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Research Article

Solar Air Heaters Classifications and Enhancement: A Review

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ABSTRACT

Solar air heaters (SAHs) are renewable energy systems that utilise solar radiation to heat air, offering sustainable solutions for space heating, agricultural drying, and industrial processes. These systems are simple in design, cost-effective, and environmentally friendly, making them essential to the renewable energy landscape. However, challenges such as low thermal efficiency, dependency on climatic conditions, and significant thermal losses limit their adoption. Recent advancements in design, materials, and operational strategies have significantly improved their performance. This review explores the principles of SAHs, innovations in design, thermal storage integration, and efficiency enhancement techniques. Applications in various sectors are discussed, highlighting ongoing research to maximise efficiency while maintaining economic viability and ecological benefits.

1. INTRODUCTION

Solar air heaters are crucial components of solar thermal systems, designed to convert solar energy into usable thermal energy directly. These systems are particularly suited for applications requiring low to medium-temperature heat, such as space heating, crop drying, and industrial air preheating. The basic structure of a conventional SAH includes an absorber plate, an insulated casing, and a transparent cover. Despite their simplicity, their performance is hindered by the inherently low thermal conductivity of air and significant heat losses through the absorber plate and transparent cover. Significant research efforts have been made to address these challenges in recent years. Innovations such as integrating porous media, adding thermal storage systems, and using advanced materials for absorber plates and covers have demonstrated improved performance. This paper comprehensively reviews SAH technology, focusing on design advancements, efficiency improvements, and practical applications [1-2].

2. THE WORKING PRINCIPLE

A solar air heater is a renewable energy device designed to harness solar energy to heat air for space heating, drying, or industrial processes. Its working principle is based on absorbing solar radiation and transferring the heat to air. The system typically consists of several basic components: a collector surface, usually coated with a black material to maximise solar radiation absorption; glazing, which is a transparent cover (glass or plastic) that traps heat through the greenhouse effect while protecting the collector; and insulation, which lines the back and sides to minimise heat loss. The airflow mechanism ensures that air is passed over or through the heated collector, where it absorbs heat via conduction and convection. Airflow can occur naturally through buoyancy or be forced using fans or blowers for improved efficiency. The ducts or passageways guide the air through the collector and to its destination. Depending on the design, the system may include additional features, such as single-pass configurations where air flows over the collector once, double-pass systems for enhanced heat transfer, or porous media-based designs that incorporate perforated plates or porous materials to improve absorption and heat exchange. These components work together to deliver heated air for various applications, making solar air heaters simple, cost-effective, and environmentally friendly solutions for reducing energy consumption [3].

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3. CLASSIFICATION OF SOLAR AIR HEATERS

Solar air heaters can be classified based on their design, operation, and method of airflow. The main classifications include:

3.1 Based on Air Flow Configuration

1) **Single-flow single pass SAH**: These are the most basic type of solar air heater, where air flows through the collector only once. They consist of a rectangular duct with a black-painted absorber plate to absorb solar radiation. A transparent cover, usually glass or plastic, is placed over the absorber plate to minimise heat loss. Air enters the duct at one end, flows over the absorber plate, and exits at the other end, carrying away the absorbed heat. While simple and cost-effective, single-pass SAHs have lower efficiency compared to multiple-pass designs due to the limited heat transfer time [4].

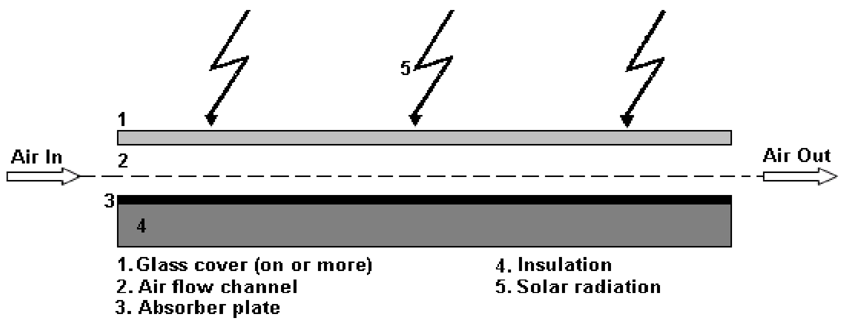

Fig.1. Single-flow Single-pass SAH

2) **Double-flow single pass SAH**

The double flow single pass solar air heater closely resembles the single flow single pass heater. The primary distinction between them is in the quantity of airflow channels. A double-flow, single-pass solar air heater comprises two air channels, as seen in Figure 2. The upper channel comprises a sun absorber and a protective glass cover. The lower channel, positioned under the first channel, comprises an identical absorber plate on the top and an insulated plate on the bottom. The air entering the collector is bifurcated; 50% traverses the top channel, while the residual goes via the lower channel. In both channels, the airflow enters and exits immediately. This kind of solar air heater is referred to as a "double flow single pass." A double-flow single, pass solar air heater enhances the heat transfer area, potentially yielding superior thermal performance compared to a single flow single pass device at an equivalent mass flow rate [5].

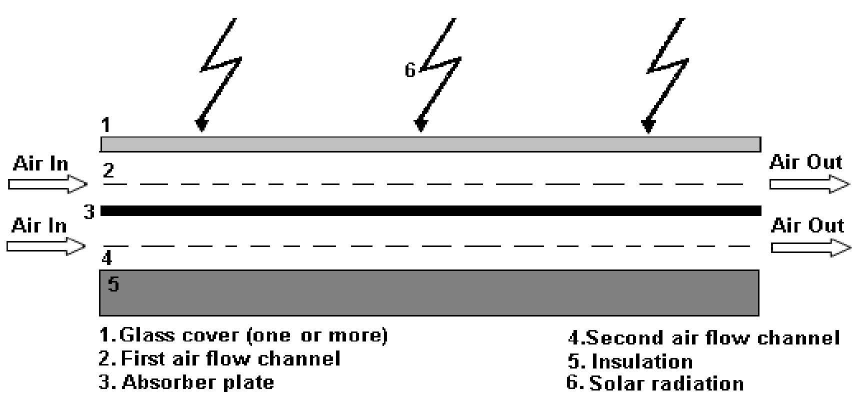

Fig.2. Double-flow Single-pass SAH

3) **Single-flow double pass SAH**

A single-flow double solar air heater has two overlapping airflow channels. Air traverses the upper channel, alters its trajectory at the channel terminus, and then enters the lower channel. It traverses directly across the lower channel. This form of solar air heater is referred to as a "single flow double pass." Literature reports two distinct builds of a single flow double pass solar air heater. Figure 3 depicts one of them. Two overlapping airflow channels are seen. The channels are partitioned by a glass or transparent sheet, with an absorber positioned at the base of the lower channel. Air is directed from the first and second transparent sheets to the absorber. The lower surface of the absorber is insulated. In the second design, the absorber plate is positioned as a divider between the upper and lower channels, as seen in Figure 4. The top airflow channel is created by the glass cover and the absorber plate, while the lower airflow channel is situated between the absorber plate and the insulated lower plate [6].

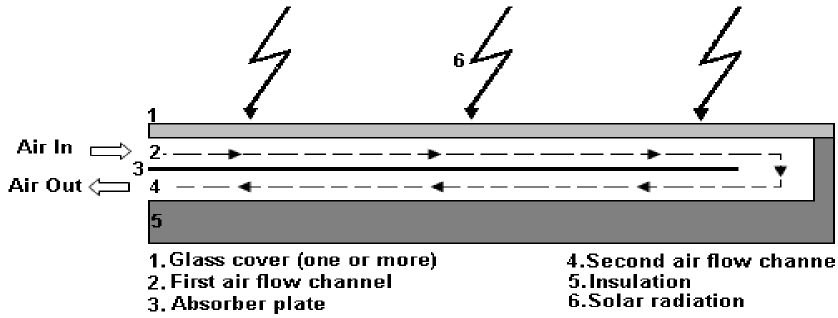

Fig.3. Single-flow double pass SAH

4) **Single Flow Recycled Double Pass SAH**
Incorporating recycled hot air into the design of a solar air heater may enhance its efficiency and regulate the air outlet temperature. The partial circulation of heated air may achieve the required air temperature at the output if the exit temperature differs from the target temperature. Figure (4) shows that the solar air heater has two channels. The upper channel is constituted by the glass cover above and the absorber plate below. The walls of the alternative channel are insulated. A segment of hot air is conveyed to the lower channel, subsequently entering the primary air flow channel [7]. This system has a single intake and output, which is why it is referred to as a “Single Flow Recycled Double Pass Solar Air Heater.”

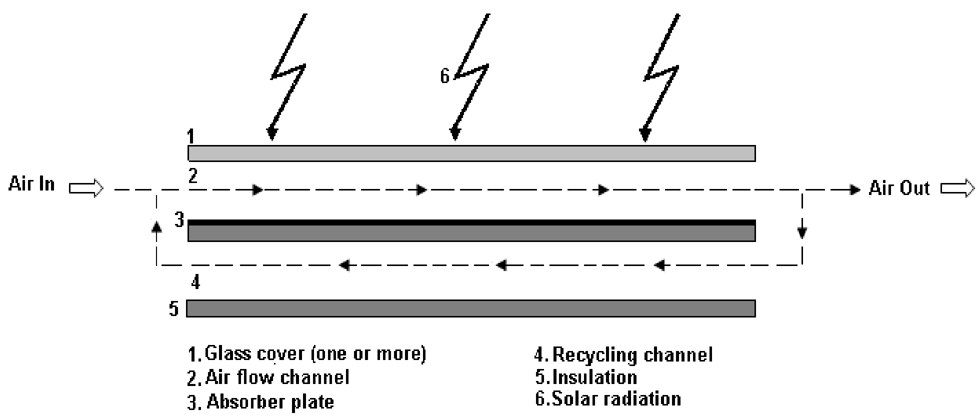

Fig.4. Single flow recycled double pass SAH

3.2 Based on Air Flow Configuration

Solar air heaters (SAHs) are devices that convert solar energy into thermal energy by heating air that passes through a heated absorber plate. The efficiency and performance of SAHs are significantly influenced by the type of absorber material used. Here's a classification of SAHs based on their absorber materials [8]:

1) **Metallic- Absorber SAH**
Metallic absorber plates are favoured for solar air heaters because of their durability, excellent thermal conductivity, and cost-effectiveness. Copper, aluminium, steel, and galvanised iron are often used materials, each with distinct benefits and downsides. Surface treatments such as painting and selective coatings may improve solar absorptivity and decrease thermal emissivity. Diverse design configurations, such as flat plates, corrugated plates, finned plates, and tube-in-plate designs, may enhance heat transfer and efficiency. Essential factors for metallic absorber plates include corrosion resistance, thermal

stress, pressure drop, and cost. Through meticulous material selection, the application of suitable surface treatments, and design optimisation, one may develop highly efficient solar air heaters capable of successfully harnessing solar energy [8].

2) **Non-Metallic- Absorber SAH**

Non-metallic absorbers in solar air heaters are constructed from materials such as polymers (e.g., polycarbonate or polyethene), ceramics, or composites, providing cost-effectiveness, lightweight design, and resistance to corrosion. These absorbers are often covered with black paint or infused with solar-absorbing pigments to augment their thermal absorption efficiency. Polymers are often used in economical home applications and small-scale drying systems because of their cost-effectiveness and simplicity of production despite having poorer heat conductivity than metals. Ceramics, recognised for their thermal endurance, are appropriate for medium-to-high-temperature applications such as industrial drying, while composites integrate polymers with reinforcing agents like carbon fibres to enhance mechanical and thermal properties. Notwithstanding its benefits, including ease of customisation and UV resistance with suitable stabilisation, non-metallic absorbers encounter difficulties such as restricted high-temperature performance and vulnerability to UV deterioration without adequate treatment. These materials are extensively used in agricultural drying, domestic heating, and small-scale industrial operations, particularly in regions emphasising cost-effectiveness and lightweight systems. To enhance efficiency, coatings such as solar absorptive pigments or selective coatings are used to optimise sun absorption and reduce thermal emissivity [9]. Non-metallic absorbers achieve an equilibrium between cost and functionality, making them suitable for low-to-moderate temperature applications (derived from several sources, including research on sun drying technologies and developments in polymer absorbers).

3) **Matrix- Absorber SAH**

Matrix-absorber solar air heaters provide a substantial enhancement compared to traditional flat-plate collectors. Incorporating a porous matrix onto the absorber plate improves heat transfer and thermal efficiency in these systems, as shown in Figure (5). The porous matrix, usually composed of materials such as metal foam, ceramic beads, or gravel, offers an extensive surface area for heat exchange, hence optimising the absorption of solar energy. The augmented surface area results in elevated heat transfer rates and diminished thermal losses. Moreover, the matrix has the capability to retain thermal energy, allowing sustained heat emission post-sunset. Matrix-absorber solar air heaters have several benefits, although they also include problems, such as heightened pressure drop and the need for meticulous material selection and design optimisation. Nevertheless, continuous research and development initiatives aim to tackle these difficulties and enhance the performance of these systems [10].

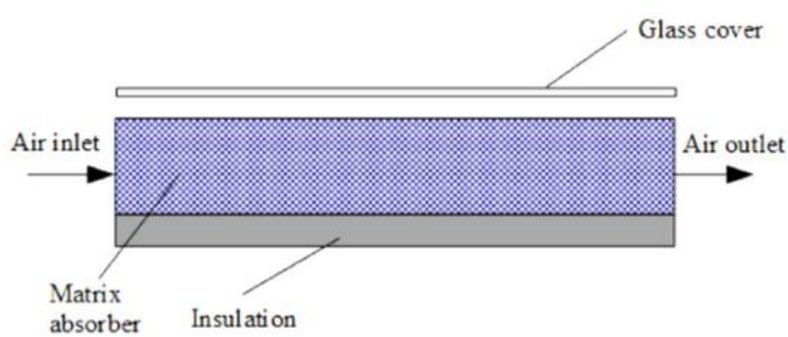

Fig.5. Matrix- Absorber SAH [11].

3.3 Based on Air Flow Configuration

Solar air heaters may be categorised according to the shape of the absorber since this shape affects heat absorption and transfer efficiency, along with the system's design and use. The configuration of the absorber influences the surface area, the interaction with airflow, and the overall efficacy of the heater. The main classes of solar air heaters are determined by the configuration of the absorber [12].

1) **Flat Plate SAH**

Flat-plate solar air heaters represent the predominant category of solar collectors, characterised by a straightforward design that incorporates a flat absorber plate, usually coated in black, situated inside an insulated enclosure as in Figure (6). Transparent glass covers the upper section to permit sunlight penetration, therefore heating the absorber, which then warms the air circulating through the system. This design's simplicity renders it cost-effective and extensively used for household heating, small-scale agricultural drying, and pre-heating air in industrial operations. Nonetheless, while the flat-plate design is straightforward to produce and install, it exhibits worse thermal efficiency relative to more intricate systems, mostly owing to its reduced surface area for heat absorption and constrained heat transfer capability.

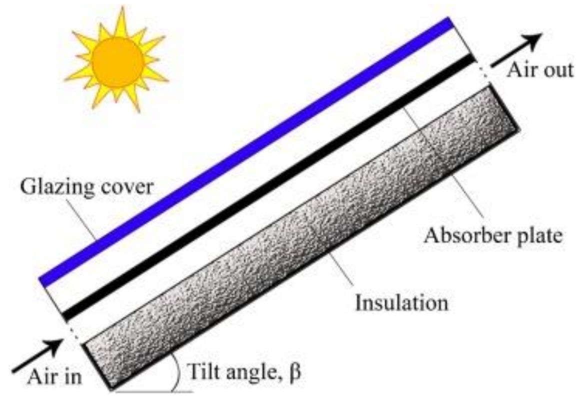

Fig.6. Flat Plate SAH

2) **Corrugated absorber SAH**

Corrugated absorber solar air heaters are a prevalent design that significantly improves the thermal efficiency of these systems. Incorporating corrugations or ribs on the absorber plate's surface significantly enhances the effective surface area for heat transfer. This leads to enhanced heat absorption and transfer to the air passing through the collector. The corrugated form also induces turbulence in the airflow, therefore increasing heat transfer. Furthermore, the corrugations may mitigate thermal losses by decreasing the contact surface between the heated absorber plate and the colder environment. The increased surface area and turbulence may result in elevated pressure drops; however, meticulous design and optimisation may alleviate this issue. Corrugated absorber solar air heaters are an economical and effective means of capturing solar energy for many uses, including room heating, water heating, and drying operations.

A V-corrugated absorber plate may significantly improve the heat transfer coefficient relative to a flat plate, as shown in figure (7). A sinusoidal corrugated plate may provide ideal performance for heat transfer and pressure drop. By meticulously choosing the corrugation geometry, including amplitude, wavelength, and orientation, the thermal efficiency of the solar air heater may be enhanced.

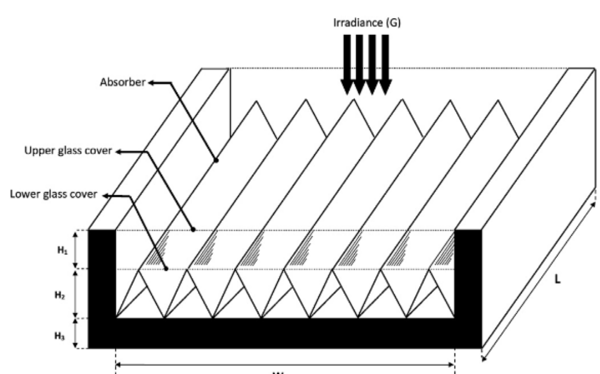

Fig.7. Corrugated absorber SAH

3) **Finned absorber SAH**

A finned absorber solar air heater is an effective solar energy device that heats air using an absorber plate with connected fins, which enhance the surface area for heat transfer. The system operates by capturing solar energy via the flat absorber plate, usually constructed from materials with high thermal conductivity, such as aluminium or copper. The thermal energy from the plate is conveyed to the air flowing over or through the affixed metal fins, as shown in Figure (8), which are optimally arranged to enhance airflow and heat transfer [14]. As air traverses the collector, it is heated, and this warm air is then pumped into a structure or used for particular purposes, such as drying procedures. The fins are essential for improving the thermal efficiency of the system by augmenting the effective surface area in contact with the air, resulting in more effective heat transfer from the plate to the air. This architecture renders the system particularly efficient for situations necessitating uniform and swift air heating. These heaters are often used for room heating, agricultural drying, and industrial purposes, offering a sustainable alternative to conventional energy sources. The primary benefit of finned absorber solar air heaters is their simplicity and cost-effectiveness relative to more complex systems such as liquid-based solar thermal collectors. Their adaptability facilitates incorporation into many environments, including residences, greenhouses, and industrial facilities. In agricultural contexts, solar air heaters equipped with finned absorbers are used to effectively dehydrate fruits, vegetables, and grains, leveraging improved heat transfer to minimise drying durations and energy expenditures. In building heating systems, these heaters may pre-heat air prior to its entry into a building's HVAC system, hence decreasing total energy use. Finned absorber solar air heaters provide a practical and environmentally sustainable method for harnessing solar energy to satisfy various heating and drying requirements, emphasising efficiency via the strategic use of fins to improve heat transfer.

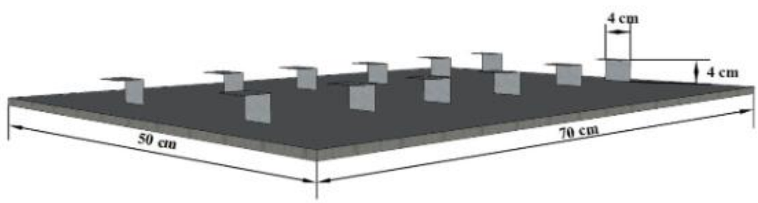

Fig.8. Finned absorber SAH

4) **Porous absorber SAH**
A porous absorber solar air heater employs a porous medium, often composed of metal or ceramic, as the absorber surface to harness and convey solar energy to the air. The material's porosity enhances the surface area for thermal exchange, facilitating more efficient absorption of solar radiation and improved heat transmission to the air passing through or over the absorber. The air traverses the pores or porous surface, where it absorbs heat, making this technology more efficient than conventional flat-plate solar air heaters. Improved heat transmission is especially beneficial for applications like space heating, drying, ventilation in buildings, and industrial operations. Porous absorber solar air heaters have advantages, including diminished thermal losses and enhanced heat efficiency owing to the augmented contact area, making them a viable choice for sustainable and economical solar thermal systems [15].

3.4 Based on the application

A porous absorber solar air heater employs a porous medium, often composed of metal or ceramic, as the absorber surface to harness and convey solar energy to the air. The material's porosity enhances the surface area for thermal exchange, facilitating more efficient absorption of solar radiation and improved heat transmission to the air passing through or over the absorber. The air traverses the pores or porous surface, where it absorbs heat, making this technology more efficient than conventional flat-plate solar air heaters. Improved heat transmission is especially beneficial for applications like space heating, drying, ventilation in buildings, and industrial operations. Porous absorber solar air heaters have advantages, including diminished thermal losses and enhanced heat efficiency owing to the augmented contact area, making them a viable choice for sustainable and economical solar thermal systems [15].
1) Space heating

- **Residential Space Heating**: Solar air heaters are used to provide thermal energy for residences, hence diminishing reliance on traditional heating methods such as gas or electric heaters.

- **business Space Heating**: Analogous to home heating, but on an expanded size, solar air heaters may be used in business edifices, workplaces, or public venues.

2)Applications in Industry:

- **Process Heating**: Solar air heaters are used in sectors requiring heated air, including the drying of agricultural goods, textiles, and food processing.

- **Building material heating**: Solar air heaters are used to elevate air temperature for the curing of concrete, ceramics, and other construction materials.

- **Agricultural Drying**: Solar air heaters are used to desiccate crops such as grains, fruits, and vegetables, therefore decreasing moisture content without reliance on fossil fuels.

3)Ventilation

- **Active Ventilation Systems**: Solar air heaters facilitate ventilation in buildings or greenhouses by heating and circulating air, enhancing the interior environment.
- **Greenhouse Applications**: Solar air heaters are used to control temperature in greenhouses, hence maintaining a consistent growth environment for plants.

4) Desalination and Water Purification

- **Solar Air Heating for Desalination**: Certain systems use solar-heated air with water to generate potable water via desalination or evaporation.

5) Drying

- **Solar Dryers for Wood or Food Products**: In several sectors, solar air warmers are incorporated into drying systems for goods like lumber or food, facilitating a reduction in energy expenses via the use of solar energy.

4. ENHANCEMENT OF SOLAR AIR HEATERS PERFORMANCE

Solar energy principles still involve solar energy, which converts saline/impure water to pure potable water by evaporation and condensation, as shown in figure (1). When the solar radiation heats the basin water quickly and evaporates, this vapour condenses at low-temperature surfaces, such as glass or plastic, and this vapour can be collected as pure water. The process can be made more efficient by advanced materials and technologies, e.g. various nano-coated films, ultrasonic atomisers, etc., for enhanced evaporation and condensation rates [10]. Design is also crucial; tubular solar still provides better evaporation surfaces and thermal performance [11]. These advanced designs and materials integrated solar stills aim for better productivity and efficiency for portable water purification, especially in regions with scarce fresh water.

4.1 Enhanced Collector Design

- Improved absorber surface: The efficiency of solar air heaters is mostly contingent upon the absorber material and its surface area. Employing materials with increased absorptivity, such as selective coatings or blackened metallic surfaces, may improve the capture of solar light. These materials absorb a greater amount of sunlight and transform it into thermal energy, which is then transported to the air.
- Improved Collector Geometry: Creating collectors with increased surface areas or specialised geometries (e.g., flat-plate collectors or concentrator designs) enhances heat absorption and optimises heat transfer efficiency. Integrating heat-absorbing fins or incorporating reflectors around the collector may enhance the exposure to sunshine on the absorber.
- Double Glazing: Double glazing, consisting of two layers of glass or transparent material separated by an air gap, mitigates heat loss via convection. This is particularly significant for systems functioning in colder climates, where heat retention is essential for enhancing performance [18].

4.2 Optimization of Flow

- Enhanced Air Circulation: The velocity of air movement through the collector is a critical determinant of efficiency. If the airflow is very rapid, the air will fail to acquire sufficient heat; conversely, if it is too sluggish, it will dissipate heat to the surrounding environment prior to entering the collector. The collector design may be modified to sustain optimal airflow velocity for enhanced heat transfer efficiency [19].

- Fan-Assisted Circulation: In several solar air heaters, particularly active systems, using fans or blowers to propel air through the collector may enhance the airflow rate and prolong the retention of heat in the air. Solar-powered fans are optimal since they may function concurrently with the system's heating capacity and save energy [20].
- The placement of air inlets and outputs is crucial for optimising air circulation efficiency. Strategically positioned inlets may inhibit the escape of hot air, while appropriately located outlets facilitate the maintenance of ideal air pressure and flow, so assuring efficient heat transmission.

4.3 Integration With Thermal Storage

- Thermal Energy Storage: Solar air heaters may enhance their efficiency by including thermal energy storage devices, such as thermal mass (e.g., water tanks or substantial stone masses) that retain heat for use when solar energy is inaccessible (e.g., during nighttime or overcast conditions). These systems maintain regular interior temperatures and reduce dependence on auxiliary heating systems by storing heat and releasing it gradually [21].
- Phase Change Materials (PCMs) may be included in solar air heating systems to enhance efficiency. These materials accumulate thermal energy by undergoing a phase transition (from solid to liquid) upon heat absorption and then release it during solidification. Phase Change Materials (PCMs) mitigate temperature variations and enhance the thermal storage capacity of the system [22].

4.4 Reflective and Absorptive Coatings

- Utilization of Reflectors: Incorporating reflecting materials around the collector may enhance the concentration of sunlight on the absorber surface. Reflectors may augment the quantity of solar energy the collector absorbs, thereby improving the system's efficiency. These reflectors must be oriented at precise angles to maximise solar exposure throughout the day [23].
- Selective coatings on absorber plates, such as black chrome or copper-based coatings, enhance solar absorption while reducing radiative heat losses. These coatings are designed to absorb sunlight within the visible and infrared spectra while emitting less heat at elevated temperatures [24].

4.5 Hybrid Systems

- Integration with Other Renewable Technologies: To enhance efficiency and provide a more dependable energy supply, solar air heaters may be combined with other renewable energy systems, such as solar photovoltaic (PV) panels or wind turbines. Excess energy produced by a photovoltaic system may be used to operate fans or pumps inside the solar air heater system, guaranteeing reliable functionality even under low-light situations [25].
- Hybrid Solar-Air and Solar-Water Systems: In some instances, solar air heaters may be integrated with solar water heaters to form a hybrid system. The surplus thermal energy from the solar air heater may be used to heat water, so a multifunctional heating system that addresses both air and water heating requirements must be established [26].

4.6 Automation and Control Systems

- Intelligent Control Systems: Contemporary solar air heating systems may integrate automation and intelligent controls to enhance performance according to meteorological circumstances, diurnal cycles, and interior temperature specifications. Sensors can monitor the temperature of heated air and alter fan speeds or collector angles in real time, assuring maximum efficiency without operator intervention [27].
- Adaptive Algorithms: Certain sophisticated systems use adaptive algorithms that analyse usage patterns and environmental circumstances to optimise settings for peak performance. These systems may evaluate data from temperature, sun radiation, and other sensors to enhance operational efficiency for energy saving [28].

4.7 Maintenance and Monitoring

- Routine Maintenance of Collectors: Accumulation of dust, dirt, and debris on the collector's surface may markedly diminish its performance by obstructing sunlight and hindering optimal heat absorption. Consistent cleaning and upkeep of the solar collectors are crucial for sustaining optimal performance [29].
- System Performance Monitoring: Ongoing surveillance of system metrics, including air temperature, sun radiation, and flow rates, facilitates the detection of inefficiencies and guarantees optimal operational

performance. Monitoring systems may identify problems such as obstructions or equipment failures, facilitating prompt repair.

5. COCNCLUSIONS

We reviewed the several types of solar air heaters and the numerous methods used to improve their efficiency. Solar air heaters are essential for decreasing energy consumption and enhancing sustainability, positioning them as a vital component of renewable energy solutions for space heating, industrial uses, and agricultural activities. We categorised solar air heaters according to their uses, emphasising their versatility in residential, commercial, industrial, and agricultural sectors, demonstrating their capacity to reduce reliance on traditional energy sources.
The efficiency of solar air heaters may be markedly increased by several means, such as better collector design, optimised airflow systems, thermal storage integration, the use of reflecting and absorptive coatings, and sophisticated heat exchanger technology. These approaches optimise heat transport and guarantee optimal use of solar energy, even amid fluctuating climatic circumstances. Moreover, the integration of hybrid systems, automation, and monitoring methodologies may enhance optimal performance and provide more dependable energy production. With the increasing need for clean and renewable energy solutions, solar air warmers emerge as a potential technology for household and industrial applications. Their adaptability, economic efficiency, and ecological advantages make them an essential instrument in the shift towards sustainable energy systems. Future progress in material science, system integration, and energy storage will improve the efficiency and application of solar air heaters, allowing them to address the varied and increasing energy demands ahead.

Conflicts Of Interest

The author's paper explicitly states that there are no conflicts of interest to be disclosed.

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