ADVANCEMENTS IN SOLAR AIR HEATER TECHNOLOGY: A COMPREHENSIVE OVERVIEW

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Abstract: *The global pursuit of sustainable energy solutions has led to a significant shift towards renewable alternatives, driven by the environmental impact of fossil fuel consumption. Among these alternatives, solar energy stands out for its abundance, affordability, and eco-friendliness. Solar air heaters (SAHs) play a crucial role in harnessing solar energy for heating purposes across various sectors. However, challenges such as low convective heat transfer coefficients and high heat losses have limited the performance of SAHs. This review paper provides a detailed examination of recent advancements in SAH technology aimed at addressing these challenges and improving overall efficiency. It discusses various methodologies, including the use of artificial roughness, extended surfaces, baffles, and porous materials, to enhance heat transfer rates. Additionally, it explores different types of SAHs, such as flat plate, transpired, unglazed, glazed, thermosiphon, and hybrid systems, elucidating their principles, applications, and comparative advantages. The integration of solar air heating systems with photovoltaic technology is also explored as a means of generating both thermal and electrical energy. Furthermore, potential applications of SAHs across various sectors and emerging trends in solar energy storage are discussed. Overall, this paper offers valuable insights into the current state of SAH technology and provides directions for future research and development in the pursuit of sustainable energy solutions*.

Keywords: *Solar air heaters, Renewable energy, Heat transfer enhancement, Artificial roughness, Solar thermal collectors, Energy storage.*

I. INTRODUCTION

Energy is the most important and serious matter worldwide. There are numerous energy sources out of which the most important and common source of energy is fossil fuel. The use of fossil fuels causes significant environmental problems due to which attention has been focused on renewable sources of energy. Solar energy is one of the best renewable energy sources because of its limitless energy, abundant quantity, cost-effectiveness, omnipresent reliability, easy-to-use, and non-pollutant nature all of the time. Solar energy has great potential to achieve the goal of sustainability due to these benefits.

SAH is known as the most attractive solar thermal system which can supply hot air for various purposes, ranging from domestic to industrial applications due to its simple design and cost-effectiveness [1,2]. However, SAH has poor performance due to the low convective heat transfer coefficient of the absorber plate and high heat losses from the top glass cover. Due to the development of the laminar sub-layer at the absorber plate, thermal resistance is generated near the plate which retards heat transfer. The convective coefficient can be augmented by using turbulators which induce turbulence in the duct near the absorber plate by disrupting and destabilizing the laminar sub-layer. The viscous sub-layer can be disrupted by using irregular shapes obstacles, called artificial roughness, in a distinct form of grits, grooves, baffles, ribs, winglets, protrusions, twisted taps, dimples, perforation and mesh wire, etc. On the other hand, the performance is also intrinsically affected due to the low heat capacity and thermal conductivity of flowing fluid [3]. To overcome these problems, distinct types of methodologies have been used by many researchers pertaining to achieve better improvement in the performance of SAH, such as using artificial roughness, extended surfaces, baffles, and porous surfaces. The basic illustration of a solar air heater (SAH) is presented in Figure 1.

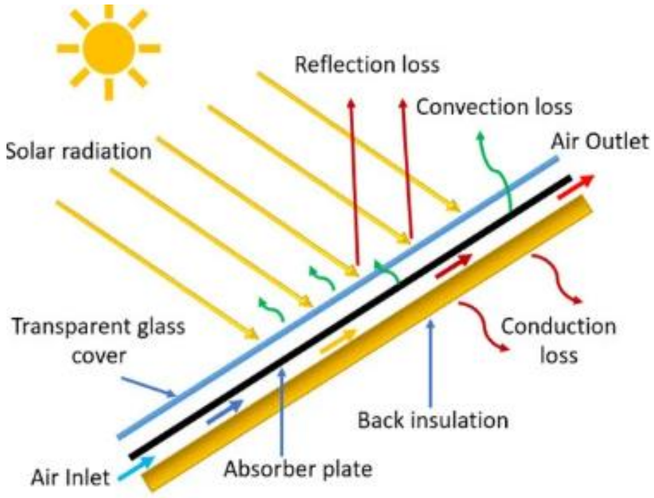

Figure 1. Basic illustration of a solar air heater (SAH).

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 [4].

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 [5].

II. DIFFERENT TYPES OF SOLAR AIR HEATERS

Solar air heaters represent a pivotal technology in the realm of renewable energy, offering a sustainable solution for harnessing solar radiation to meet heating and ventilation needs across various sectors. With the ever-growing emphasis on mitigating climate change and reducing dependence on fossil fuels, solar air heaters have emerged as viable alternatives, embodying the promise of clean, abundant energy. This introduction sets the stage for delving into the world of solar air heaters, exploring their principles, applications, and potential for efficiency enhancement. In this era of environmental consciousness and energy transition, the importance of renewable energy sources cannot be overstated. Solar energy, in particular, stands out as a ubiquitous and inexhaustible resource, offering immense potential for powering a greener future. Solar air heaters, a subset of solar thermal technologies, leverage this abundant resource to heat air for various purposes, ranging from space heating in buildings to industrial processes and agricultural applications [6]–[10]. The fundamental principle underlying solar air heaters is simple yet ingenious: harnessing solar radiation to heat air. This process typically involves capturing sunlight using a solar collector, transferring the absorbed heat to the air, and circulating the heated air to the desired space. While the basic concept remains consistent, solar air heaters come in diverse configurations, each tailored to specific applications and performance requirements. The versatility of solar air heaters is exemplified by their various types, ranging from flat plate and transpired solar air heaters to glazed and unglazed variants. Each type offers unique advantages and is suited to different environments and usage scenarios. Moreover, advancements in materials, design, and control systems continue to push the boundaries of efficiency and applicability, driving innovation in the field [11]–[13].

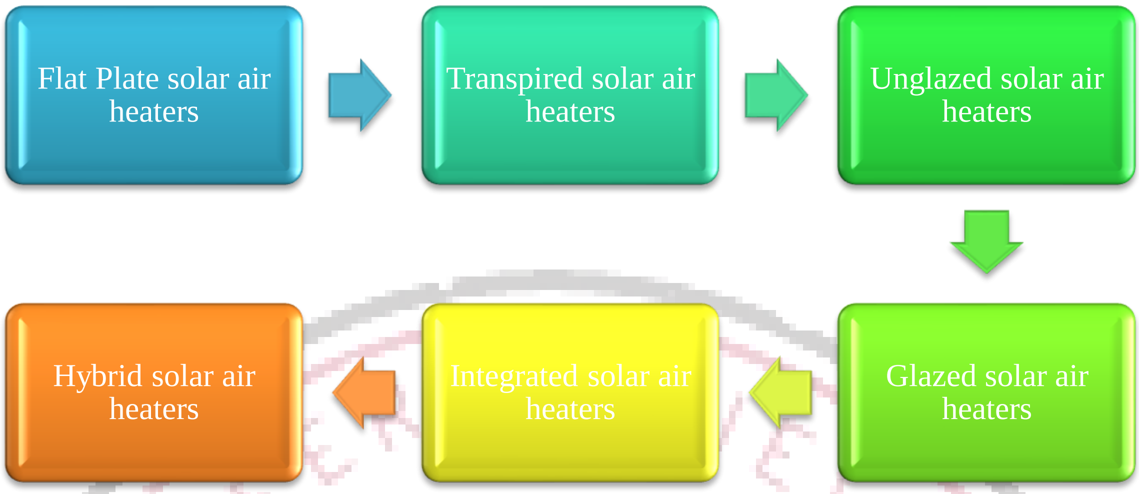

Figure 2 Types of Solar Air Heaters

Flat Plate Solar Air Heaters: These are the most common type of solar air heaters, consisting of a flat absorber plate covered with a transparent cover. The air passes through channels or ducts on the absorber plate, where it absorbs solar radiation and heats up before being circulated into the space to be heated.

Transpired Solar Air Heaters: In transpired solar air heaters, the absorber plate is perforated, allowing air to pass through thousands of small holes. This design increases the surface area exposed to sunlight, enhancing heat transfer efficiency. Transpired solar air heaters are often used in commercial and industrial applications for space heating and ventilation.

Unglazed Solar Air Heaters: Unglazed solar air heaters consist of a dark-colored absorber plate without a transparent cover. They are typically used for preheating ventilation air in commercial and industrial buildings, agricultural facilities, and solar drying applications. Unglazed solar air heaters are simpler and less expensive than glazed models but may have lower efficiency and require more maintenance.

Glazed Solar Air Heaters: Glazed solar air heaters feature a transparent cover, usually made of glass or polycarbonate, which traps solar radiation and reduces heat losses. These heaters are more efficient than unglazed models and are suitable for residential, commercial, and institutional applications where higher thermal performance is required.

Integrated Solar Air Heating Systems: Integrated solar air heating systems combine solar air heating with other building components, such as roofing or facade elements, to provide both thermal energy and architectural functionality. These systems can be aesthetically pleasing and space-saving while contributing to energy efficiency and sustainability in buildings.

Thermosiphon Solar Air Heaters: Thermosiphon solar air heaters operate based on natural convection currents, where heated air rises and cold air sinks, creating a continuous flow of air through the system without the need for mechanical pumps or fans. These heaters are simple, reliable, and suitable for off-grid or remote locations where electricity is limited or unavailable.

Hybrid Solar Air Heaters: Hybrid solar air heaters integrate solar thermal collectors with other heat sources, such as biomass, geothermal, or waste heat, to provide a more reliable and consistent supply of heated air. These systems offer flexibility and resilience, especially in areas with variable weather conditions or fluctuating solar radiation level

III. LITERATURE REVIEW

Abu Hamed and Alkharabsheh (2020) conducted a study on evacuated tube solar air heaters (ETSH) focusing on efficiency and thermal performance optimization. Their experimental setup involved novel configurations with different types of metal fins and coils to enhance heat transfer. Results showed that aluminum fins exhibited the highest efficiency at the highest flow rate, reaching 37%, with a maximum temperature difference of 88°C at a flow rate of $0.6m^3/min$ under solar irradiation of $1000\ W/m^2$.

Pathak et al. (2023) reviewed the integration of phase change materials (PCMs) in solar air heaters (SAHs) to address the intermittency of solar energy. They discussed various enhancements like modified absorber plates, recycled SAHs, and artificially roughened absorbers, noting improved performance with PCMs integration. SAHs with PCMs showed higher energy and exergy outputs and shorter payback periods compared to those without.

Alam and Kim (2017) examined the impact of artificial roughness on absorber plates in solar air heaters. They reviewed literature on different roughness patterns and their effects on heat transfer enhancement, compiling Nusselt number and friction factor correlations. The study aimed to provide insights into the thermohydraulic characteristics of artificial roughness elements.

Fadala and Yousef (2023) investigated the use of synthetic roughness elements to improve the performance of solar air heaters (SAHs). Through experiments, they explored how the shape, type, and properties of these elements influence heat transfer efficiency. The study aimed to provide valuable insights into enhancing SAH performance.

Hu and Zhang (2019) conducted a comprehensive review of techniques aimed at enhancing the thermal performance of solar air collectors. They categorized improvement methods under "airflow reorganization," including adding ribs, fins, or meshes, employing air impinging jets, transitioning to multi-pass duct configurations, and introducing baffles. The review aimed to offer insights for future research in this field.

Prakash et al. (2018) focused on the application of artificial roughness to absorber plates in solar air heaters. They highlighted the effectiveness of specific roughness geometries, particularly W-shaped rectangular ribs within a double-pass configuration, in increasing heat transfer rates. The study provided correlations between Nusselt number and friction factor as functions of system and operating parameters.

Niyonteze et al. (2021) reviewed metaheuristic algorithms for optimizing solar air heaters (SAHs). They discussed approaches like simulated annealing, particle swarm optimization, genetic algorithm, and others, highlighting efficiency improvements achieved through these methods. The study suggested elitist teaching-learning-based optimization as a competitive approach for SAH optimization.

Chhaparwal et al. (2019) meticulously examined the evolution and performance enhancements associated with artificial repeated-rib roughness applied to absorber plates in solar air heaters (SAHs). They discussed four primary types of rib-roughness and analyzed over forty variables influencing SAH performance. The review aimed to provide a comprehensive understanding of advancements in rib-roughness technology for SAHs.

IV. APPLICATION OF SOLAR AIR HEATERS

Because of their inherent simplicity and cost effectiveness, solar air heaters (SAHs) have been widely used for years. It's a type of heat exchanger that converts solar energy into thermal energy. Because the fluid does not freeze or boil in these systems, they have a benefit above other exchangers. Small heat conductivity, low thermal capacity, and low air density are all drawbacks of SAH. SAHs are used to cure and dry concrete and clay building materials. Seasoning of wood, space heating, and curing of industrial products are some of the other applications. SAH is an essential component between many available solar heating systems because of its minimal use of materials and low cost. Solar energy can be used to heat the fluids as well. It can be used for a variety of things, including the drying of vegetables, fruits, and meats, as well as the incubation of eggs and other industrial purposes.

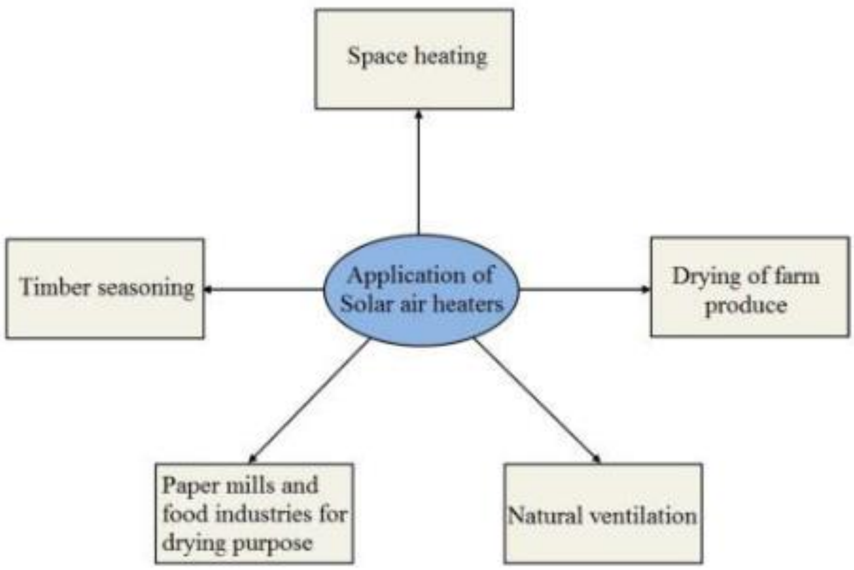

Figure 3 Application of Solar Air Heaters [15]

When combined with photovoltaic (PV) systems, SAHs produce both thermal and electrical energy. PV/T collectors are what they're called [16]. Solar thermal systems also have the following benefits: they produce very little noise, they do not produce undesirable waste such as radioactive materials, and they are one of the cleanest technologies available. They are highly reliable systems with a lifespan of 20 to 30 years and low maintenance requirements. Solar systems have a number of drawbacks, including the need for innovative absorber design, non-uniform cooling, a longer payback period, lower efficiency, high production and installation costs, incompatibility with existing roof systems, and the need for more space for separate systems. SAHs could also be used to heat spaces throughout the autumn and spring seasons, but their efficiencies are still lower than other systems. Numerous studies on heat transfer enhancement techniques for SAHs, such as attaching different shaped fns or baffles, surface treatment, flow direction change, and so on, have been published in the literature. Solar energy storage is critical for the long-term success of solar energy use. The main issue is a lack of materials with adequate thermo-physical properties for storing solar energy as heat. These substances can be divided into two groups: those which store energy in the type of sensible heat, as well as those who change state or undertake a physical–chemical change at a specific temperature inside the pragmatic temperature range generated by solar heat collectors. Thermal heat storages for solar thermal applications include: (i) Sensible heat storage (SHS): sensible heat in solids.(ii) Latent heat storage (LHS): as latent heat of fusion in appropriate chemical compounds, the heat storage medium observations an uptick without changing phase [14]–[18].

The amount of solar energy striking the earth's surface depends on the season, local weather conditions, location, and orientation of the surface, but it averages about 1000 W/m^2 (if the absorbing surface is perpendicular to the beam radiation with a clear sky). There are several ways of absorbing and using this free, clean, renewable, and long lasting source of energy. Solar collectors absorb and transfer the energy of the sun to a usable or storable form. Solar thermal collectors can be made in different shapes based on their application [19]–[23]. FPCs are the most common types of solar collectors and are usually used as SAH for preheating the air in domestic or industrial heating, ventilation, and air conditioning systems. There are many FPC designs but generally all consist of four major parts: (i) a flat plate absorber, which absorbs the solar energy, (ii) a transparent cover that allows solar energy to pass through and reduces heat loss from the absorber, (iii) a heat-transport fluid (air or water) flowing through the collector to remove heat from the absorber, and (iv) a heat insulating backing . There are different types of solar air heaters that have been developed and can be classified as shown in Figure 3.

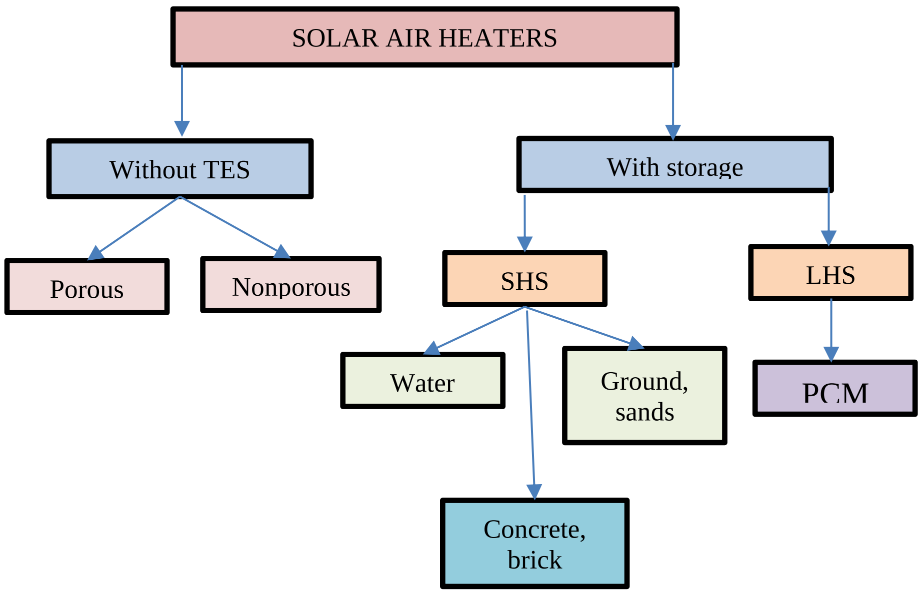

Figure 4 Classification of solar air heaters on the basis of TES.

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) represent a promising solution for meeting heating and ventilation needs sustainably across diverse sectors. Despite facing challenges such as low convective heat transfer coefficients and high heat losses, recent advancements in SAH technology have significantly improved performance and efficiency. Through innovative methodologies like artificial roughness and extended surfaces, researchers have successfully enhanced heat transfer rates and optimized system performance. The integration of SAHs with photovoltaic technology offers further potential for dual-energy generation. As the global demand for sustainable energy solutions grows, the applications of SAHs continue to expand, driving innovation and adoption. Moving forward, continued research and development efforts in energy storage and system integration will be vital for unlocking the full potential of solar air heating technology and accelerating the transition towards a cleaner, more sustainable energy future.

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