Advancements and Integration Strategies in Solar Air Heaters: A Comprehensive Review of Design Innovations, Applications, and Energy Storage Solutions

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Abstract: *As the world pivots toward sustainable and eco-friendly energy solutions, solar air heaters (SAHs) have emerged as a promising technology for fulfilling thermal energy demands across residential, industrial, and agricultural sectors. Despite their inherent limitations, such as low convective heat transfer and thermal losses, recent advancements have significantly enhanced their performance. This review critically examines the latest developments in SAH design, with particular attention to heat transfer enhancement techniques including artificial roughness, extended surfaces, baffles, and innovative absorber configurations. It further explores the integration of SAHs with photovoltaic systems, creating hybrid PV/T collectors capable of delivering both thermal and electrical energy. The paper categorizes and compares different SAH configurations such as flat plate, transpired, glazed, unglazed, and concentrating types—highlighting their operational principles and optimal applications. Additionally, the role of thermal energy storage (TES) in improving system reliability and extending functionality beyond daylight hours is analyzed, with a focus on both sensible and latent heat storage materials. By synthesizing research findings from various studies, this paper provides valuable insights into the current state, challenges, and future directions of SAH technology, emphasizing its role in advancing global clean energy initiatives.*

Keywords: *Solar Air Heaters (SAHs), Heat Transfer Enhancement, Artificial Roughness, Photovoltaic/Thermal (PV/T) Systems, Renewable Energy, Solar Thermal Collectors, Energy Storage, Sensible Heat Storage (SHS).*

I. INTRODUCTION

Energy is one of the most critical and pressing issues worldwide. Among the various sources of energy, fossil fuels remain the most commonly used. However, the extensive use of fossil fuels leads to severe environmental challenges, prompting a global shift in focus toward renewable energy sources [1]–[3]. Solar energy stands out as one of the most promising renewable options due to its limitless availability, widespread presence, cost-effectiveness, ease of use, and environmentally friendly nature. These advantages make solar energy a vital contributor to the goal of sustainability.One of the most efficient solar thermal systems is the Solar Air Heater (SAH), which can supply hot air for a variety of domestic and industrial applications thanks to its simple design and low cost. Nevertheless, the performance of SAHs is often hindered by the low convective heat transfer coefficient of the absorber plate and significant heat losses through the top glass cover. A major contributing factor is the formation of a laminar sub-layer near the absorber plate, which generates thermal resistance and inhibits effective heat transfer [4]–[8].

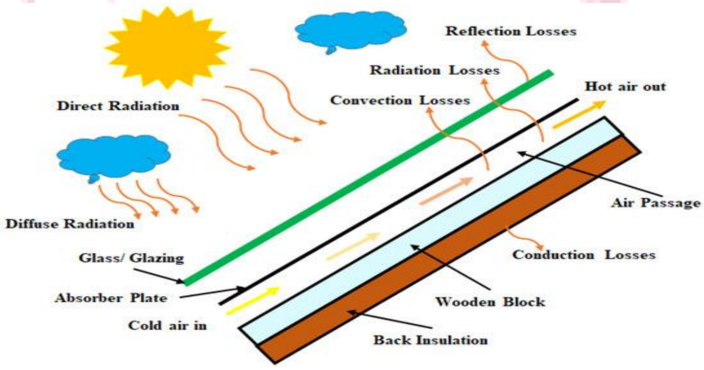

Figure 1. Basic illustration of a solar air heater (SAH).

To address this issue, turbulators are employed to enhance the convective heat transfer by disrupting the laminar sub-layer and promoting turbulence within the airflow. This can be achieved by incorporating artificial roughness elements, which come in various forms such as grits, grooves, baffles, ribs, winglets, protrusions, twisted tapes, dimples, perforations, and mesh wires. These elements disturb the viscous sub-layer and enhance mixing, thereby improving heat transfer.Another factor limiting SAH performance is the low thermal conductivity and heat capacity of the working fluid [9]–[11]. To mitigate these limitations, researchers have explored several performance enhancement strategies, including the use of artificial roughness, extended surfaces, baffles, and porous materials. Figure 1 presents a basic schematic of a Solar Air Heater (SAH).

The application of artificial roughness or turbulators, such as ribs, wires, sand grains, and metal grits on a heated duct surface, is an effective technique to augment the heat transfer rate to a flowing fluid.

In SAH, the aspect ratio of the duct is generally higher in comparison to other applications, while a range of Re and roughness to hydraulic diameter ratio, e/Dh are smaller in order to avoid the higher value of frictional losses and pumping power required to pump the flowing air [12]–[15].

II Types of Solar Air Heaters

Solar air heaters are broadly categorized based on their construction and heat transfer mechanism. The main types include:

A. **Flat Plate Solar Air Heaters**
These are the most common and simplest form of SAHs. They consist of a flat absorber plate enclosed in a box with a transparent cover (glazing) and insulation at the back. Air flows either above, below, or on both sides of the absorber plate. Variants include:

- *Single pass* or *double pass* configurations
- *With or without fin enhancements*

B. **Transpired Solar Air Heaters (TSAHs)**
Also known as **solar walls**, TSAHs consist of a perforated absorber plate mounted on a south-facing wall. Ambient air is drawn through the perforations, absorbing heat from the heated plate surface. These are highly efficient and primarily used for **ventilation air preheating** in large commercial or industrial buildings.

C. **Glazed vs. Unglazed Solar Air Heaters**

- **Glazed SAHs** use a transparent glass cover to reduce heat losses and are suitable for colder climates or applications requiring higher temperatures.
- **Unglazed SAHs**, lacking a cover, are less efficient but cheaper, often used in applications where lower temperatures are acceptable or overheating is a risk.

D. **Integrated Collector Storage Systems**
In this design, the collector and air storage are combined into a single unit. These are often used in small-scale or portable systems.

E. **Concentrating Solar Air Heaters**
These use reflective surfaces to focus sunlight onto a smaller absorber area, thereby achieving higher temperatures. Though more complex and costly, they are used in industrial applications where high-grade heat is required.

Ongoing Innovations and Efficiency Enhancements

Advancements in absorber plate materials, surface coatings, flow channel geometry, and air flow enhancement techniques (e.g., artificial roughness, extended surfaces, and baffles) have significantly improved the thermal performance of solar air heaters. Moreover, the integration of smart control systems**,** hybrid photovoltaic-thermal (PV/T) systems, and thermal energy storage is expanding their applicability and efficiency**.**

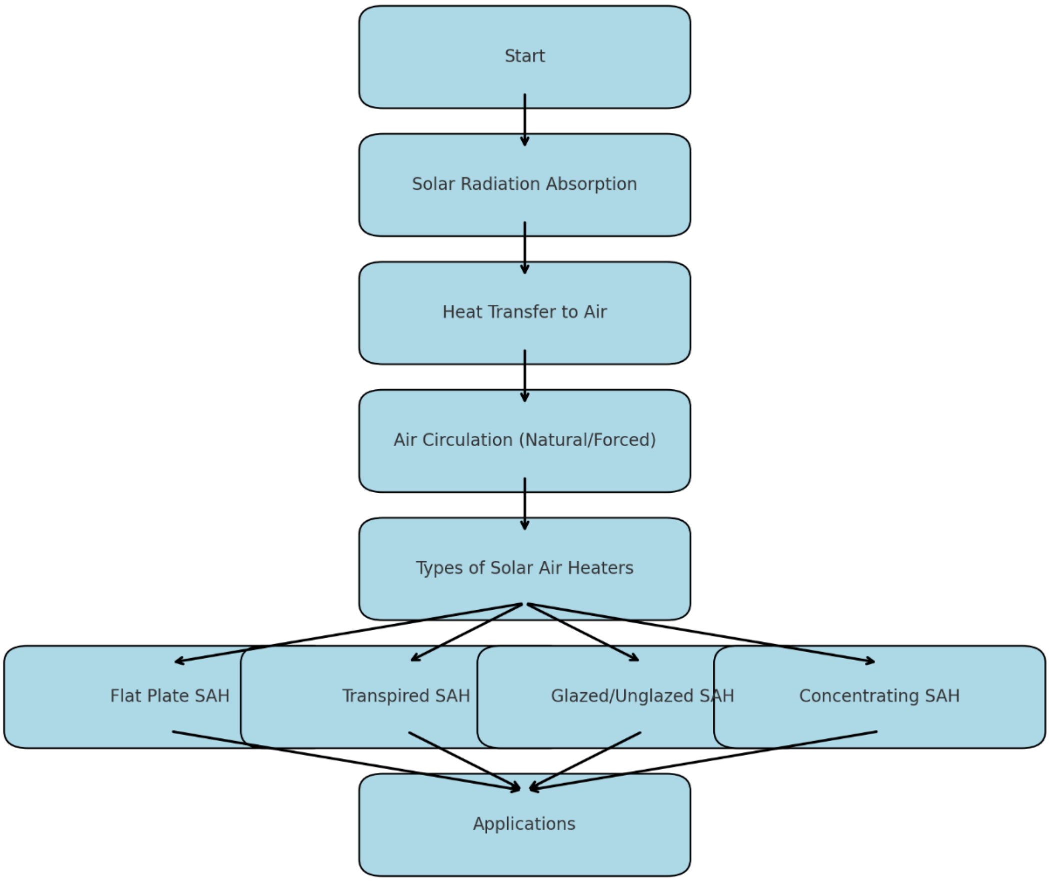

Figure 2 Types of Solar Air Heaters.

III. APPLICATION OF SOLAR AIR HEATERS

Solar air heaters (SAHs) have a wide range of applications across various sectors due to their simplicity, cost-effectiveness, and environmentally friendly operation. In residential and commercial buildings, SAHs are commonly used for space heating, especially in colder climates, where they help reduce reliance on conventional heating systems and lower energy bills. In the agricultural sector, they are extensively utilized for drying crops such as grains, fruits, vegetables, herbs, and spices, offering faster, more hygienic, and controlled drying compared to traditional sun-drying methods. Industrial applications include the preheating of air for boilers and furnaces, as well as drying materials like textiles, paper, leather, and ceramics—resulting in significant energy savings and improved process efficiency. Transpired solar air heaters are particularly effective for preheating ventilation air in large commercial or industrial facilities, enhancing indoor air quality while reducing energy consumption. In greenhouses, SAHs help maintain optimal growing temperatures, boosting crop yields during colder months. Additionally, they are used in combination with heat pumps in solar-assisted heating systems to improve performance and reduce power consumption. In remote or off-grid areas, SAHs offer a dependable and sustainable heating solution, especially where conventional energy infrastructure is lacking. They are also valuable in emergency shelters and military applications, providing thermal comfort without the need for fuel-based heating devices. Overall, the versatility of solar air heaters makes them an essential component in the transition toward renewable energy solutions [14]–[19].

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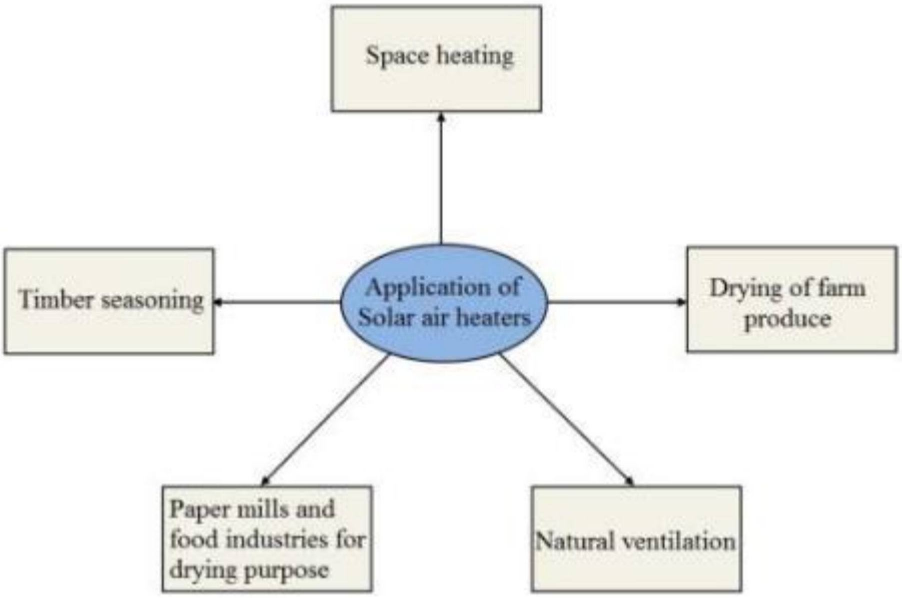

Figure 3 Application of Solar Air Heaters [15]

When combined with PV systems, solar air heaters become hybrid devices known as photovoltaic/thermal (PV/T) collectors simultaneously producing thermal and electrical energy [16]. Solar thermal systems may present many advantages: they function with hardly any noise, don't generate any hazardous by-products like radioactive waste, and are among the cleanest renewable technologies. These systems are also rather reliable, existing for about 20 to 30 years with minimal maintenance. Despite these advantages, solar systems have some drawbacks. These include advanced absorber designs needed, problems with non-uniform cooling, lengthy payback periods, less efficiencies on the lower side, and initial costs too high for production and installation; with some incompatibilities with existing roof structures. They also demand considerably more surface area, especially when thermal and electrical systems are installed separately. While SAHs can prove useful for space heating during autumn and spring, their efficiency still lags behind that of a few other systems. Several research avenues have been employed to increase the heat transfer performance of SAHs. The use of fins or baffles with different geometries, surface texturing, and flow modifications have been investigated in an effort to improve thermal performance.

Above all, one needs solar energy storage for solar energy utilization to be sustainable in the long run. The main problem is the lack of materials with appropriate thermo-physical properties for heat storage. Solar thermal storage materials are divided mainly into two categories:

Sensible Heat Storage (SHS): Energy stored by raising the temperature of a solid or liquid, which does not undergo a phase change.

Latent Heat Storage (LHS): Energy stored while the material changes phase (e.g., melting or solidifying), usually in the temperature range generated by solar collectors.

The solar radiation intensity or solar flux is a function of the season, local weather phenomena, exact geographical location, and designation of the collector surface. On average, it is about 1000 W/m^2 if the absorbing surface is oriented perpendicular to the incident solar beam under clear sky conditions. Solar collectors use solar energy-the abundant and renewable energy source-and convert it into a useful or storable form.Solar thermal collectors come in various configurations depending on their application. Among these configurations, flat plate collector types are the best-known, especially when coupled with solar air heaters for preheating air for domestic and industrial HVAC systems. Although different designs exist, they generally have four main components:The flat plate absorber for capturing solar energy,The transparent cover or glazing that allows sunlight to pass through while minimizing heat loss,Heat transfer fluids such as air or water carry the heat away from the absorber.A thermal insulation layer on the backside curtails conductive heat loss.Multiple designs and performances of the solar air heaters are developed, as shown in Figure 3.Finally, several types of solar air heaters have been developed and classified according to design and performance characteristics as shown in Figure 3..

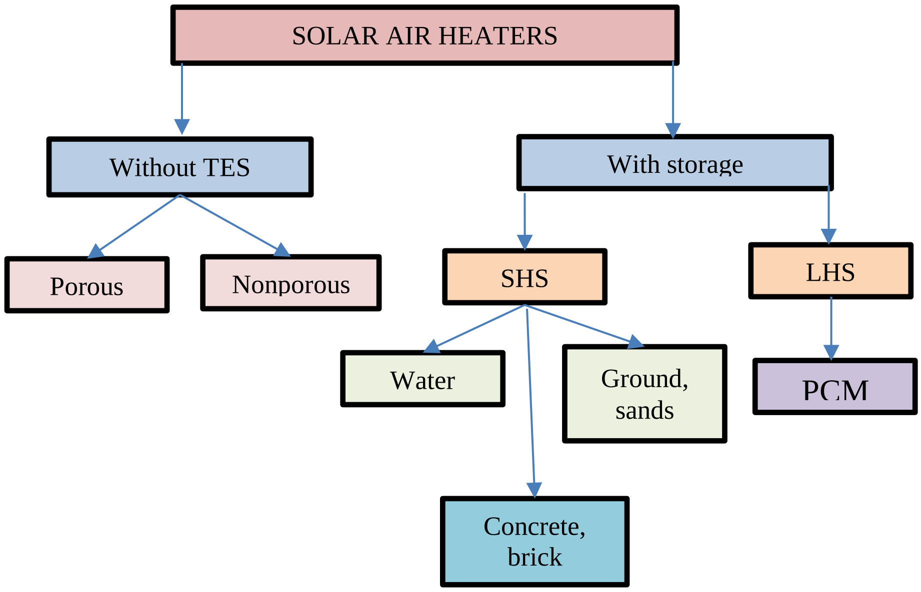

Figure 4 Classification of solar air heaters on the basis of TES.

Really can these heat-storing substances enhance the thermal effectiveness of a SAH, but they can also prolong the timeframe of heating up to several hours. Aside from that, Solar Air Heater and its Classification – A Review 4 these materials' high heat-storage capacity is very helpful for solar thermal systems to operate in poor environmental temperature or at night.

V. CONCLUSION

Solar air heaters (SAHs) offer a compelling, sustainable solution for addressing heating and ventilation demands across a wide range of sectors. Although SAHs have traditionally faced limitations such as low convective heat transfer coefficients and significant thermal losses, recent technological advancements have markedly enhanced their performance and efficiency. Innovative strategies—such as the application of artificial roughness, extended surfaces, and baffle designs—have been instrumental in improving heat transfer and optimizing airflow dynamics. Additionally, the integration of SAHs with photovoltaic (PV) systems has opened new avenues for dual-mode energy generation, delivering both thermal and electrical output from a single system. As the global focus on renewable energy intensifies, the scope and relevance of SAH applications continue to grow, driving forward innovation and wider adoption. Looking ahead, ongoing research and development in areas such as thermal energy storage, advanced materials, and system integration will be essential to fully realize the potential of solar air heating. These efforts are crucial for advancing the transition to a low-carbon, energy-efficient future powered by clean and sustainable technologies.

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