Thermal Efficiency Enhancement of Solar Air Heaters through CFD-Based Review of Rib Geometries

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Abstract

Solar air heaters (SAHs) are clean, efficient technology for low-grade thermal applications such as space heating, crop drying, and preheating with ample solar irradiation. This study emphasizes the augmentation of SAH performance by optimizing design, most specifically artificial geometry of roughness on the absorber plate. Different rib configurations including V-shaped, multi-V-shaped, and gap-V ribs have been analyzed via Computational Fluid Dynamics (CFD) to determine their thermal-hydraulic performance. The outcome indicates that enhanced rib geometries highly enhance convective heat transfer through the destruction of the boundary layer and turbulence generation, where the multi-V-shaped ribs display an optimum relationship between pressure drop and heat transfer. Besides, this study also discusses other significant parameters affecting SAH performance such as collector geometry, airflow management, reflective coatings, and integration with thermal energy storage systems like phase change materials (PCMs). Intelligent control systems, automation, and hybrid systems with photovoltaic systems or solar water heaters are also discussed to enhance operation efficiency. High solar insolation and seasonal variations—render it a proper place to deploy optimized SAHs. Combination of state-of-the-art CFD tools with innovative rib concepts represents a fertile path for forthcoming investigations to establish cost-effective, climate-resilient, high-efficiency solar air heating systems.

Keywords: Solar air heater, Computational Fluid Dynamics (CFD), Rib geometry, V-shaped ribs, Heat transfer enhancement, Thermal-hydraulic performance, Phase Change Materials (PCMs), Renewable energy, Artificial roughness.

I Introduction

Utilizing solar radiation to heat air, solar air heaters (SAHs) are renewable energy sources that provide environmentally friendly solutions for industrial operations, agricultural drying, and space heating. Due to their low environmental effect, low cost, and basic technology, these systems are essential to the renewable energy landscape [1]. A collecting surface that is frequently painted black to absorb solar radiation, glazing a transparent cover made of glass or plastic that traps heat by the greenhouse effect and protects the collector, insulation on the back and sides to prevent heat loss, and airflow which moves air over or through the heated collector, where it absorbs heat through conduction and convection are some of the system's basic components [2]. Depending on how the system is designed, it may also have additional features like single-pass (air flows along the collector surface only once), double-pass (air is moved from one collector surface to another to increase heat transfer), or porous media (with porous materials or perforated plates to improve absorption and heat exchange). Together, these parts provide warm air for a variety of uses, making solar air heaters affordable, simple to use, and eco-friendly choices for lowering energy consumption. [3].

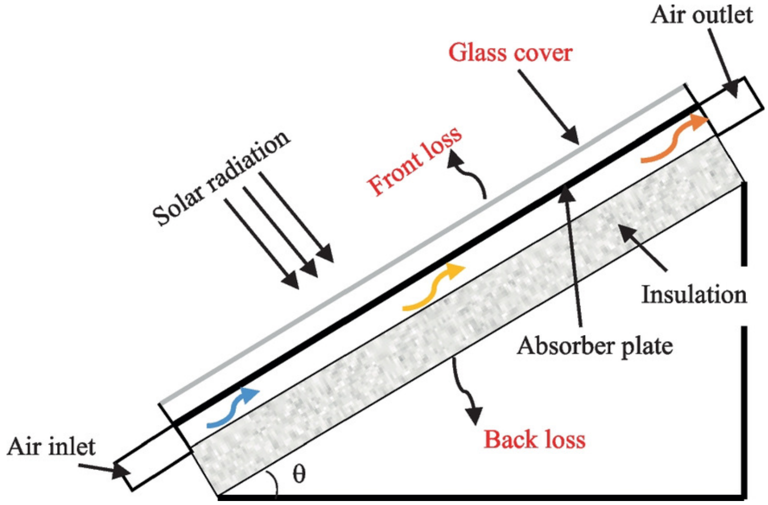

Fig.1 Typical solar air heater (SAH) [4]

Figure 1 shows a generic Solar Air Heater (SAH) and indicates the key components and heat transfer processes involved. The solar radiation passes through the transparent surface (glass cover), and reaches the absorber plate, which allows the conversion of the solar energy into heat. The air passes through the inlet to the surface of the absorber plate and upon hitting the absorber plate, the air exits as heated air out of the outlet. To reduce thermal inefficiencies, the bottom and sides are covered with insulation. However, some energy is inevitably lost as front loss (through the glass cover) and back loss (through the insulated base). The system is installed at a tilt angle (θ) to optimize solar capture based on geographical latitude. This design is key to passive solar heating systems and emphasizes efficiency through controlled air movement and minimized heat losses.

An apparatus used to heat air as an energy-transfer medium that has many benefits over liquid is called a solar air heater (SAH). Liquid solar heaters are vulnerable to a number of issues, including corrosion, fluid leakage, and power transfer issues. By employing air rather than liquid in solar heating equipment, all of these issues are resolved. The SCS distributes the cold air that the SAH gathers from the space's bottom. These straightforward techniques and direct transfers are useless at night or in depressing situations because they don't retain heat. [5].

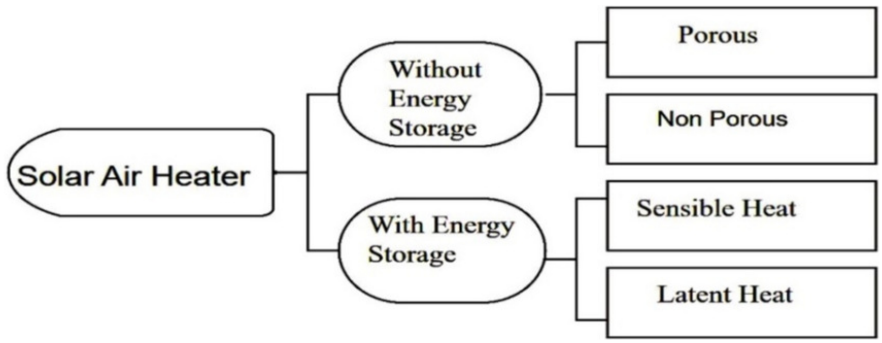

Fig. 2 Classification of solar air heaters [6]

Figure 2 shows the subdivision of solar air heaters in accordance with whether energy storage systems exist or not. Solar air heaters are broadly split into two: without storage and with storage. The non-storage variety is in turn sub-classified as porous and non-porous systems in accordance with whether the absorber medium structure permits porous or is non-porous, as these conditions determine airflow dynamics and heat transfer. Conversely, storage-type solar air heaters are classified according to the type of stored heat: sensible heat, in which energy is stored by heating a medium (such as rocks or water), and latent heat, in which energy is stored through phase change materials (PCMs) that capture/reject heat in phase changes. This categorization helps to clarify the efficiency of operation and suitability for application among various SAH designs.

Solar air heaters (SAHs) can be generally categorized according to airflow configuration, absorber material, and absorber shape—each playing a critical role in thermal performance and use. According to airflow, SAHs consist of single-flow single-pass, double-flow single-pass, single-flow double-pass, and recycled double-pass types, each design promoting heat transfer through channel variation and air recirculation [7]. According to absorber material, SAHs use metallic (e.g., copper, aluminum), non-metallic (e.g., polymers, ceramics), or matrix absorbers (e.g., porous media such as foams or beads) in order to maximize thermal conductivity, cost, and longevity. As for the shape of the absorber, designs vary from flat plates to sophisticated geometries such as corrugated, finned, and porous surfaces that enhance surface area and turbulence, thus improving heat transfer [8]. These categories allow for specific design of SAHs for various uses, ranging from residential heating to farm drying and industrial applications, especially in areas prioritizing cost-effectiveness and use of renewable energy [9].

II Enhancement of Solar Air Heaters Performance

As illustrated in figure (3), solar energy is still used in solar energy principles to transform saline or unclean water into pure drinking water by evaporation and condensation. This vapor condenses at low-temperature surfaces, such glass or plastic, and can be collected as pure water when the solar radiation rapidly heats the basin water and causes it to evaporate. Advanced materials and technologies, such as different nano-coated films and ultrasonic atomizers, can increase the process' efficiency.for enhanced evaporation and condensation rates [10]. Design is also crucial; tubular solar still provides better evaporation surfaces and thermal performance [11]. Better productivity and efficiency for portable water purification are the goals of these cutting-edge designs and materials integrated solar stills, particularly in areas with limited fresh water supplies.

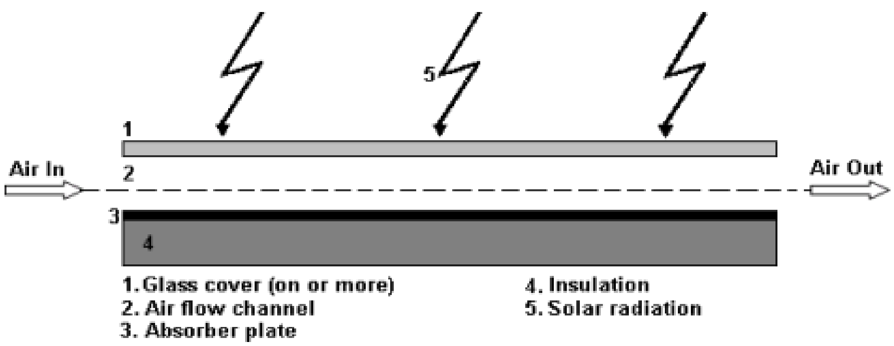

Fig.3 Single-flow Single-pass SAH

A. Enhanced Collector Design

The performance of solar air heaters depends to a great extent on the absorber surface properties and general design of the collector. Improving the absorber surface by using high solar absorptivity materials such as blackened metal surfaces or selective coatings considerably enhances the capacity to absorb and utilize solar radiation in converting it into thermal energy, which is transferred to the air passing through the system. Furthermore, the geometry of the collector is critical in enhancing performance [12]. Collector geometries that expand surface area, for example, flat-plate designs or concentrator systems, allow for better heat absorption. The installation of heat-absorbing reflectors or fins around the collector further increases the maximum incident solar energy on the absorber surface [13]. Another important design factor is double glazing, or two layers of transparent material (generally glass) with a gap between the layers. This design minimizes convection heat loss and is particularly advantageous in colder climates where it is desirable to retain as much heat as possible in order to achieve the overall efficiency of the heater. These additions all contribute to a more efficient and stable solar air heater. [14].

B. Optimization of Flow

Higher airflow is an important factor in improving the performance of solar air heaters, because the rate of flow is directly correlated with the amount of heat absorbed by the air. If air flows too quickly, it won't have enough time to absorb heat; too slowly, and it may lose heat to the surroundings before exiting. To find the sweet spot for airflow and improve heat transfer, the design of the collector can be adjusted to control airflow velocity [15]. In active systems, most commonly using solar-powered fans or blowers, air is moved by a type of fan-assisted circulation system that is designed to control and boost airflow delivering consistent heating with less energy use. Also, the proper strategic location of air outlets and inlets is critical; well-placed inlets avoid losing heated air, while properly located outlets ensure adequate air pressure and direction of airflow, both factors that assist in efficient and consistent heat distribution within the system [16]

C. Integration With Thermal Storage

Incorporating thermal energy storage into solar air heaters can greatly improve their efficiency by allowing the heat obtained from solar energy to be captured and utilized at times other than when solar radiation is available (i.e. night, cloudy periods, etc.). Thermal mass elements can be incorporated into a solar air heater in the form of water tanks, or basic mass elements like dense stones that can absorb and store large amounts of heat energy from the sun during times of solar radiation and can be released gradually afterwards to stabilize indoor temperatures and to mitigate dependence on auxiliary heat [17]. Furthermore, more sophisticated thermal storage can be achieved using Phase Change Materials (PCMs), which offer advanced thermal storage solutions. PCMs are able to capture thermal storage through phase transitions (typically from solid to liquid) and release it when it solidifies. Best of all, PCMs is great in supporting consistent thermal behaviour, primarily to flatten out temperature fluctuations, and extending the duration of time energy in stored and available. If properly utilized, PCMs can greatly increase the efficiency of solar air heating systems, offering direct benefits. [19].

D. Reflective and Absorptive Coatings

Using reflectors in a solar air heater will increase the system performance by adding more sunlight on top of the absorber surface area, and therefore capturing more solar energy as well. Correctly oriented reflectors will help to ensure that the sunlight will be available to the solar heater throughout the day, and this insures heat will be effectively absorbed by the solar heater. Selected coatings, comprised of materials like black chrome and copper, applied to the absorber plate area will further enhance performance. Selective coatings increase the solar absorptivity of the plate while lowering the potential for radiative heat losses. Selective coatings are engineered to absorb the entire visible and infrared spectrum while emitting very little heat, thus further increase the potential for thermal retention [20]

E. Hybrid Systems

Coordinating solar air heaters with other renewable energy technologies is a viable way to improve the efficiency and reliability of solar air heaters. Integration makes the solar air heater system's energy output much more consistent and diverse. For example, a solar photovoltaic (PV) panel could generate more electricity than is needed to operate the fans/pumps being powered in the solar air heating system. When the solar air heaters pump warm air during cloudy periods or in the winter, they are still able to provide a thermal source of heat filling heat loss gaps [21]. Integrated systems create hybrid models. For instance, if solar air heaters were integrated with water heaters powered by PV electricity, the thermal energy that was produced by the solar air heaters could also be used for heating water. This arrangement achieves two thermal energy heating systems in one, maximizing the usage of renewable energy and offering the advantage of an integrated system that would produce wind/solar energy to heat both water and air. [22]

F. Automation and Control Systems

Modern solar air heating systems are increasingly incorporating intelligent control technologies to optimize performance dynamically based on real-time environmental and operational conditions. By using automation and sensor-based controls, these systems can monitor variables such as solar radiation, ambient temperature, and heated air output to automatically adjust fan speeds, airflow rates, or even collector tilt angles, ensuring maximum efficiency throughout varying meteorological conditions and diurnal cycles without requiring manual intervention [23]. Furthermore, advanced systems are equipped with adaptive algorithms that analyze historical usage data and environmental inputs to fine-tune operations proactively. These algorithms can predict optimal system settings by learning from temperature patterns, solar intensity, and user preferences, thereby maximizing energy efficiency and delivering consistent thermal comfort while reducing overall energy consumption [24].

III Rib Geometries for Heat Transfer Augmentation

The purpose of the ribs, which are situated on the surface of the absorber plate and aid in improving the efficiency of the solar air heaters, is to transfer the most heat and raise the pressure inside the cabin. Ribs can increase a solar air heating system's efficiency, and this technology can be utilized to generate power, improve heat transport, and meet global energy needs. [25]. V-shaped ribs are a common artificial roughness geometry for solar air heaters aimed at improving heat transfer by enhancing the turbulence of the flow. Placed on the bottom of the absorber plate, the ribs break the laminar boundary layer, ensuring improved mixing of air and enhanced convective heat transfer. The "V" angle (referred to as the attack angle), rib height, pitch, and direction of orientation all have an effect on thermal performance. V-shaped ribs are especially efficient as they produce secondary flows and re-circulating zones that augment heat transfer without a high pressure drop. The design is in a balance between improved thermal efficiency and acceptable friction losses, thus being compatible for application in a solar air heater under high-performance conditions. Multi V ribs are an advanced roughness design in solar air heaters to positively enhance the heat transfer performance. This artificial roughness design features Multi V rib now with gap and this is a V rib, but rather than a single V rib there are a series of V ribs, with each rib being placed in the same V configuration along the absorber plate spacing them close to create multiple re-circulating zones and increasing turbulence, as the number of V ribs increases the area exposed to airflow and disturbance to the boundary layer also increases, resulting in higher convective rates to the absorber plate. Since the V ribs intersect in the multi-V ribbed, increased secondary flow circulation is also allowed and improved thermal mixing is achieved without increasing friction losses or pressure drop. Multi-V ribs is very efficient in solar air heater applications and could be applied in systems to achieved maximum thermal energy output of absorption or based on the volume of the system [27]. The gap V-shaped rib multi design is further extended artificial roughness for solar air heaters and reduces the heat transfer performance while controlling the pressure loss at the same time better. The gap multi V shape rig consists of many V shape ribs along the absorber plate but designed with intentional gaps in the center of the rib lines or at intervals along the rib lines. Such openings serve a useful purpose; they break the steady flow separation to allow some air to reattach, which limits further excessive pressure drop, and dead zones. There will be turbulent intensity and thermal mixing close to the ribs, but overall flow distribution is improved. Thus, the gap V-shaped rib with multi-V shapes provides a better tradeoff for increased heat transfer vs. frictional losses in performance-critical systems (such as solar air heating systems). [28].

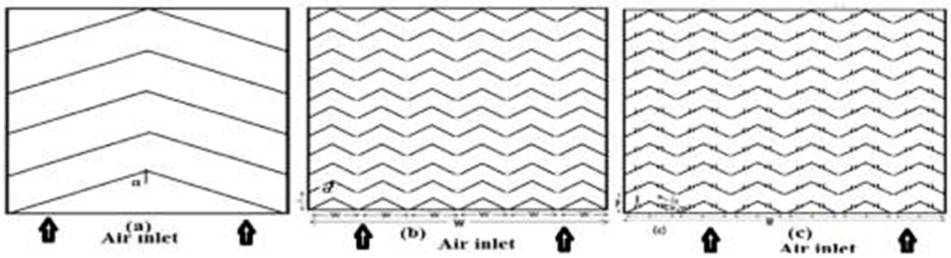

Fig. 4 Ribs geometries: (a) V-shaped, (b) Multi v-shaped and (c) Multi v-shaped with gap [29].

Figure 4 displays three various geometries of ribs utilized as artificial roughness elements on the absorber plate of solar air heaters for the improvement of heat transfer. Subfigure (a) displays the V-shaped ribs, where ribs are uniformly arranged in a V-pattern with a specific angle of attack (α), generating secondary flows and turbulence at the surface. Subfigure (b) shows the multi-V-shaped ribs, where repeated, densely spaced V-patterns on the absorber plate create highly intensified turbulence intensity and convective heat transfer by multiple flow interruptions. Subfigure (c) introduces the multi-V-shaped ribs with gaps, where intentional interruptions or gaps along the rib lines are added. These gaps interrupt the continuity of the flow separation to enable partial reattachment and even air distribution, thus lowering the pressure losses but with high thermal performance. Each of the three configurations targets thermal efficiency enhancement for solar air heaters with different combinations of heat transfer improvement and resistance to flow.

IV Computational Fluid Dynamics (CFD) in Performance Evaluation

Computational fluid dynamic (CFD) is the science of predicting fluid flow and heat transfer through solving governing equations with the assistance of numerical analysis. Many studies have been documented in the literature on designing solar air heaters experimentally avoiding computer limitations and the complexity of flow such as in references [30]. Due to the development in numerical methodology, computer and hardware, CFD has grown to be an established tool in the field of solar air heating systems design including critical investigations [31]. A simple principle is used in CFD which includes the discretization of the entire geometry through small cells or grids and employing governing equations to determine the numerical solutions in terms of temperature gradients, pressure distribution, and flow parameters [32]. This takes a short time and low cost resulting in a significant reduction in the experimental cost. When CFD is used to design solar air heaters, it should be taken into consideration a challenge in selecting the appropriate turbulence model which requires sufficient experience from researcher. A computational model is a set of several equations which are solved in coupling with appropriate forms of continuity and momentum equations to approximate the behavior of Reynolds stresses [33].

Different geometries of ribs have been explored with Computational Fluid Dynamics (CFD) simulation for improving thermal performance of solar air heaters. S-rib shapes studied by RNG k-ε turbulence model in a structured 3D mesh configuration resulted in a highest thermal-hydraulic performance parameter (THPP) of 1.48 at a Reynolds number of 11,000 [34]. A comparative analysis of several rib cross-sections—semi-circular, circular, rectangular, square, and triangular—utilizing the SST k-ω model and unstructured mesh exhibited a much higher THPP of 2.75 at Re = 18,700 [39]. Multi V-shaped ribs, tested under comparable turbulence modeling with a structured mesh, achieved a THPP of 2.35 at Re = 10,000 [35]. Conical protrusion ribs and semi-elliptical ribs, simulated using RNG k-ε on hybrid and unstructured meshes separately, resulted in THPPs of 1.35 at Re = 16,000 and 1.15 at Re = 18,000 [36]. Square wave profiled ribs showed a THPP of 1.43 at Re = 12,000 with RNG k-ε simulation and unstructured meshing [37], whereas rectangular-sectioned tapered ribs achieved 1.91 in the same conditions [38]. Arc and V-shaped rib geometries employing SST k-ω modeling resulted in 2.21 at a significantly reduced Reynolds number of 3,000 [39]. Aerodynamically shaped ribs like NACA 0040 profiles proved to be extremely effective, producing a THPP of 2.53 by 2D structured mesh analysis at Re = 6,000 [40]. Sophisticated geometries consisting of multiple T- and Y-type ribs indicated relatively fair performance at a THPP of 1.79 under Re = 7,000 [41], while twisted ribs, modelled with unstructured mesh-based SST k-ω modeling, displayed a THPP of 2.1 for Re = 10,000 [42]. The research reflects that the design of ribbing and calculation procedure both are primarily responsible for deciding thermal performance efficiency and pressure loss in solar air heaters.

TABLE 1 CFD analysis of various rib geometries used in solar air heaters

Reference No.	**Rib Geometry**	**CFD Tool / Model**	**Mesh Type**	**Max THPP**	**Reynolds No.**
[34]	S-shaped ribs	RNG k-ε	3D Structured	1.48	11,000
[39]	Semi-circular, circular,	SST k-ω	3D Unstructured	2.75	18,700

	rectangular, square, triangular				
[35]	Multi V-shaped ribs	RNG k-ε	3D Structured	2.35	10,000
[36]	Conical protrusion ribs	RNG k-ε	3D Hybrid	1.35	16,000
[36]	Semi-elliptical ribs	RNG k-ε	3D Unstructured	1.15	18,000
[37]	Square wave profiled ribs	RNG k-ε	3D Unstructured	1.43	12,000
[38]	Rectangular-sectioned tapered ribs	RNG k-ε	3D Hybrid	1.91	12,000
[39]	Arc and V-shaped ribs	SST k-ω	3D Unstructured	2.21	3,000
[40]	NACA 0040 profile ribs	RNG k-ε	2D Structured	2.53	6,000
[41]	T- and Y-shaped ribs	SST k-ω	3D Unstructured	1.79	7,000
[42]	Twisted ribs	SST k-ω	3D Unstructured	2.10	10,000

This table 1 highlights how both rib geometry and computational methodology (like turbulence models and mesh types) critically affect the thermal-hydraulic performance parameter (THPP) of solar air heaters.

V Climatic Considerations

Central India, being tropical in climate, has a good climate for the efficient application of solar air heaters. It receives high solar irradiance with an average value of 5–6 kWh/m²/day, particularly between the summer months of March to June, which allows efficient collection of solar energy. Ambient temperatures during this period can reach well above 40°C, and thus solar air heaters can find use in processes such as crop drying, pre-heating in industrial processes, and space heating in shaded areas [43]. During winter (December to January), while the surrounding temperature varies from 8°C to 25°C, the higher temperature difference between the absorber surface and the surrounding air increases convective heat transfer, thus enhancing the thermal efficiency of the system.

Nevertheless, some climatic issues in Central India also need to be overcome for regular solar air heater performance [44]. The monsoon months (June to September) experience high humidity and high cloud cover, which diminishes the amount of direct solar radiation. This necessitates the inclusion of thermal storage systems like phase change materials (PCMs) or high-thermal-mass materials to accumulate heat during bright days for utilization on cloudy or rainy days. In addition, dust deposition as a result of dry winds and air pollution can cause a considerable decrease in the transmissivity of the glazing and the absorptivity of the collector surface, requiring periodic cleaning or the application of anti-soiling coatings. In addition, moderate wind speeds prevalent in certain locations can augment natural ventilation through the system with potential for designing passive or hybrid SAHs with reduced dependence on active elements such as fans, promoting energy efficiency and robustness on a year-round basis [45].

VI Future Scope for Rib Pattern Design and CFD Integration

The future of solar air heaters' rib pattern design is in the innovation of high-performance, next-generation geometries that realize optimal heat transfer with low pressure drop. New ideas like bio-inspired, fractal, or hybrid geometries of the ribs can potentially augment turbulence and enhance efficiency of heat exchange. Adaptive rib designs and next-generation thermal materials have the potential to optimize performance under different circumstances. On the computational front, the combination of sophisticated CFD methods such as Large Eddy Simulation (LES), machine learning algorithms, and optimization methods such as genetic algorithms will enable more accurate and automated analysis of intricate flow phenomena. The combination of CFD with real-time data and digital twin models can make predictive maintenance and performance optimization possible, and solar air heaters more efficient, adaptive, and intelligent in future use.

VII Conclusion

This study determines that it is highly dependent on the absorber surface structure and incorporation of advanced computational models like CFD to improve the thermal efficiency of solar air heaters. Among several rib geometries, multi-V-shaped ribs and gap-designed ribs have the highest potential by developing turbulent air flow and maximizing heat transfer with tolerable pressure drop. With CFD simulations coupled to these designs, they can be optimized systematically for various operating conditions. Additionally, the combination of thermal energy storage (such as PCMs), reflective coatings, and smart control systems dramatically enhances overall system performance, guaranteeing efficient operation under changing climatic conditions. Central India's high solar radiation and seasonal variability present an optimum test bed for such technologies. The complementarity of experimental results, CFD simulation, and climatic optimization allows for the creation of high-performance SAH systems that are both economically sustainable and energy efficient. Further research must target the combination of AI-driven optimization tools, real-time monitoring, and hybrid renewable configurations to further extend the role of solar air heating in domestic and industrial applications. This multidisciplinary approach makes solar air heaters develop further as a fundamental element of sustainable and decentralized energy solutions.

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