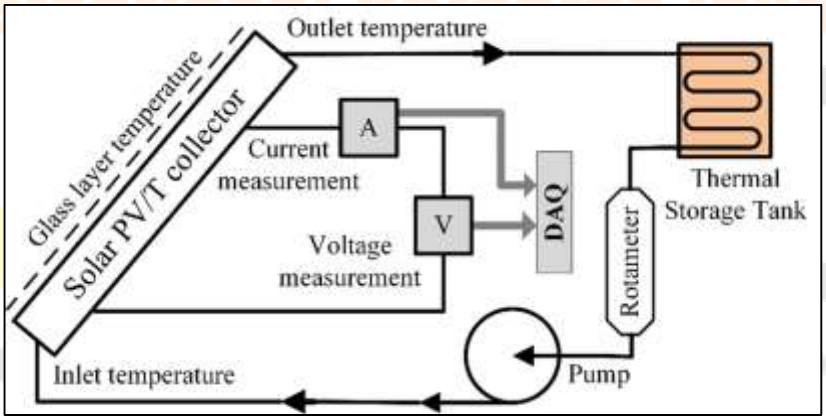


Figure 4 Schematic diagram of PV/T collector

The research investigated a PV/T system in which multiple solar panels were arranged in parallel and mounted within an air channel above a thin metal sheet (TMS) made of aluminum. This aluminum sheet, suspended mid-height within the air channel, functioned as a secondary absorber plate, enhancing heat extraction by increasing the effective heat exchange surface. The air channel itself was constructed using Medium Density Fiberboard (MDF), providing structural support .The system's performance was evaluated under both natural (free) and forced convection conditions, with forced convection scenarios tested using configurations of two, four, and eight operating fans. Experimental results revealed a contrasting effect of installing a glass cover over the photovoltaic (PV) panels: under forced convection, the presence of the glass cover led to a reduction in air mass flow rate, while under natural convection, it resulted in a notable increase in airflow.Regardless of the convection mode, thermal efficiency improved with increased air mass flow rate, attributed to the enhancement in convective heat transfer coefficients. However, the addition of a glass cover had a dual effect—it contributed to a rise in thermal efficiency due to better heat retention, but simultaneously caused a decline in electrical efficiency, likely due to increased panel temperature and reduced solar irradiance reaching the PV cells.

6. Conclusion

Solar air heaters (SAHs) continue to evolve as efficient and sustainable solutions for thermal energy applications. This review has highlighted significant developments in SAH technologies, including diverse system configurations, innovative absorber plate geometries, and the integration of thermal energy storage, particularly phase change materials (PCMs). Design enhancements such as the incorporation of fins, obstacles, and textured surfaces have been proven to markedly improve heat transfer performance under solar exposure, while PCMs play a crucial role in maintaining thermal output during periods without sunlight.These advancements not only enhance the overall efficiency of SAHs but also broaden their applicability across sectors such as agriculture, building heating, and industrial drying. As the demand for renewable energy technologies grows, further research into hybrid systems, optimized material selection, and real-time control strategies will be essential to fully harness the potential of SAHs. Collectively, the progress in this field underscores the importance of continued innovation in solar thermal technologies for achieving energy sustainability.

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