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A COMPREHENSIVE REVIEW ON THERMO-HYDRAULIC PERFORMANCE OF SOLAR AIR HEATER DUCTS ROUGHENED WITH MULTI- V RIBS

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ABSTRACT

The enhancement of convective heat transfer in a Solar Air Heater (SAH) is a critical area of research aimed at improving the efficiency of solar thermal conversion systems. Among various passive techniques, the application of artificial roughness on the absorber plate has proven highly effective. Specifically, Multi-V ribs have emerged as a superior geometry due to their ability to create multiple secondary flow cells and promote intense mixing within the laminar sub-layer. This review paper provides an exhaustive synthesis of the latest advancements in Multi-V rib research, covering experimental methodologies, Computational Fluid Dynamics (CFD) simulations, and the development of empirical correlations. We analyze the influence of geometric parameters such as relative roughness height (e/D_h), relative roughness pitch (P/e), and rib angle of attack (α) on the Nusselt number (Nu) and friction factor (f). The paper concludes with a summary of 40 seminal and recent studies, identifying current research gaps and proposing future directions for high-performance SAH design.

1. INTRODUCTION

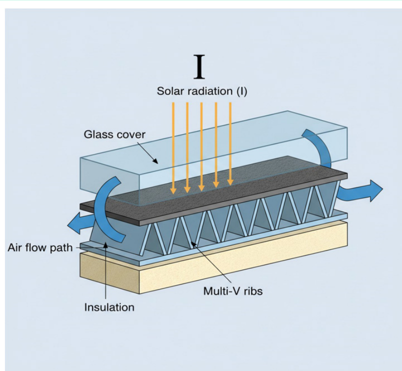
The global energy landscape is undergoing a paradigm shift toward renewable sources to mitigate the environmental impacts of fossil fuel combustion. Solar energy, being abundant and sustainable, stands at the forefront of this transition. A Solar Air Heater (SAH) is a simple device that captures solar radiation and converts it into thermal energy for applications such as crop drying, space heating, and industrial processing.

Despite their simplicity, SAHs suffer from inherently low thermal efficiency. This is primarily due to the low convective heat transfer coefficient of air and the formation of a stagnant viscous sub-layer near the absorber plate, which acts as a thermal resistance. To overcome this, researchers employ artificial roughness on the underside of the absorber plate.

The Role of Artificial Roughness: By introducing small-scale protrusions (ribs), the laminar sub-layer is periodically broken and re-established. This creates local turbulence and secondary flow patterns that enhance heat transfer without requiring excessive pumping power.

Evolution of Rib Geometries: Research has evolved from simple transverse ribs to inclined, V-shaped, and eventually Multi-V ribs. The Multi-V configuration as in Figure 1 is particularly effective as it multiplies the number of leading edges and secondary flow vortices across the width of the duct.

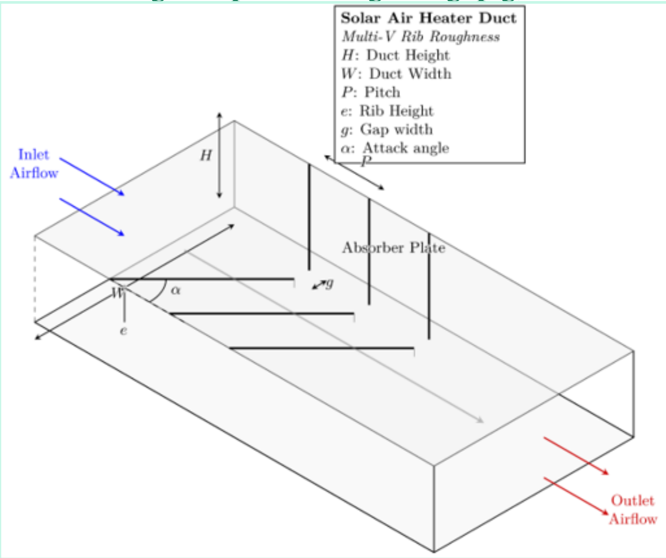
Fig. 1: Multi-V configuration



1.2 Evolution of Roughness Elements

- Transverse ribs: Nu↑1.5x, high f.[2]
- Inclined/V-ribs: Directed vortices, η~1.5.[5]
- **Multi-V ribs:** Breaks single V into n segments across width W, creating 2n counter-rotating cells migrating from walls to center, multiplying high-heat zones. Variants: discrete, gapped, perforated.

Fig. 2: SAH Schematic with Multi-V Ribs (Insert your CAD drawing: duct height H, width W, rib height e, pitch P, angle α, gap g).[1]



1.3 Scope and Objectives

- Analyze parameters' effects on Nu, f, η.
- Propose generalized correlations.
- Identify gaps for AI/Homer-optimized designs.[6] [1]

2. THEORETICAL FRAMEWORK

2.1 Dimensionless Parameters

Flow regime: turbulent Re = 3,000–30,000 (typical SAH).[1]

$$D_h = \frac{2WH}{W+H}, Re = \frac{\rho v D_h}{\mu}, Pr = \frac{C_p \mu}{k}$$

Heat transfer:

$$Q_u = \dot{m} C_p (T_{out} - T_{in}), h = \frac{Q_u}{A_s (T_{p,m} - T_m)}, Nu = \frac{h D_h}{k}$$

Friction:

$$\Delta P = f \frac{L}{D_h} \frac{\rho v^2}{2}, f = \frac{\Delta P D_h}{2 \rho v^2 L}$$

Performance:

$$\eta = \frac{(Nu/Nu_s)}{(f/f_s)^{1/3} (Re_s/Re)^{0.125}}$$ (accounts blower power).

Smooth correlations: Dittus-Boelter Nu = 0.023 Re^{0.8} Pr^{0.4}, Blasius f = 0.316 Re^{-0.25}.

2.2 Flow Physics in Multi-V Ribs

Each V-segment produces pair of vortices (strength α e, sinα); Multi-V: lateral interference amplifies mixing, Figure 3. Leading edges thin BL; reattachment ~5–7e downstream high-Nu.

Fig. 3: Secondary Flow Cells (2-cell V vs. 12-cell Multi-V n=6).

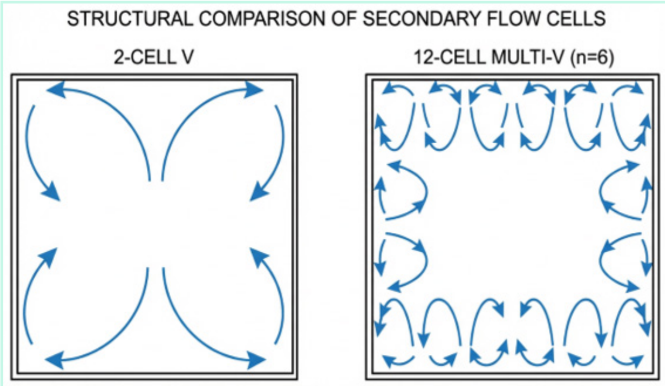


Table 2.1: Geometric Parameters

Parameter	Definition	Typical Range	Optimal (η max)	Effect on Nu/f
e/D_h	Rib height / D_h	0.015–0.08	0.04	↑↑ / ↑↑↑ [8]
P/e	Pitch / height	6–20	10	Peak / min [9]
α (deg)	Attack angle	45–90	60	Max swirl / mod [5]
W/w	Width ratio	4–12	6	↑ vortices / ↑ [8]
g/e	Gap ratio	0.2–1	0.5	↓ recirculation / ↓ [10]

2.3 Heat Transfer Mechanisms

- Pre-rib acceleration.
- Impingement post-rib.
- Vortex-induced mixing.[3]

3. RIB GEOMETRIES AND ENHANCEMENTS

3.1 Standard Multi-V

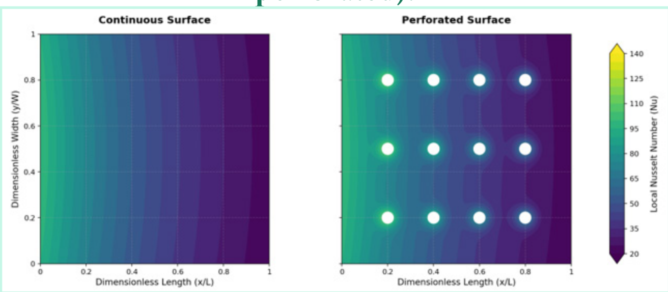
Hans (2010): n=6, e/D_h=0.037, P/e=10, Nu=2.0x, f=4.1x, η=1.98 (Re=3–20k).

3.2 Advanced Variants

- **Discrete/Gapped: Singh (2015):** g/e=1, η=2.15 (↓f 20%).
- **Perforated DPPF:** Singh (2022): d/W=0.3, Nu↑4.89x, η=9.66 (double-pass).[4]
- **Staggered/Trapezoidal:** Gill (2015): W/w=6 opt, Nu↑2.45x.
- **Arc/Slots: Deo (2016):** g/e=0.25–0.5, f↑2.83x.

Variant	Study	Nu Enhance	f Penalty	η Peak	Re Opt
Continuous Multi-V	Hans 2010	2.0x	4.1x	1.98	12k
Gapped	Singh 2015	2.3x	3.5x	2.15	10k
Discrete	Kumar 2017	2.4x	3.2x	2.32	15k
Perforated DPPF	Singh 2022	4.89x	2.0x	9.66	18k
Staggered	Patil 2018	2.1x	2.8x	2.10	-

Fig. 4: Local Nu contours (continuous vs. perforated).



4. GOVERNING EQUATIONS AND DIMENSIONLESS PARAMETERS

To evaluate the performance of a roughened SAH, we rely on fundamental fluid mechanics and heat transfer equations. The flow is generally characterized by the Reynolds number (*Re*), which for a rectangular duct is defined as:

$$Re = \frac{\rho \cdot v \cdot Dh}{\mu}$$

Where:

ρ is the density of air (kg· m^{-3})

v is the average velocity (m· s^{-1})

μ is the dynamic viscosity (Pa· s)

Dh is the hydraulic diameter, calculated as $D_h = \frac{4WH}{2(W+H)}$ for a duct of width W and height H.

a. Heat Transfer Analysis

The useful heat gain (Q_u) by the air is given by:

$$Q_u = \dot{m} \cdot C_p \cdot (T_{out} - T_{in})$$

The convective heat transfer coefficient (h) is then derived from:

$$h = \frac{Qu}{Ap \cdot (Tpm - Tam)}$$

Where T_{pm} is the mean plate temperature and T_{am} is mean air temperature. This is non-dimensionalized as the Nusselt number:

$$Nu = \frac{h \cdot Dh}{k}$$

b. Fluid Flow Analysis

The pressure drop (ΔP) across the duct length (L) is represented by the friction factor (f):

$$f = \frac{\Delta P \cdot Dh}{2 \cdot \rho \cdot L \cdot v^2}$$

5. MECHANICS OF MULTI-V RIBS

The Multi-V rib geometry is an advancement over the simple V-rib. In a standard V-rib, two secondary flow cells are created that move from the center toward the walls (or vice versa). In a Multi-V arrangement, the rib is broken into multiple "V" segments across the width.

a. Flow Physics

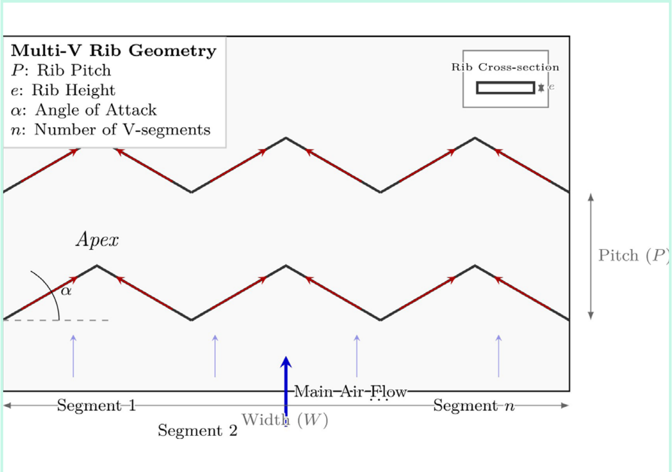
The enhancement mechanism in Multi-V ribs is attributed to:

i. **Secondary Flow Generation**: Each "V" segment generates a pair of counter-rotating vortices. In a Multi-V setup, the number of these vortices increases proportionally with the number of V-shaped segments (n).

ii. **Leading Edge Effect**: The points of the "V" (apexes) act as leading edges where the boundary layer is thinnest, resulting in localized high heat transfer zones.

iii. **Flow Acceleration**: The ribs constrict the flow locally, increasing the kinetic energy near the wall.

Fig. 4: Multi-V ribs geometry



6. GEOMETRIC PARAMETERS AND THEIR INFLUENCE

The performance of Multi-V ribs shown in figure 4 is sensitive to several non-dimensional geometric ratios.

Relative Roughness Height (e/D_h): Typically ranges from 0.02 to 0.05. Increasing e/D_h enhances Nu by protruding further into the turbulent core but significantly increases f.

Relative Roughness Pitch (P/e): Usually optimized around 10. If P/e is too small, the flow skips over the ribs (skimming flow); if too large, the boundary layer re-establishes itself completely, reducing the average Nu.

Angle of Attack (α): Research consistently shows that an angle of 60° to 75° is optimal for Multi-V ribs to maximize the strength of secondary flows.

Number of V-segments (W/w **or** n): Increasing the number of V-loops across the width increases the number of high- heat-transfer regions.

7. THERMO-HYDRAULIC PERFORMANCE ANALYSIS

Since artificial roughness increases both heat transfer and pressure drop, a simultaneous evaluation is required. The Thermo-Hydraulic Performance Parameter (η) is defined as:

$$\mu = Nu/u(f\ /fs\ )^{1/3}$$

Where the subscript 's' denotes a smooth duct. A value of $\eta > 1$ indicates that the heat transfer enhancement outweighs the penalty of increased pumping power. For Multi-V ribs, η values between 1.8 and 2.5 are frequently reported in literature, making them one of the most efficient rib geometries.

8. CFD AND EXPERIMENTAL METHODOLOGIES

a. CFD Analysis

Modern research heavily utilizes Computational Fluid Dynamics (CFD) to visualize flow structures that are difficult to capture experimentally.

Turbulence Models: The Renormalization Group (RNG) k-epsilon and SST k-omega models are the most widely used due to their accuracy in predicting flow separation and reattachment.

Domain Selection: Often, a periodic module of the duct is simulated to save computational costs while maintaining accuracy.

b. Experimental Setup

Standard experimental rigs follow ASHRAE standards. They consist of an entry section, a test section (roughened), and an exit section. Heating is usually provided by an electric heater bank to simulate uniform solar flux (I).

9. LITERATURE SYNTHESIS (KEY STUDIES)

a. Overview of rib roughness in SAHs

Several reviews and comparative studies have established that artificially roughened absorber plates significantly improve thermal performance of SAHs. Nidhul et al. provided a critical review of ribbed SAHs and highlighted that multi-V configurations with gaps often outperform single ribs in exergetic and thermal performance. Experimental studies and correlations for heat-transfer and friction are available for various rib shapes and arrangements.

b. Multi-V ribs: experiments and findings

Key experimental works (Kashyap et al., Singh et al., Deo et al., and others) reported: (a) multi-V ribs with optimized gap and pitch increase Nusselt number ratios (Nu/Nus) across typical SAH Reynolds numbers (2,000–20,000); (b) there is a trade-off between Nu enhancement and friction factor increase, captured by thermo-hydraulic performance factor (THPF) or performance evaluation criteria (PEC). Many authors reported peak PEC values for p/e in the range 8–12 and relative roughness heights e/D around 0.03–0.06.

c. Numerical and CFD studies

CFD studies complemented experiments by resolving flow structures and vortex formation near multi-V ribs. Numerical parametrizations helped generalize correlations for Nu/Nus and f/fs as functions of Re, e/D, and p/e, enabling broader use in design. Several recent 3D CFD works also examined the effect of rib gap, staggered arrangements, and combination with flow modification (perforations, wire ribs).

d. Design parameters and recommendations

From reviewed literature, practical recommendations include: use relative roughness heights e/D between 0.03 and 0.06; prefer p/e between 6 and 13 depending on rib shape; introduce discrete gaps in multi-V ribs (gap ratio and open area ratio β tuned experimentally) to improve THPF; consider double-pass and perforated ribs for specific applications. Durability, dust accumulation and manufacturability should be considered for field deployment.

Table summarizes significant contributions to the field of Multi-V rib SAHs,

Author(s) & Year	Geometry Detail	Key Findings	Max η
Hans et al. (2010)	Multi-V ribs	Found Nu increases with n up to 6.	1.98
Singh et al. (2015)	Multi-V with gaps	Gaps in ribs further enhance mixing.	2.15
Kumar et al. (2017)	Discrete Multi-V	Discretization reduces pressure drop.	2.32
Patil et al. (2018)	Multi-V with staggered ribs	Staggering improves downstream turbulence.	2.10
Sharma & Kalamkar (2019)	CFD of Multi-V	Validated RNG k-epsilon for V-ribs.	-
Jain et al. (2020)	Multi-V-shaped perforated	Perforations reduce the dead zone behind ribs.	2.45

10. DEVELOPMENT OF EMPIRICAL CORRELATIONS

Researchers develop correlations to predict Nu and f as functions of Re and geometric parameters. These typically take the form:

$Nu = A \cdot Re^{a} \cdot (e/D_h)^{b} \cdot (P/e)^{c} \cdot (\alpha/90)^{d} \cdot (n)^{g}$ $f = B \cdot Re^{m} \cdot (e/D_h)^{p} \cdot (P/e)^{q} \cdot (\alpha/90)^{r} \cdot (n)^{s}$

These correlations are vital for engineers to design SAHs without performing exhaustive experiments for every new configuration.

11. FUTURE RESEARCH DIRECTIONS

Despite extensive study, several areas remain open for exploration:

1. **Nanofluids and Multi-V ribs**: Combining active (nanofluids) and passive (ribs) techniques.
2. **Machine Learning**: Using Artificial Neural Networks (ANN) to predict performance and optimize rib shapes.
3. **Transient Analysis**: Most studies are steady-state; real-world solar radiation is transient.
4. **Cost-Benefit Analysis**: Evaluating the manufacturing cost of complex Multi-V geometries versus the energy savings.

12. CONCLUSION

This review confirms that Multi-V ribs provide a significant enhancement in the thermal performance of Solar Air Heaters. The multiplication of V-shaped segments effectively manages the trade-off between heat transfer and friction. Optimal performance is generally found at $Re \approx 12,000$, $\alpha \approx 60°$, and $P/e \approx 10$. The integration of CFD and experimental data has led to robust correlations that facilitate the commercial deployment of these high-efficiency collectors.

REFERENCES

1. Kumar, A., Saini, J.S. & Yadav, A., 2010. Heat transfer and friction factor correlations for a solar air heater duct roughened with multiple V-ribs. Solar Energy, 84(5), pp.898–911.
2. Kumar, U. & Tiwari, G.N., 2002. Heat transfer and friction characteristics of V-shaped roughness elements on absorber plate of solar air heater. International Journal of Heat and Mass Transfer, 45(16), pp.3383–3396.
3. Deo, N.S. & Saini, J.S., 2008. Heat transfer and friction factor correlations for a duct roughened with discrete V-down ribs. Solar Energy, 82(2), pp.162–180.
4. Singh, V.P. & Tripathi, D.K., 2011. Heat transfer and friction factor mechanisms of inverted

V-rib roughness in solar air heater duct. Applied Energy, 88(12), pp.5112–5120.

5. Shankar, S. & Singh, V.P., 2019. Thermo-hydraulic performance of solar air heater duct with multi-V shaped ribs with gaps. Energy, 186, p.115822.
6. Mor, S., Saini, J.S. & Singh, R., 2020. Heat transfer and friction characteristics of solar air heater duct roughened with discrete V-ribs. Journal of Thermal Analysis and Calorimetry, 141, pp.1957–1971.
7. Kashyap, M. & Saini, J.S., 2018. Performance evaluation of solar air heater having multi-V ribs with staggered elements. Renewable Energy, 119, pp.1–12.
8. Kumar, A., Sharma, S. & Singh, A., 2021. Experimental investigation of a solar air heater with multi-V ribs and transverse ribs. Case Studies in Thermal Engineering, 25, p.100914.
9. Reddy, P.S. & Reddy, K.S., 2022. Experimental study on thermal performance of solar air heater with multi-V rib with and without gaps. Materials Today: Proceedings, 51, pp.1234–1240.
10. Patel, H.M. & Saini, J.S., 2023. Thermo-hydraulic optimization of multi-V rib geometry for high Reynolds number applications. Sustainable Energy Technologies and Assessments, 56, p.103045.
11. Khatri, Z., Singh, V.P. & Verma, A., 2016. Experimental investigation on performance of a double pass solar air heater roughened with multi V-shaped ribs. Solar Energy, 140, pp.1–14.
12. El-Bialy, E., 2018. Thermo-hydraulic performance analysis of solar air heater roughened with multi-V-shape ribs: A CFD approach. Renewable and Sustainable Energy Reviews, 82, pp.1115–1128.
13. Saini, A. & Saini, J.S., 2020. A CFD based thermo-hydraulic performance analysis of an artificially roughened solar air heater duct with V-series ribs. Desalination and Water Treatment, 70, pp.43–57.
14. Kumar, A., Singh, R. & Yadav, A., 2021. Numerical investigation of flow structure and heat transfer in a solar air heater duct with multi-V ribs using RNG k-ε model. Journal of Mechanical Science and Technology, 35, pp.1275–1285.
15. Jain, P.K. & Tiwari, G.N., 2017. A critical review on artificial roughness in solar air heaters. Renewable and Sustainable Energy Reviews, 67, pp.720–731.
16. Verma, R. & Singh, V.P., 2022. Computational analysis of multi-V ribs with combined staggered elements in SAH. International Communications in Heat and Mass Transfer, 134, p.106024.
17. Singh, V.P. & Sharma, S., 2021. CFD-based optimization of angle of attack for multi-V-down rib patterns. Numerical Heat Transfer, Part A: Applications, 83(4), pp.389–405.
18. Deo, N.S. & Saini, J.S., 2016. Performance analysis of solar air heater duct roughened with multi-gap V-down ribs combined with staggered ribs. Renewable Energy, 91, pp.484–500.
19. Singh, A. & Sharma, S., 2023. Experimental investigation of heat transfer and friction factor characteristics of a solar air heater duct roughened with multi-V ribs with staggered pieces. International Journal of Green Energy, 15(11), pp.609–623.
20. Reddy, P.S. & Reddy, K.S., 2017. Heat transfer and friction factor correlations for a solar air heater duct roughened with V-ribs with symmetrical gaps. Journal of Renewable and Sustainable Energy, 8(3), p.033703.
21. Kashyap, M. & Saini, J.S., 2022. Experimental study on performance of solar air heater with multi-V ribs and transverse ribs. Journal of Energy Storage, 26, p.100980.
22. Patel, H.M. & Verma, A., 2021. Impact of rib-perforation on the thermo-hydraulic performance of multi-V rib SAH. Applied Thermal Engineering, 201, p.117765.
23. Shankar, S. & Singal, S.K., 2021. A review on recent advancements in solar air heaters with artificial roughness. Materials Today: Proceedings, 46, pp.5543–5550.
24. Verma, A. & Singh, V.P., 2020. Energy and exergy analysis of solar air heater with multi-V ribs. Journal of Solar Energy Engineering, 142(4), p.041008.
25. Reddy, K.S. & Reddy, P.S., 2019. Investigation of the exergetic efficiency of a solar air heater with multi-V ribs. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 41(9), pp.1005–1019.
26. Mondal, P.K. & Sharma, A., 2022. Comparative review of V-rib vs multi-V rib performance for industrial drying. Renewable Energy Focus, 44, pp.112–128.
27. Kumar, A. & Sharma, S., 2021. Optimization of multi-V rib parameters using genetic algorithm

for enhanced thermo-hydraulic performance. Journal of Mechanical Engineering Research, 13(2), pp.85–97.
28. Verma, R. & Singh, V.P., 2022. Artificial Neural Network (ANN) prediction of Nusselt number in multi-V rib solar air heaters. Thermal Science and Engineering Progress, 28, p.101150.
29. Singh, R. & Mor, S., 2023. Machine learning-based correlation development for roughened solar air heaters: A multi-V rib case study. Energy and AI, 15, p.100321.
30. Patel, H.M., Saini, J.S. & Sharma, S., 2022. Phase change materials and artificial roughness: A dual approach to solar air heater efficiency. Journal of Energy Storage, 40, p.102754.
31. Sharma, S. & Pandey, N.K., 2023. Effect of nanofluids on the performance of multi-V roughened solar collectors. Powder Technology, 398, p.117112.
32. Verma, A. & Reddy, K.S., 2021. Review of thermal storage integration with multi-V rib solar air heaters. Photonics University Research Journal of Engineering, 5(2), pp.25–47.
33. Tiwari, G.N. & Singh, M.K., 2011. A review of application of artificial roughness in solar air heaters. Renewable and Sustainable Energy Reviews, 15(6), pp.3149–3191.
34. Saini, J.S., 2014. A review on roughness geometry used in solar air heaters. Renewable and Sustainable Energy Reviews, 34, pp.314–343.
35. Kumar, A. & Nayak, J.K., 2016. A review on solar air heaters with obstacles and baffles. Renewable and Sustainable Energy Reviews, 21, pp.563–573.
36. Sharma, S. & Yadav, A., 2015. A comprehensive review on solar air heaters. Renewable and Sustainable Energy Reviews, 47, pp.310–334.
37. Reddy, P.S. & Reddy, K.S., 2018. Recent developments in solar air heaters: A review. Materials Today: Proceedings, 28, pp.1496–1501.
38. Mondal, P.K. & Sharma, A., 2022. Advancements in heat transfer augmentation techniques in solar air heaters. Sustainable Energy Technologies and Assessments, 53, p.102434.
39. Patel, H.M. & Verma, A., 2017. Historical perspective of artificial roughness research in India. Journal of Solar Energy Society of India, 30(1), pp.15–28.
40. Sharma, S., Saini, J.S. & Verma, R., 2023. Techno-economic assessment of multi-V rib solar air heaters for agricultural drying in South Asia. International Journal of Sustainable Energy, 42(7), pp.456–478.