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Advancements in Ribbed Solar Air Heaters: A Comprehensive Review on Thermal Performance Enhancement and Optimization Techniques

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The global energy landscape is rapidly transitioning toward renewable sources to mitigate environmental impacts and address growing energy demands. Solar air heaters (SAHs) are pivotal in this transformation, offering cost-effective and sustainable thermal energy solutions for various applications such as space heating, drying, and industrial processes. However, conventional SAHs suffer from suboptimal thermal efficiency due to the low thermal conductivity of air and uneven heat transfer. This paper reviews the advances in enhancing SAH performance through the application of artificial roughness, particularly ribbed absorber plates. Experimental, numerical, and analytical studies are examined, highlighting the influence of rib geometries, materials, and operational parameters on heat transfer and pressure drop. Optimization techniques, including machine learning and computational methods, are discussed alongside emerging trends such as additive manufacturing and hybrid systems. Despite challenges like increased pressure drops and material sustainability, this review underscores the potential of ribbed SAHs to revolutionize renewable energy systems, paving the way for eco-friendly and efficient energy solutions.

Keywords: Solar air heaters (SAHs), Ribbed absorber plates, Artificial roughness, Heat transfer enhancement, Thermal efficiency, Pressure drop.

1. Introduction

The twenty-first century has seen a heightened emphasis on the essential interaction among energy, economy, and environment, collectively termed the "three Es." Historically, energy needs have been satisfied by fossil fuels; however, their detrimental environmental effects, such as air pollution, water contamination, and ecological disruption, have hastened the transition to renewable energy sources. Solar energy is a sustainable, environmentally friendly, and plentiful resource that has become significant for mitigating greenhouse gas emissions and tackling climate change issues [1].

Solar air heaters (SAHs) provide one of the most efficient and economical approaches of using solar energy. Solar air heaters (SAHs) are extensively used in applications including room heating, crop drying, and industrial operations, significantly enhancing energy efficiency and diminishing dependence on fossil fuels. A standard solar air heater consists of a clear glass cover, an absorber plate, and insulated walls. Solar radiation penetrates the glass cover, elevates the temperature of the absorber plate, and conveys this heat to the air circulating underneath it. Notwithstanding their simplicity, solar air heaters (SAHs) often suffer from inadequate thermal performance, mostly because to the poor thermal conductivity of air and the inconsistent heat transfer over the absorber plate [2].

Improving the efficiency of SAHs is crucial for their viability in large-scale applications. The integration of artificial roughness, namely ribs on the absorber plate, has emerged as a potential strategy. Artificial roughness interrupts the laminar sub-layer of airflow, generates turbulence, and promotes improved convective heat transfer. Ribs, extensively studied as a kind of artificial roughness, have considerable potential to enhance the heat transfer coefficient and minimise thermal losses while sustaining acceptable pressure drop levels [3, 4].

The progression of rib designs has been characterised by ongoing innovation and exploration. Initial designs used basic transverse ribs, which, although efficient, were constrained by high frictional losses. Subsequent study presented inclined, V-shaped, W-shaped, and hybrid arrangements to optimise the balance between heat transfer increase and pressure drop. These designs use intricate flow dynamics to generate secondary flows and turbulent mixing, which are crucial for enhancing thermal performance [5]. Fig. 1 showed the 3D printed ribbed structure.

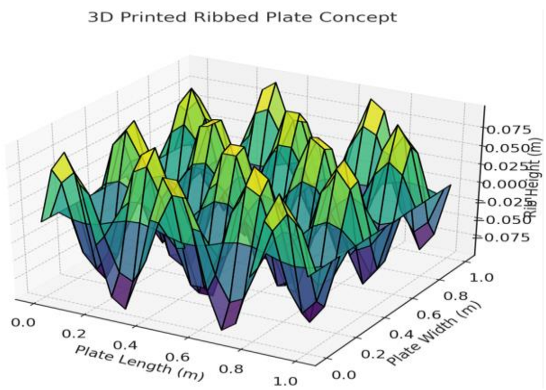

Figure 1. 3D printed ribbed structure

Recently, hybrid turbulators and three-sided ribbed arrangements have garnered interest because to their enhanced thermo-hydraulic performance. These designs seek to optimise the Nusselt number and reduce frictional penalties by integrating characteristics like as gaps, staggered configurations, and varying geometries. Moreover, sophisticated computational and experimental methodologies have enabled a more profound comprehension of the flow dynamics and heat transfer processes in ribbed solar air heaters, hence allowing for enhanced optimisation.

The configuration of ribs is affected by several geometric and operational factors, such as rib height, pitch-to-height ratio, angle of attack, and relative roughness. These metrics are essential in ascertaining the flow patterns, heat transfer rates, and pressure drops inside the SAH. An ideal pitch-to-height ratio guarantees efficient boundary layer disruption while minimising flow resistance. The angle of attack similarly affects the generation of vortices and secondary flows, which are crucial for improved thermal performance [8].

Experimental investigations have yielded significant insights into the influence of rib shapes on SAH performance. These studies generally assess metrics like the Nusselt number, friction factor, and thermal efficiency under regulated settings. Research has shown that V-shaped ribs may attain thermal efficiency levels up to 60% greater than those of smooth absorber plates. Inclined ribs, however, have shown the ability to generate whirling flows that enhance heat transfer while sustaining reduced pressure decreases [9].

Numerical models using Computational Fluid Dynamics (CFD) have become essential instruments for evaluating the efficacy of ribbed Solar Air Heaters (SAHs). CFD models provide comprehensive visualisations of flow patterns, temperature distributions, and turbulence intensities, enabling researchers to anticipate the effects of different rib designs on thermal performance. CFD studies have substantially enhanced the optimisation of rib designs and the formulation of empirical correlations for heat transmission and friction factor by supplementing experimental results [10, 11].

Notwithstanding the progress in rib design, obstacles persist in attaining the ideal equilibrium between heat transmission augmentation and pressure reduction. Excessive turbulence, while advantageous for heat transmission, may result in increased pumping power demands and decreased overall efficiency. Moreover, the longevity and manufacturability of ribbed absorber plates are essential factors, especially for extensive installations [12].

Current advancements in ribbed SAH design include the use of new materials, such composites and phase-change materials, to enhance heat conductivity and energy storage capabilities. The amalgamation of photovoltaic-thermal (PVT) systems with ribbed solar air heaters (SAHs) gives a significant opportunity for the concurrent production of thermal and electrical energy. Additionally, machine learning and optimisation methods are being investigated to determine the most efficient rib designs for certain applications [13].

This paper seeks to provide a thorough examination of the current advancements in ribbed SAH design and performance evaluation. This work aims to elucidate the principal elements affecting thermal performance by synthesising data from experimental, numerical, and theoretical investigations, while also identifying avenues for future research. The primary objective is to enhance the development of efficient, economical, and sustainable solar air heating systems that can facilitate the worldwide shift towards renewable energy.

2. Techniques for Enhancing Heat Transfer in Solar Air Heaters

The thermal efficiency of solar air heaters (SAHs) is fundamentally constrained by the poor thermal conductivity of air, which impedes effective heat transmission from the absorber plate to the air circulating underneath it. To tackle this difficulty, several heat transfer augmentation approaches have been investigated, including improved materials and geometric alterations. The use of artificial roughness on the absorber plate has shown to be one of the most efficient and cost-effective alternatives.

2.1. Artificial Roughness

Artificial roughness denotes the intentional incorporation of roughness components onto the absorber plate to disturb the laminar boundary layer and enhance turbulence. This method improves convective heat transmission with little pressure drop penalty. The predominant kind of artificial roughness involves the use of ribs, which are crafted in diverse forms, orientations, and combinations to enhance thermal performance. The following subsections examine the main kinds of artificial roughness and their influence on SAH performance.

2.2 Categories of Ribs

Transverse Ribs: These are the most basic kind of artificial roughness, orientated perpendicular to the direction of airflow. Transverse ribs efficiently induce turbulence yet may result in considerable pressure losses. Research indicates that increasing the rib height-to-spacing ratio may augment the thermal efficiency of transverse ribbed solar air heaters (SAHs) [16].

Inclined and V-Shaped Ribs: Inclined ribs, positioned at an angle to the airflow, and V-shaped ribs, which produce a chevron configuration, have been thoroughly investigated for their capacity to generate secondary flows. These designs increase turbulence and provide superior heat transmission relative to transverse ribs. V-shaped ribs have shown an enhancement of up to 60% in thermal efficiency compared to smooth absorber panels [17].

W-Shaped and Hybrid Ribs: W-shaped ribs and hybrid arrangements, which integrate several rib patterns, seek to optimise turbulence while reducing frictional losses. These designs often include elements like as gaps and staggered configurations to optimise heat transmission [18].

Discrete and Staggered Ribs: Rather of using continuous rib patterns, discrete and staggered ribs are used to interrupt the flow at designated intervals. This method reduces pressure losses while sustaining elevated turbulence levels in the flow field [19].

2.3 Geometric features

The efficacy of ribbed Solar Air Heaters (SAHs) is affected by many geometric features, including:

Rib Height (e): The elevation of the ribs influences the degree of flow disruption and turbulence production. Optimal rib height guarantees efficient heat transmission while minimising frictional losses [20].

The Pitch-to-Height Ratio (P/e) denotes the relationship between the spacing of ribs and their height, influencing the flow reattachment point and the degree of turbulence. A ratio of 8 to 10 is often advised for optimal thermal efficiency [21].

Angle of Attack (α): The alignment of the ribs in relation to the airflow influences the flow configuration and secondary vortices. Angles ranging from 30° to 60° are often ideal for sloped and V-shaped ribs [22].

Relative Roughness Height (e/D): The ratio of rib height to hydraulic diameter affects the friction factor and Nusselt number. An appropriate value guarantees improved heat transmission with minimum flow resistance [23].

2.4 Sophisticated Methods

Recent advancements in artificial roughness encompass:

Multi-Sided Roughness: The addition of ribs on numerous facets of the absorber plate, such as three-sided roughness, significantly improves thermal efficiency. This method has shown an efficiency enhancement of up to 40% relative to single-sided roughness [24]. Hybrid Turbulators: The integration of ribs with other roughness features, such as dimples or vortex generators, produces synergistic effects that enhance heat transmission while preserving acceptable pressure losses [25].

Dynamic Roughness: Adaptive systems that alter rib structure or spacing in real-time according to airflow conditions represent a burgeoning field of study. These systems have the possibility for excellent performance under diverse operating circumstances [26].

2.5 Substances and Coatings

The selection of materials and surface coatings is essential for the efficacy of ribbed solar air heaters (SAHs). Materials with high conductivity, like aluminium and copper, enhance heat transmission but may elevate expenses. Selective coatings exhibiting strong absorptivity and low emissivity significantly improve the thermal efficiency of the absorber plate [27].

2.6 Performance Metrics

The efficacy of heat transfer augmentation methods is assessed with measures such as:

Thermal Efficiency (η): The proportion of beneficial heat acquisition to the incoming solar energy.

Effective Efficiency (η_{eff}): Considers both thermal performance and penalties from pressure loss.

Thermal Hydraulic Performance Parameter (THPP): Equilibrates heat transfer augmentation with fluid flow resistance.

3. Rib Configuration and Geometric Parameters

The configuration of ribs is crucial for the thermal and hydraulic efficiency of solar air heaters (SAHs). Geometric aspects, including rib configuration, elevation, spacing, orientation, and material, substantially affect heat transmission and pressure drop characteristics. This section examines these characteristics comprehensively, emphasising their influence on the efficacy of SAHs.

3.1 Rib Morphology

The morphology of the ribs is a pivotal component in assessing their efficacy. Frequently utilised rib configurations comprise:

Square ribs provide uniform turbulence and are simple to fabricate, making them one of the most extensively researched layouts [28]. Triangular ribs provide increased turbulence intensity owing to their acute edges, resulting in improved heat transmission [29]. Semi-circular and trapezoidal ribs are often used to optimise the balance between heat transmission and pressure drop, facilitating mild turbulence while minimising frictional losses [30]. Fig. 2 showed the heat transfer vs pressure drop in ribbed plates

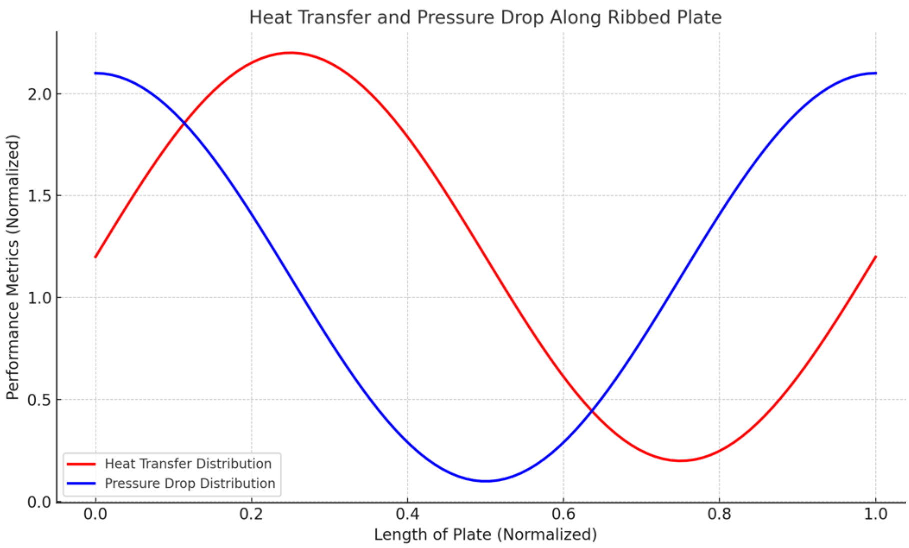

Figure 2. Heat transfer vs pressure drop in ribbed plates

3.2 Rib Orientation

The alignment of ribs in relation to the airflow direction considerably influences flow dynamics and heat transfer rates:

Transverse Ribs: These are orientated perpendicular to the airflow, generating significant turbulence and increased pressure decreases [31].

Inclined Ribs: Positioned at an angle to the airflow, inclined ribs provide whirling flows that improve heat transmission while minimising friction losses [32].

V-Shaped Ribs: These ribs provide a chevron configuration that generates secondary flows and enhances the homogeneity of heat transmission over the absorber plate [33]. Fig. 3 showed the different types of ribs with heat transfer efficiency

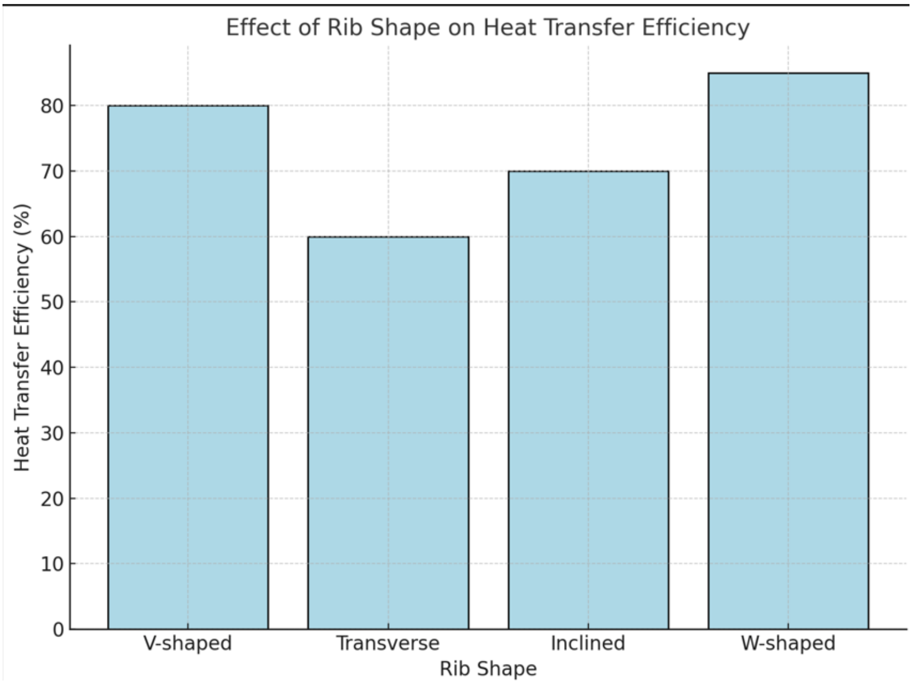

Figure 3. Different types of ribs with heat transfer efficiency

3.3 Rib Spacing and Height

The spacing (pitch) and height of the ribs are important factors that affect the reattachment point of airflow and the degree of turbulence. Optimal values of the pitch-to-height ratio (P/e) and relative roughness height (e/D) are essential for maximising heat transmission and minimising pressure drop penalties [34].

3.4 Multi-Sided Rib arrangements

Recent innovations in rib design have investigated multi-sided arrangements, whereby ribs are affixed to several sides of the absorber plate. This method markedly improves turbulence and heat transport, although it may elevate production complexity and costs [35].

3.5 Material Selection

The thermal conductivity and durability of the rib material significantly influence the performance of ribbed solar air heaters (SAHs). Materials with high conductivity, such as aluminium and copper, are favoured for optimising heat transmission, although potentially elevating total system expenses. Innovative materials such as composites and coatings exhibiting high solar absorptivity and low emissivity are being investigated to improve performance [36].

3.6 Optimisation of Geometrical Parameters

Optimisation approaches, including experimental design and computer modelling, are extensively used to ascertain the most efficacious combinations of rib geometry and operational parameters. Studies using the Taguchi technique and response surface methodology (RSM) have shown substantial improvements in thermal performance via the optimisation of rib design parameters [37].

4. Empirical Investigations

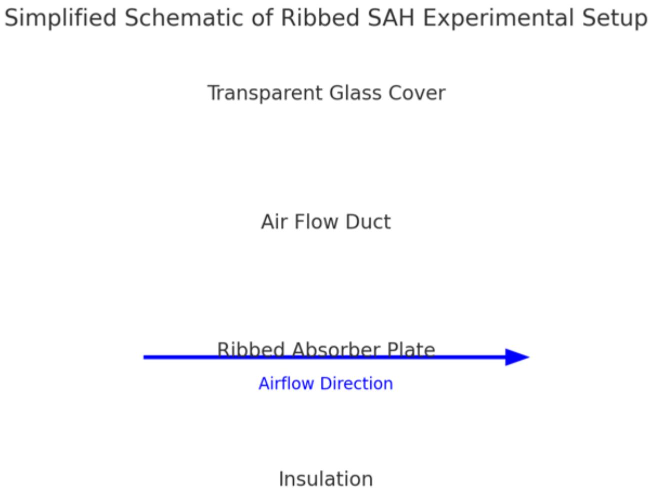

Figure 4. Schematic of a ribbed SAH design

Fig. 4 showed the schematic of a ribbed SAH design Experimental studies have yielded significant insights into the efficacy of ribbed solar air heaters under diverse operating situations. These studies have methodically assessed the influence of rib designs, materials, and ambient factors on thermal efficiency and pressure drop characteristics. Several essential elements comprise:

4.1 Impact of Rib Configuration

Experimental investigations have repeatedly shown that rib morphology considerably influences the thermal transfer efficiency of solar air heaters (SAHs). V-shaped ribs have been shown to surpass transverse ribs owing to their capacity to induce robust secondary flows and whirling motion. This intensified turbulence facilitates efficient airflow mixing, resulting in elevated Nusselt numbers and greater thermal efficiency [38]. W-shaped and hybrid rib designs have proven effective in enhancing heat transmission by optimising flow dynamics and reducing dead zones [39].

4.2 Inclined Ribs and Vortex Flows

Inclined ribs, positioned at an angle to the airflow, provide distinctive flow patterns marked by whirling movements. These turbulent flows more effectively disturb the thermal barrier layer than perpendicular ribs, leading to enhanced heat transmission. Experimental studies indicate that the ideal inclination angle ranges from 30° to 60°, contingent upon the rib height and pitch [40]. The tilt reduces the magnitude of pressure loss, making these structures very appropriate for practical purposes.

4.3 Rib Constituents and Thermal Conductivity

The selection of rib material is vital in influencing the overall efficacy of ribbed solar air heaters (SAHs). Materials with high conductivity, like as aluminium and copper, have been widely used in experimental configurations to optimise heat transmission. Nonetheless, these materials incur elevated production expenses. Researchers have investigated composite materials and coatings that possess high heat conductivity and are cost-effective to tackle this difficulty. Selective coatings exhibiting strong absorptivity and low emissivity have shown the ability to improve the thermal performance of ribs without substantially raising prices [41].

4.4 Impact of Airflow Velocity

Airflow velocity is a significant variable examined in experimental research. Increased velocities often result in enhanced turbulence and augmented heat transfer rates. Nonetheless, this results in heightened pressure decreases. Experimental configurations often use controlled conditions to ascertain the ideal airflow velocity that reconciles thermal efficiency and hydraulic losses [42].

4.5 Effects of Temperature

The temperature of the absorber plate and the incoming air considerably influences the thermal efficiency of ribbed solar air heaters. Experiments indicate that elevated absorber plate temperatures enhance convective heat transfer, but increasing input air temperatures diminish the temperature gradient, hence reducing the heat transfer rate. These results have resulted in the formulation of solutions for enhancing input air preheating and absorber plate design [43].

4.6 Environmental Conditions

Experimental investigations have investigated the influence of environmental factors, including ambient temperature, solar radiation intensity, and wind speed, on the efficacy of ribbed solar air heaters (SAHs). These considerations significantly influence the practical usefulness of rib designs. For example, variable wind speeds may modify convective heat transfer rates, while changes in solar radiation intensity influence thermal efficiency [44]. Fig. 5 showed the Nusselt number vs friction factor in ribbed design SAH's

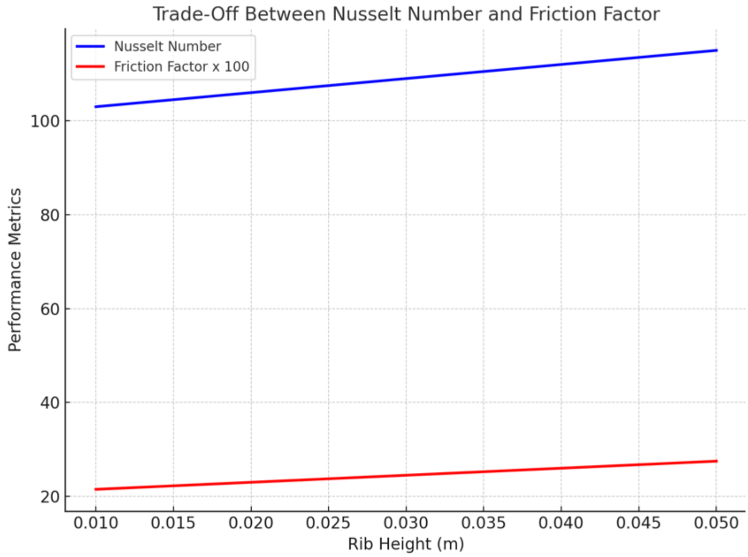

Figure 5. Nusselt number vs friction factor in ribbed design SAH's

4.7 Experimental Techniques and Verification

Diverse experimental techniques have been used to assess the efficacy of ribbed solar air heaters (SAHs). This encompasses infrared thermography for temperature distribution analysis, wind tunnel studies for flow visualisation, and hot-wire anemometry for turbulence intensity measurement. Experimental findings are often corroborated using numerical simulations to guarantee dependability and precision [45].

5. Quantitative and Qualitative Analyses

Numerical simulations using Computational Fluid Dynamics (CFD) are essential for the analysis of ribbed Solar Air Heaters (SAHs). These investigations provide comprehensive insights into intricate flow dynamics and thermal interactions, allowing researchers to refine rib topologies and improve overall system efficiency. Essential elements of numerical studies encompass:

5.1 Flow Patterns and Visualisation

CFD models provide accurate visualisation of velocity and temperature distributions, enabling researchers to examine the complex flow structures inside ribbed SAHs. These simulations demonstrate the emergence of secondary flows, instabilities in the boundary layer, and areas of recirculation, which are essential for comprehending heat transfer processes [46]. Through the analysis of flow patterns, researchers may pinpoint regions of stagnation and dead zones, which can be mitigated by optimising rib shapes.

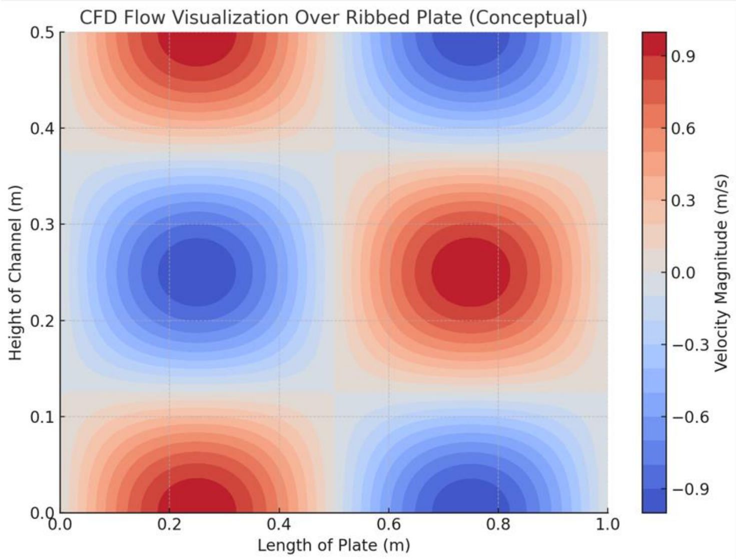

Figure 6. CFD visualization

5.2 Turbulence Modelling

The level of turbulence and its effect on heat transmission are critical factors in the effectiveness of ribbed solar air heaters. CFD techniques use sophisticated turbulence models, including k-ε, k-ω, and Reynolds Stress Models (RSM), to precisely forecast flow behaviour. These models measure turbulence levels, which closely correspond with heat transfer rates. Turbulence modelling assists in determining ideal rib arrangements that equilibrate heat transfer enhancement with pressure drop penalties [47]. Fig. 7 depicted the pareto chart of thermal efficiency

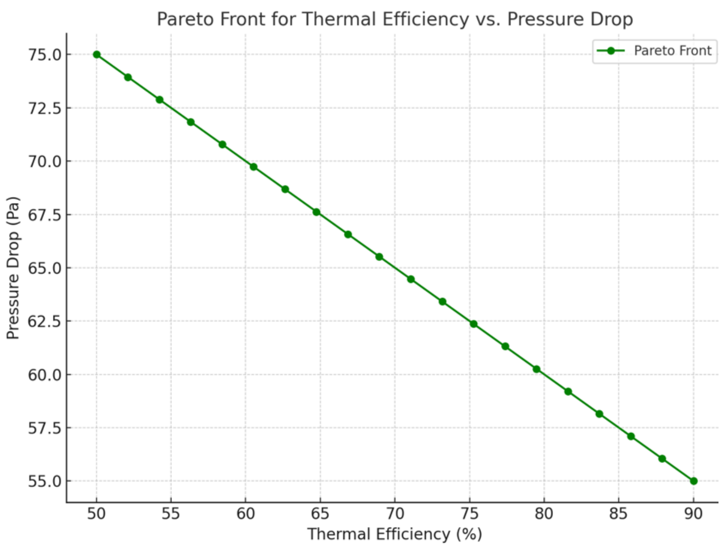

Figure 7. Pareto chart of thermal efficiency

5.3 Parametric Analyses and Optimisation

CFD simulations provide extensive parametric analyses to assess the impacts of geometric and operational variables, including rib height, pitch-to-height ratio, and angle of attack. These investigations provide the optimal layouts for enhancing thermal efficiency and reducing hydraulic losses. Optimisation methods, such as genetic algorithms and response surface methodology (RSM), have been incorporated with CFD tools to enhance the design process [48].

5.4 Verification using Empirical Data

Numerical results are often corroborated with experimental data to guarantee precision and dependability. Validation entails juxtaposing CFD predictions with empirical measurements of Nusselt number, friction factor, and temperature distribution. Discrepancies between numerical and experimental data are examined to enhance turbulence models and boundary conditions, resulting in more precise simulations [49].

5.5 Analytical Methodologies

Besides numerical methods, analytical techniques are used to establish correlations for heat transmission and friction factor in ribbed solar air heaters (SAHs). These correlations are founded on basic concepts of fluid mechanics and heat transmission, integrated with actual data from experiments. Analytical models provide rapid assessments of system performance and function as a standard for verifying numerical outcomes [50].

5.6 Emerging Trends in Quantitative Research

Recent progress in CFD tools and processing capabilities has facilitated high-resolution simulations and extensive parametric analyses. The use of machine learning algorithms to forecast performance measures using CFD data is a burgeoning topic. Moreover, hybrid methodologies that integrate computational fluid dynamics with empirical data are being examined to improve the precision and efficacy of numerical analyses [51]. By amalgamating numerical and analytical techniques, researchers get a profound comprehension of the intricate interplay between heat transport and fluid dynamics in ribbed solar air heaters, allowing creative designs and optimised configurations.

6. Metrics for Performance Evaluation

The assessment of the thermal efficacy of ribbed solar air heaters (SAHs) necessitates rigorous and dependable criteria that elucidate the equilibrium between heat transfer augmentation and corresponding energy losses. The following parameters are often used to evaluate the efficacy of ribbed SAHs:

6.1 Thermal Efficiency (η)

Thermal efficiency is the primary criterion for assessing the performance of solar air heaters (SAHs). It is defined as the ratio of the beneficial heat uptake by the air to the total incident solar energy.

Where is the beneficial heat gain, is the collector area, and is the intensity of solar radiation. Thermal efficiency measures the effectiveness of solar energy conversion into useable heat and serves as a key criterion for design enhancements [52, 53].

6.2 Thermal Hydraulic Performance Parameter (THPP)

THPP is a dimensionless measure that weighs the advantages of heat transfer improvement against the drawbacks of elevated pressure drop [54].

6.3 Trade-Off Evaluation

Optimising ribbed SAHs necessitates a compromise between the augmentation of heat transmission and the increase in pressure drop. Metrics such as THPP and effective efficiency assist designers in pinpointing setups that attain this equilibrium. Increasing rib height may improve heat transmission but also elevates the friction factor, necessitating a thorough evaluation of the overall advantages.

6.4 Multi-Objective Optimisation

Advanced optimisation methodologies, including multi-objective genetic algorithms and machine learning, are progressively used to concurrently optimise various parameters. These approaches allow the discovery of rib designs that optimise thermal efficiency and minimise pressure loss, offering customised solutions for particular applications [58]. Utilising these performance assessment parameters, researchers and designers may methodically assess and enhance ribbed SAHs, guaranteeing their practical feasibility and efficiency across various working situations.

7. Techniques for Optimisation

The design and development of high-performance ribbed solar air heaters (SAHs) are increasingly influenced by optimisation approaches that enable researchers to determine the most efficient rib layouts. These strategies integrate experimental, numerical, and computational methodologies to enhance thermal efficiency, reduce pressure drop, and attain an ideal equilibrium between the two. Principal optimisation methods encompass:

7.1 Taguchi Method

The Taguchi method is a resilient experimental design technique used to ascertain critical parameters and their optimum values. It used an orthogonal array to methodically investigate the impacts of various factors with a minimised number of tests. This approach optimises parameters for ribbed SAHs, including rib height, pitch-to-height ratio, and angle of attack. The Taguchi approach assesses the interaction effects among factors, allowing researchers to optimise the design for enhanced thermal efficiency [59].

7.2 Response Surface Methodology (RSM)

RSM is a statistical methodology used to model and optimise multi-variable systems. It entails the development of mathematical models to forecast system performance based on input characteristics. Response surface methodology (RSM) is used to create response surfaces for measures such as thermal efficiency and pressure drop in ribbed staggered array heat exchangers (SAHs). These surfaces facilitate the identification of ideal rib designs by evaluating the trade-offs among conflicting goals. RSM is especially efficacious for intricate systems characterised by the non-linear interaction of many variables [60].

7.3 Genetic Algorithms (GAs)

Genetic algorithms are optimisation methods derived on the principles of natural selection. They investigate extensive design spaces by iterative selection, crossover, and mutation of alternative solutions. Genetic algorithms are used to optimise rib designs, material choices, and operating parameters for ribbed SAHs. Through the assessment of performance measures like the Nusselt number and friction factor, genetic algorithms discern designs that attain an optimal equilibrium between heat transport and hydraulic losses. The probabilistic characteristics of genetic algorithms make them particularly effective for addressing multi-objective optimisation challenges [61].

7.4 Machine Learning

Machine learning has arisen as a potent instrument for predictive modelling and design optimisation in ribbed solar air heaters. Methods such as artificial neural networks (ANNs) and support vector machines (SVMs) are used to forecast performance measures based on input parameters. Machine learning algorithms are trained on experimental and numerical data to develop prediction models that inform the design process. Furthermore, reinforcement learning is being investigated for adaptive optimisation, whereby algorithms progressively enhance designs depending on input from simulations or tests [62].

7.5 Multi-Objective Optimisation

Ribbed SAHs sometimes need a compromise between opposing goals, such as optimising thermal efficiency and reducing pressure loss. Multi-objective optimisation methods, such as Pareto front analysis and weighted-sum procedures, are used to determine trade-off solutions. These methodologies provide designers with a variety of ideal configurations, enabling them to choose solutions according to unique application needs [63].

7.6 Hybrid Methodologies

The amalgamation of several optimisation strategies has shown efficacy for ribbed SAHs. Integrating RSM with GAs utilises the predictive modelling strengths of RSM with the exploratory capabilities of GAs. Likewise, machine learning methods are progressively integrated with computational fluid dynamics simulations to expedite the optimisation process. These hybrid methodologies provide a thorough foundation for addressing the intricacies of ribbed SAH design [64].

7.7 Practical Applications of Optimisation

Optimisation methods extend beyond laboratory investigations and are increasingly used in real-world applications. Optimised ribbed SAHs have been used in industrial drying systems, space heating, and agricultural applications. These designs exhibit improved performance and decreased operating expenses, confirming the efficacy of optimisation techniques [65].

7.8 Prospective Trends in Optimisation

Current advancements in optimisation include the use of sophisticated machine learning methodologies, such as deep learning and generative design. These methodologies provide the automated creation of rib configurations according to performance standards. Furthermore, real-time optimisation using Internet of Things (IoT) sensors is being investigated, enabling Smart Adaptive Homes (SAHs) to dynamically adjust to fluctuating environmental circumstances [66].

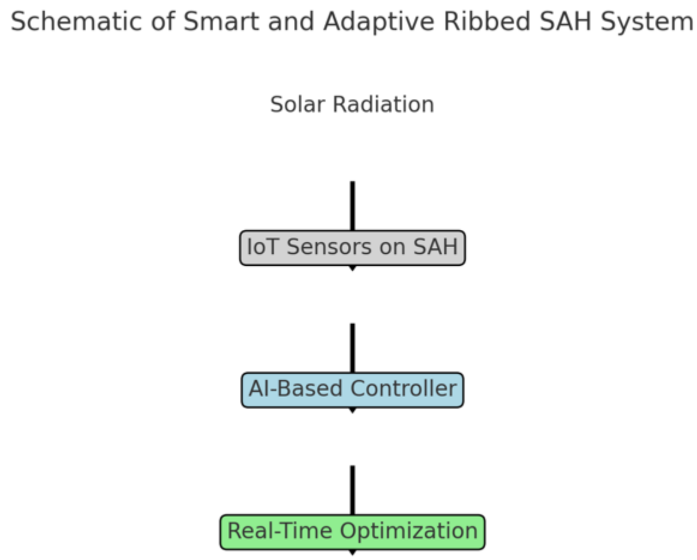

Figure 8. Schematic of ribbed SAH system

Figure 8 illustrated the schematic of ribbed SAH system. Utilising these innovative optimisation methodologies, researchers and engineers may create ribbed SAHs that provide enhanced performance, guaranteeing their practicality and sustainability across many applications.

8. Obstacles and Constraints

Notwithstanding considerable progress in the design and optimisation of ribbed solar air heaters (SAHs), several hurdles and restrictions impede their extensive acceptance and efficiency in practical applications. The difficulties encompass:

8.1 Pressure Drop

The principal trade-off linked to ribbed SAHs is the augmented pressure drop resulting from heightened turbulence. Turbulence enhances heat transmission but also elevates airflow resistance, necessitating more pumping power and escalating operating expenses. Achieving a balance between heat transfer increase and permissible pressure reductions is a significant issue for designers [67].

8.2 Selection of Materials

Selecting appropriate materials for ribbed solar air heaters is a multifaceted endeavour that necessitates a balance of thermal conductivity, mechanical resilience, and expense. High-conductivity materials such as copper and aluminium improve heat transmission; yet, they are costly and less sustainable. under contrast, inexpensive materials may undermine performance and durability, particularly under severe weather conditions [68].

8.3 Scaling and Practical Applications

The majority of rib design research is performed on laboratory-scale apparatus under regulated settings. Applying these insights to large-scale or real-world scenarios often uncovers unexpected hurdles, like unequal heat distribution, manufacturing limitations, and maintenance issues. Scaling these systems without sacrificing efficiency requires more research [69].

8.4 Environmental and Sustainability Issues

The ecological consequences of ribbed SAHs must be evaluated throughout production and disposal. Utilisation of metals and synthetic coatings may lead to carbon emissions and trash generation. Creating eco-friendly, recyclable, and sustainable materials is crucial for minimising the environmental impact of these systems [70].

8.5 Complexity of Optimisation

As rib arrangements advance in complexity, the optimisation process also intensifies. Multi-objective optimisation concerning thermal efficiency, pressure drop, cost, and environmental effect requires sophisticated computing resources and knowledge, potentially restricting its use in resource-limited environments [71]. Confronting these issues with creative designs, materials, and optimisation methodologies is essential for rendering ribbed SAHs a feasible alternative for renewable energy applications.

9. Emerging Trends

The future of ribbed solar air heaters (SAHs) depends on using technical innovations and sustainable methods to improve efficiency, lower expenses, and expand their use. Encouraging developments encompass:

9.1 Sophisticated Materials

The advancement of lightweight, high-conductivity, and environmentally sustainable materials is set to transform ribbed SAHs. Graphene, nanocomposites, and phase-change materials provide superior thermal performance and durability while reducing environmental effect. These advances may facilitate more sustainable manufacturing methods [72].

9.2 Hybrid Systems

The integration of ribbed solar air heaters (SAHs) with photovoltaic (PV) systems provides a twofold advantage: the creation of thermal energy and the production of electrical power. Photovoltaic-thermal (PVT) systems with ribbed absorber plates may attain enhanced overall efficiency by efficiently harnessing solar energy for both thermal and electrical applications. This method is especially beneficial for applications necessitating both energy types, such as household heating and electricity generation [73].

9.3 Additive Manufacturing and Three-Dimensional Printing

3D printing technology enables the fabrication of intricate and customisable rib shapes that were previously unachievable with conventional production techniques. Additive manufacturing allows meticulous control of rib configurations, dimensions, and placements, resulting in optimised designs that improve heat efficiency and minimise material use [74]. Figure 9 showed different types of ribbed structures

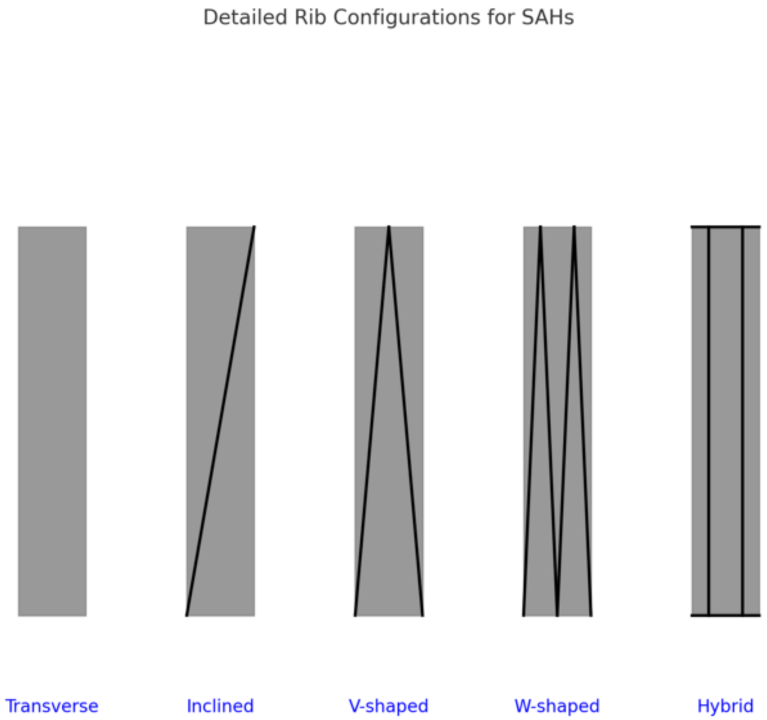

Figure 9. Different types of ribbed structures

9.4 Artificial Intelligence (AI) with the Internet of Things (IoT)

Artificial Intelligence and Internet of Things technologies are emerging as transformative forces in the design and operation of ribbed Solar Air Heaters. AI algorithms may enhance rib designs in real-time, while IoT sensors can assess system performance and adjust operating settings according to environmental circumstances. This adaptive method guarantees optimal efficiency and dependability under diverse settings [75].

9.5 Sustainable Production

Future ribbed SAHs would likely emphasise sustainable manufacturing processes, using renewable energy in manufacture, material recycling, and waste minimisation. These techniques correspond with global sustainability objectives and enhance the attractiveness of ribbed SAHs in environmentally aware markets [76].

9.6 Intelligent and Adaptive Systems

The incorporation of adaptive technologies that may modify rib topologies or airflow patterns in real-time is a potential research domain. These systems may dynamically enhance performance according to variables such as sun intensity, ambient temperature, and user demand, so assuring constant efficiency [77]. By adopting these emerging trends, ribbed SAHs may serve as a fundamental component of sustainable energy systems, providing improved efficiency, reduced costs, and wider application across many industries.

10. Conclusion

Ribbed solar air heaters (SAHs) represent a transformative advancement in renewable energy technology, addressing the critical need for efficient and cost-effective thermal systems. The integration of artificial roughness, particularly ribbed designs, has demonstrated substantial improvements in heat transfer and overall thermal performance. This review has explored the extensive body of research on rib geometries, materials, and optimization strategies, shedding light on the intricate balance between heat transfer enhancement and hydraulic losses.

Numerical and experimental studies have provided valuable insights into the dynamics of ribbed SAHs, enabling the development of optimized designs that cater to specific applications. Optimization methodologies, including genetic algorithms, response surface techniques, and machine learning, have further accelerated innovation in this field. Moreover, emerging technologies like 3D printing, hybrid photovoltaic-thermal systems, and IoT-based smart systems promise to elevate the functionality and sustainability of ribbed SAHs.

However, challenges such as pressure drop penalties, scaling issues, and environmental considerations remain significant barriers to widespread adoption. Addressing these limitations requires interdisciplinary approaches, combining advanced materials, computational models, and sustainable manufacturing practices.

In conclusion, ribbed SAHs hold immense potential to contribute to global renewable energy goals. By overcoming existing challenges and leveraging emerging trends, these systems can be integral to achieving energy efficiency and sustainability in diverse sectors. Future research should focus on adaptive designs, scalable solutions, and lifecycle sustainability to maximize the impact of ribbed SAHs in real-world applications.

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