A Review of Thermo-Hydraulic Performance in Rib-Roughened Solar Air Heater Ducts: Inclined and Modified V-Shaped Ribs on a Single Heated Wall of a Square Channel

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***Abstract*—A solar air heater is a simple idea that is hard to execute well. Sunlight falls on a blackened absorber plate, and a stream of air moving behind it is supposed to carry that heat away. In practice the plate and the air barely interact: a thin, slow-moving layer of air clings to the plate and blocks much of the heat transfer the collector is built to deliver. Roughening the underside of the absorber plate with small ribs is the standard fix, and it has occupied researchers for more than three decades. This paper reviews that literature, concentrating on transverse, inclined (30–90°), V-shaped and modified V-shaped rib geometries applied to a single heated wall of a square or rectangular duct. It traces the field from the equal-pumping-power theory of Webb and Eckert and the early rib-turbulator work of Han and coworkers, through the solar air heater roughness correlations that Prasad, Saini and their collaborators built up over the following decades. Reported Nusselt number gains typically run from about 1.5 to just over 3 times the smooth duct value, and the friction factor usually rises by a comparable or larger amount, which is why a thermo-hydraulic performance parameter, not Nusselt number alone, ultimately determines which geometry is worth building.**

***Index Terms*—Solar air heater, rib roughness, V-shaped ribs, thermo-hydraulic performance, square channel, Nusselt number, friction factor.**

I. INTRODUCTION

Solar air heaters occupy an odd position in solar technology. They are unglamorous compared to photovoltaics, and yet they remain one of the cheapest ways to convert sunlight into usable heat for crop drying, space heating, timber seasoning and a long list of low-temperature industrial processes. Their design is almost embarrassingly simple: a flat, blackened absorber plate, a glass cover to trap the radiation, and an air stream pushed underneath the plate by a small blower or by natural buoyancy. That simplicity is also where the trouble starts. Air conducts heat poorly, so under ordinary duct flow conditions a thin, nearly stagnant boundary layer forms next to the absorber plate and holds back much of the heat that should be reaching the airstream. The convective heat transfer coefficient between plate and air ends up low, and the collector's thermal efficiency falls well short of what the incoming solar radiation could support.

There are two general ways to close that gap. One is to increase the heat transfer area with fins or corrugations. The other is to disturb the boundary layer directly, so that turbulent mixing does the work that slow molecular conduction cannot. Artificial surface roughness, usually in the form of small repeated ribs bonded or extruded onto the underside of the absorber plate, has attracted the most research attention among the passive options. It is cheap, it retrofits easily onto an otherwise conventional flat plate collector, and it works reliably. Air flowing over a rib separates just upstream of the rib crest, forms a recirculating vortex in the rib's wake, and reattaches to the plate a short distance downstream before the cycle repeats at the next rib. That repeated separation and reattachment breaks up the insulating boundary layer far more effectively than a smooth wall, and the local and average heat transfer coefficients rise as a result.

The same disruption that helps heat transfer also raises the pressure drop across the duct, so a bigger fan and more pumping power are needed to move the same volume of air. A rib geometry cannot be judged on Nusselt number alone. It has to be judged on what that improvement costs, following the equal pumping power criterion Webb and Eckert set out [1]. That is the standard applied throughout this review: every rib geometry discussed below — transverse, inclined, V-shaped, W-shaped, and the modified V-shaped ribs that are the specific focus of the present project — is ultimately competing for the best combination of heat transfer gain and friction penalty.

II. PASSIVE ROUGHNESS TECHNIQUES AND HOW RIBS ARE CLASSIFIED

Heat transfer augmentation techniques are usually grouped into three families. Active methods need an outside power input, such as surface vibration or electrostatic fields. Passive methods need none: extended surfaces, swirl generators, and surface roughness all fall here. Compound methods combine two or more of the above. For a solar air heater, whose whole purpose is to harvest energy rather than spend it, passive roughness is the obvious fit, and rib turbulators in particular have become close to a default choice, because they are inexpensive to fabricate, simple to bond onto an absorber plate, and effective across a wide Reynolds number range.

Within the rib roughness family, geometries are usually distinguished by their orientation and shape relative to the flow direction, as follows:

- Transverse (90°) ribs — continuous ribs set perpendicular to the flow, the simplest geometry and the baseline everything else is measured against.
- Inclined ribs — continuous ribs set at an angle of attack other than 90°, commonly 30–70°, which tilt the secondary flow so it develops a spanwise component instead of staying purely two-dimensional.
- V-shaped and inverted-V ribs — two inclined rib legs joined at a central apex, oriented either V-down (apex pointing downstream, the more common choice in the solar air heater literature) or V-up (apex pointing upstream), generating a pair of counter-rotating secondary vortices instead of the single cell a plain inclined rib produces.
- Multi-V, discrete-V and V-with-gap ribs — which repeat the V motif several times across the duct width, break it into discrete segments, or leave a small gap near the apex so the vortex core does not stagnate.
- W-shaped ribs — essentially a double V formed by joining two V-elements, meant to double the number of secondary-flow cells across the duct width.
- Other cross-sectional variants — chamfered, wedge, arc, dimple, metal-grit, trapezoidal and similar sections, which generally trade a controlled amount of extra pressure drop for a more favourable local heat transfer distribution.

The specific geometry of interest here, the modified V-shaped rib (MVR), takes this a step further. Instead of simply changing the angle of attack, it alters the V-rib's cross-section, apex treatment, gap arrangement or support geometry, aiming to push the thermo-hydraulic performance parameter beyond what the classical V-rib of Momin et al. [11] can deliver, while in some variants also improving the structural robustness of the rib itself, a real concern for absorber plates that are stamped, glued or extruded rather than machined.

III. FOUNDATIONAL STUDIES ON RIB-TURBULATED CHANNELS

Webb and Eckert [1] laid the theoretical groundwork for evaluating enhanced surfaces at equal pumping power, and their performance evaluation criterion is still the yardstick nearly every later rib roughness study measures itself against. Han and Park [2], and Han et al. [3], ran some of the earliest systematic experiments on rib-turbulated rectangular channels for gas turbine blade cooling, varying rib angle of attack (30–90°), pitch-to-height ratio and channel aspect ratio. Inclined ribs at 30–45° gave the best heat transfer performance at equal pumping power in their tests, with a noticeably lower pressure drop than 90° ribs for a comparable heat transfer gain, and a near-square channel aspect ratio came out ahead of the other aspect ratios examined.

Around the same time, Prasad and Saini [4, 5] pioneered the study of artificially roughened solar air heater ducts using transverse wire roughness. They worked out empirical correlations for Nusselt number and friction factor in terms of relative roughness height, relative roughness pitch and Reynolds number, and settled on an optimum relative pitch of roughly 8–10, a figure that keeps reappearing across almost every rib geometry studied since. Gupta et al. [6] extended this into a systematic thermo-hydraulic performance evaluation of roughened absorber plates, and Karwa et al. [10] developed correlations for chamfered ribs that hold into the transitional flow regime, reporting close to a two-fold rise in Stanton number and a three-fold rise in friction factor for a 15° chamfer angle. Taslim et al. [7, 8] and Ekkad and Han [9] pushed the geometric investigation specifically into square passages roughened with angled, V-shaped and discrete ribs, producing some of the earliest square-channel heat transfer distributions for rib turbulators, work that bears directly on the square-channel configuration considered here.

IV. STUDIES ON INCLINED RIBS AND ANGLE-OF-ATTACK EFFECTS

A good deal of work has focused on how the rib angle of attack shapes heat transfer and friction. Ahn et al. [15] looked at a square channel with one, two or four inclined ribbed walls and found that both heat transfer and friction penalty scale with the number of ribbed walls, confirming that a single-wall ribbed configuration — the natural configuration for a solar air heater, where only the absorber plate carries the ribs — gives the lowest friction penalty of the arrangements tested while still delivering substantial heat transfer enhancement on the roughened wall itself. Kaewchoothong et al. [32] tested inclined ribs at 30–90° alongside V-shaped and inverted-V ribs at 45° and 60° in a stationary square channel, and found the average Nusselt number for a 60° inclined rib to be about 20% higher than for the 90° transverse rib, with a 60° V-shaped rib adding a further 30% improvement on top of that. They traced the gap to a genuinely three-dimensional secondary-flow structure that differs qualitatively between inclined-rib and V-rib configurations.

It is worth being careful here, because the angle that maximises the heat transfer coefficient is not always the angle that maximises thermo-hydraulic performance. Lee, Kim and Ahn [44] measured a square convergent channel with parallel angled ribs on one wall only, at $\alpha = 30°, 45°, 60°$ and $90°$ over Reynolds numbers of 22,000–79,000, and found the average Nusselt number rising monotonically in the order $30° < 45° < 60° < 90°$, the opposite ranking from what several other studies report once friction is taken into account. A related study by the same research group examined angled ribs in a rectangular divergent channel [43], a useful reminder that rib performance in this family of geometries is sensitive to the channel's streamwise cross-sectional development, not just the rib angle itself. That distinction matters directly here, since the present investigation evaluates all four angles (30°, 45°, 60°, 90°) under one identical set of thermal and flow boundary conditions rather than relying on a single reported optimum. More recently, Kaplan [41] applied ANSYS-based CFD to a double-passage square duct with 45° inclined ribs and reported a marked improvement in thermo-hydraulic performance over the transverse-rib baseline, which at least confirms that the earlier experimental trend carries over into modern computational studies.

On the solar-air-heater side specifically, Varun et al. [17] combined inclined and transverse ribs on the same absorber plate and found the combination could outperform either geometry alone, and Aharwal et al. [16] showed that a gap introduced within an inclined rib arrangement raises Nusselt number further, by letting the otherwise stagnant secondary-flow vortex vent and refresh itself, a mechanism exploited more fully in the V-rib-with-gap literature discussed next.

V. STUDIES ON V-SHAPED AND MODIFIED V-SHAPED RIB ROUGHNESS

V-shaped rib roughness was first systematically investigated by Momin et al. [11], who tested angles of attack from 30° to 90° at a fixed relative pitch ($p/e = 10$) and relative roughness height (e/Dh) of 0.02–0.034 over Re = 2,500–18,000. The V-rib configuration consistently beat the equivalent inclined single-leg rib at the same angle in their tests, with the 60° V-rib producing the largest enhancement, about 2.30 times the smooth-duct Nusselt number and 2.83 times the friction factor. They attributed the gain to a pair of counter-rotating secondary vortices generated along the two rib legs, which intensify near the apex and drive a locally very high heat transfer coefficient. Gao and Sundén [12] later mapped the local heat transfer distribution around V-ribs in a rectangular duct and confirmed this apex-driven mechanism in detail.

From there, the plain V-rib branched into a family of multi-V and V-with-gap geometries meant to intensify or better distribute the secondary flow. Hans et al. [20] tested multiple repeated V-ribs across the duct width, in both continuous and split arrangements, and reported Nusselt number enhancements of 1.48–2.26 times (continuous) and 1.71–2.59 times (split) relative to a smooth duct. Kumar et al. [25, 28, 29] ran an extensive experimental programme on multi-V ribs with a gap at the apex, developing correlations that capture the effects of gap width, gap position and relative rib width ratio, with a width ratio of about 6 maximising thermo-hydraulic performance at the highest Reynolds number they tested. Singh et al. [24, 26] examined discrete and gapped V-down ribs and identified an optimum flow-attack-angle for maximum thermo-hydraulic performance, and in a related paper [46] went further and reframed the evaluation in exergy terms rather than Nusselt number and friction factor alone, a distinction taken up again in Section XI. Jain et al. [34], in a comprehensive review of V-rib geometries, pulled together the correlations and enhancement ranges reported across this literature, confirming that gapped and multi-V variants generally reach higher thermo-hydraulic performance than the plain single V-rib of Momin et al., at the cost of steadily more complex fabrication.

Boonloi and Jedsadaratanachai [39] ran a CFD study that coined the term modified V-shaped ribs, MVR. Rather than varying the angle of attack, they structurally modified the classical V-rib, varying the rib-height-to-duct-height ratio ($b/H = 0.05$–0.30), the V-bar thickness-to-duct-height ratio ($a/H = 0.025$–0.050), and the flow direction (V-upstream versus V-downstream), for ribs spanning a square duct in both a single-row, mid-duct arrangement and an opposite-wall arrangement. The MVR geometry reproduced the flow and heat transfer mechanisms of the conventional V-rib, impinging and swirling flows that disrupt the thermal boundary layer, while offering better structural stability, with heat transfer enhanced by up to about 18 times the smooth-duct value and a maximum thermal enhancement factor of about 4.16 over the parameter range studied. That very high enhancement reflects the geometry: these are duct-spanning baffle-type ribs rather than short wall-mounted ribs, so the numbers are not directly comparable to the other values quoted in this section. Numerical work on multi-V-shaped ribs in solar air heater ducts by Jin et al. [30, 31], and two-phase nanofluid simulations of 90° V-shaped ribs in a square channel by Bahiraei et al. [33], point the same way: three-dimensional CFD is now the standard tool for resolving the secondary-flow structures behind V-rib heat transfer enhancement, consistent with the ANSYS Fluent methodology.

VI. STUDIES ON W-SHAPED AND OTHER RIB GEOMETRIES

Lanjewar et al. [21, 22, 23] investigated W-shaped ribs, effectively a double V-rib meant to double the number of secondary-flow cells across the duct width, in both W-up and W-down orientations, reporting a maximum Nusselt number and friction factor enhancement of about 2.36 and 2.01 times the smooth-duct values respectively. Thermo-hydraulic performance peaked at an angle of attack of 60°, and W-down ribs (performance ratio 1.46–1.95) outperformed W-up ribs (1.21–1.73). Their analysis also found W-ribs thermo-hydraulically superior to the plain V-rib geometry of Momin et al. under comparable conditions. Kumar et al. [19] discretised the W-rib further and reported additional gains from the larger number of secondary vortices generated by the broken geometry.

Beyond the V and W family, researchers have tried a long list of other rib cross-sections on solar air heater absorber plates: wedge [13], metal-grit [14], chamfered [10], dimple [27], and various arc, trapezoidal, circular and semicircular sections, generally chasing the same goal of raising the local heat transfer coefficient without a matching rise in friction.

VII. STUDIES ON SINGLE-WALL RIBBED SQUARE CHANNELS

Ahn et al. [15], already discussed in Section IV, gave one of the earliest systematic comparisons of one-, two- and four-wall ribbed square channels, establishing the baseline expectation that a single ribbed wall produces the smallest friction penalty of the three while still delivering strong local heat transfer enhancement on the roughened surface itself. Taslim and Wadsworth [8] focused specifically on the rib-surface-averaged heat transfer coefficient in a rib-roughened square passage, data that is directly usable when only one wall's performance, rather than the whole duct's, is what matters.

A more recent and unusually detailed line of work is the direct numerical simulation, or DNS, studies by Mahmoodi-Jezeh and Wang [35, 36, 37], who resolved turbulent flow and heat transfer in a square duct with transverse, inclined and V-shaped ribs mounted on one wall only, without any turbulence-model assumptions standing in the way. Their results showed that duct confinement together with one-wall roughening generates large, streamwise-elongated secondary-flow vortices that interact strongly with both the ribbed wall and the two adjoining smooth sidewalls, a three-dimensional flow structure quite different from the idealised two-dimensional picture of a ribbed flat plate that much of the earlier correlation-based literature implicitly assumes. They also found drag and heat transfer in this configuration to be highly sensitive to rib height (blockage ratio). Ruck and Arbeiter [38] complemented this with high-Reynolds-number (50,000–100,000) laser-Doppler-anemometry measurements in a one-sided ribbed square channel, giving exactly the kind of experimental benchmark data that CFD turbulence-model predictions in this configuration need to be checked against.

VIII. NUMERICAL AND CFD STUDIES USING ANSYS FLUENT

A few CFD studies are worth calling out specifically. Kumar and Saini [18] validated an RNG k-ε-based ANSYS Fluent model for arc-shaped roughness and obtained an enhancement ratio of up to 1.7. Al-Chlaihawi et al. [40] reported a thermal performance factor of up to 1.64 for transverse-trapezoidal ribs using the same turbulence model over Re = 6,000–18,000. Yadav and Bhagoria [45] ran an equilateral-triangular-sectioned rib CFD study over Re = 3,800–18,000 that matched experimental Nusselt numbers closely. Together with the modified V-rib CFD study discussed in Section V [39], this body of work supports both the numerical methodology, ANSYS Fluent with RNG k-ε turbulence closure, second-order upwind discretisation, SIMPLE pressure-velocity coupling, and the Reynolds number and heat-flux boundary conditions (a uniform heat flux close to 1,000 W/m² applied to a single wall is typical) that have repeatedly proved reliable for predicting rib-roughened duct performance.

IX. THERMO-HYDRAULIC PERFORMANCE EVALUATION METHODOLOGY

Because rib roughness always raises both heat transfer and friction together, comparing two geometries, or a roughened duct against a smooth one, on Nusselt number alone would be misleading. The criterion most widely used in this literature, following Webb and Eckert [1] and later restated with clearer constraints by Karwa [42], compares the roughened and smooth ducts at equal pumping power:

$$THPP = (Nu_r / Nu_s) / (f_r / f_s)^{1/3} \quad (1)$$

where the subscripts r and s denote the roughened and smooth duct respectively, evaluated at the Reynolds numbers that draw the same pumping power. A THPP above unity means the heat transfer gain outweighs the friction penalty. The geometry that maximises THPP over the Reynolds number range of interest is generally taken as the practical optimum. Values reported across the literature reviewed here typically span about 1.2 to 2.7, with the upper end generally belonging to multi-V, gapped-V and modified-V geometries rather than plain transverse or single inclined ribs.

X. SUMMARY OF REVIEWED LITERATURE

Table I summarises the geometry, method and principal findings of the studies discussed above, presented in approximately the order in which they entered the field. The final two rows correspond to the exergy-based and structural-modification-generalisation strands taken up in Section XI.

TABLE I SUMMARY OF REVIEWED STUDIES ON RIB-ROUGHENED DUCTS

S.No.	Author(s) / Year	Rib Geometry & Method	Key Findings
1	Prasad & Saini (1988)	Transverse wire ribs; SAH absorber plate; experimental	Optimum relative pitch about 8–10; laid the empirical foundation for SAH roughness research.
2	Webb & Eckert (1972)	General rough-surface theory	Proposed the equal-pumping-power performance criterion underlying THPP.
3	Han & Park (1988); Han et al. (1989)	Transverse & inclined ribs, two-wall rectangular channels; experimental	Inclined ribs (30–45°) give higher heat transfer than 90° ribs at equal pumping power; channel aspect ratio matters.
4	Taslim et al. (1996); Taslim & Wadsworth (1997)	Angled, V-shaped, discrete ribs; square passage; experimental	V-down ribs at low blockage ratio gave the highest heat transfer and friction among configurations tested.
5	Gupta et al. (1997)	Wire roughness; SAH absorber plate; experimental	Quantified the thermo-hydraulic trade-off; confirmed net benefit after the friction penalty.
6	Karwa et al. (1999)	Integral, chamfered, transverse ribs; SAH; experimental	Chamfered ribs (15°) improved Stanton number about 2x and friction factor about 3x; extended correlations into transitional flow.
7	Momin et al. (2002)	V-shaped ribs, $\alpha = 30–90°$, $p/e = 10$; SAH duct; experimental	Seminal SAH V-rib study; 60° V-rib gave maximum Nu and f enhancement (2.30–2.83x smooth duct).
8	Gao & Sundén (2001)	V-shaped ribs; rectangular duct; experimental	Mapped local heat-transfer distribution around V-ribs; confirmed apex-driven secondary-flow enhancement.
9	Bhagoria et al. (2002)	Wedge-shaped transverse ribs; SAH; experimental	Developed Nu and f correlations; identified optimum wedge angle.
10	Karmare & Tikekar (2007)	Metal-grit ribs; experimental + CFD	Strong dependence of Nu/f on rib geometry; CFD validated against experiment.
11	Ahn et al. (2008)	Inclined ribs on 1, 2 or 4 walls; square channel; experimental	Heat transfer and friction penalty both scale with the number of ribbed walls; one-wall gives the lowest penalty.
12	Aharwal et al. (2008)	Inclined ribs with a gap; SAH duct; experimental	Gap increases Nu by venting the otherwise stagnant secondary-flow vortex.
13	Varun et al. (2008)	Combined inclined + transverse ribs; SAH; experimental	Combination roughness outperformed either single geometry over the tested range.
14	Kumar & Saini (2009)	Arc-shaped roughness; CFD (ANSYS Fluent, RNG k-ε); SAH	Validated RNG k-ε against Dittus-Boelter; enhancement ratio up to 1.7.
15	Kumar et al. (2009)	Discrete W-shaped ribs; SAH; experimental	Discretising the W-rib increased secondary-vortex count and improved Nu/f correlations.
16	Hans et al. (2010)	Multiple V-ribs (split & continuous); SAH; experimental	Continuous multi-V: Nu 1.48–2.26x; split multi-V: 1.71–2.59x over smooth duct.
17	Lanjewar et al. (2011a, b, c)	W-shaped ribs (W-up / W-down); SAH; experimental	Max Nu/f enhancement 2.36x/2.01x; THPP peaks at $\alpha = 60°$; W-ribs beat plain V-ribs.

18	Singh et al. (2011)	Discrete V-down ribs; SAH; experimental	Discrete V-down configuration outperformed continuous V and transverse discrete ribs.
19	Kumar et al. (2012)	Multi-V rib with gap; SAH; experimental	Gap at the V-apex intensifies local turbulence; among the highest Nu enhancements reported.
20	Singh et al. (2012)	V-down rib with gap, varying flow-attack-angle; SAH; experimental	Identified optimum flow-attack-angle for maximum thermo-hydraulic performance.
21	Sethi et al. (2012)	Dimple-shaped roughness; SAH; experimental	Competitive Nu enhancement with a comparatively lower friction penalty than sharp-edged ribs.
22	Kumar et al. (2013)	Multi-V rib with gap; correlation development	Generalised Nu and f correlations for multi-V-with-gap roughness.
23	Kumar et al. (2015)	Discrete multi-V rib, varying width ratio; SAH; experimental	Optimum relative width ratio (W/w = 6) identified at Re = 20,000.
24	Jin et al. (2015, 2019)	Multi V-shaped ribs; 3-D CFD (ANSYS Fluent); SAH	Numerically resolved secondary-flow structures and their contribution to local Nu distribution.
25	Kaewchoothong et al. (2017)	Inclined (30–90°), V- and inverted-V ribs; square channel; experimental (TLC)	60° V-rib gave the highest local Nu (about 30% above the 90° transverse rib); revealed the 3-D secondary-flow mechanism.
26	Lee, Kim & Ahn (2016)	Parallel angled ribs (30–90°), one wall; square convergent channel; experimental	Average Nu rose monotonically 30°<45°<60°<90° over Re = 22,000–79,000, showing that the angle for max Nu is not the angle for max THPP.
27	Bahiraei et al. (2019)	90° V-shaped ribs; square channel; two-phase nanofluid CFD	V-rib secondary flow synergises with nanofluid effects to further raise thermo-hydraulic performance.
28	Jain et al. (2019)	Review of V-rib geometries	Consolidated correlations and enhancement ranges for V, multi-V, discrete-V and V-with-gap ribs.
29	Mahmoodi-Jezeh & Wang (2020, 2021, 2022)	Transverse, inclined & V-ribs, one wall only; square duct; DNS	Resolved streamwise secondary-flow vortices from one-wall ribs; quantified sensitivity to blockage ratio and angle.
30	Boonloi & Jedsadaratanachai (2022)	Modified V-shaped ribs (MVR), duct-spanning baffle-type; square duct; CFD	Directly matches present nomenclature; structural modification preserved the V-rib mechanism with improved structural stability; Nu enhancement up to about 18x, max thermal enhancement factor about 4.16.
31	Ruck & Arbeiter (2021)	One-sided ribbed square channel; LDA measurements, Re = 50,000–100,000	High-Re experimental benchmark data for single-wall ribbed square-channel flow, useful for CFD validation.
32	Al-Chlaihawi et al. (2023)	Transverse-trapezoidal ribs; CFD (RNG k-ε); SAH	Confirmed RNG k-ε as the most accurate turbulence model against experimental data; TPF max about 1.64.
33	Kaplan (2024)	45° inclined ribs; double-passage square duct; CFD (comparative)	Reported a significant thermo-hydraulic performance gain for 45° inclined ribs over transverse ribs in a square-section duct.
34	Singh, Chander & Saini (2012)	Discrete V-down rib; exergy-based analysis (analytical)	Configuration minimising exergy destruction does not always match the one maximising THPP; argues for reporting both metrics.

35	Boonloi & Jedsadaratanachai (2026)	Modified V-orifice (MVO) turbulator; circular duct; CFD	Extends the same structural-modification philosophy used for MVR to a different turbulator family, indicating the design route is being generalised beyond the square-channel V-rib case.

XI. EMERGING TRENDS: HYBRID ENHANCEMENT, EXERGY-BASED EVALUATION, AND DATA-DRIVEN DESIGN

Three trends stand out in the more recent literature and are worth flagging on their own, since none of them is captured well by the THPP-only framing used in Sections III through X.

The first is hybrid enhancement, combining rib roughness with a second augmentation mechanism, most often a nanofluid working fluid. This is now a recognisable strand of research rather than a one-off curiosity. Bahiraei et al. [33] showed, for 90° V-shaped ribs in a square channel, that the secondary flow generated by the rib and the enhanced thermal conductivity of a Cu-water nanofluid reinforce one another rather than simply adding independently. For modified-V geometries specifically, this implies that a rib shape optimised under a single-phase air assumption is not guaranteed to stay optimal once a nanofluid or other enhanced working fluid is introduced.

The second is a smaller but methodologically important strand of work arguing that THPP, useful as it is, is not the last word on performance. Singh, Chander and Saini [46] re-analysed discrete V-down rib roughness through the lens of exergy, accounting for the quality of the heat delivered and the irreversibility generated by friction and by heat transfer across a finite temperature difference, rather than treating Nusselt number and friction factor as independent ratios. Their finding that the configuration minimising exergy destruction does not always coincide with the one maximising THPP is a useful caution for any V-rib or modified-V-rib study. A geometry that looks best on THPP grounds is not automatically the one an exergy-based, second-law analysis would recommend, and reporting both, where feasible, gives a fuller picture of the real thermodynamic benefit.

The third is that the structural-modification philosophy Boonloi and Jedsadaratanachai [39] applied to the V-rib is still being generalised rather than treated as a one-off result. Their more recent work on a modified V-orifice, or MVO, turbulator in a circular duct [47] applies essentially the same design logic, altering support and thickness ratios and flow direction rather than the planform angle, to a different turbulator family entirely. That suggests structural modification, independent of angle, is becoming a general design lever across turbulator types rather than a feature specific to the square-duct V-rib case. Separately, although not yet common in the rib-roughness literature specifically, surrogate-model and machine-learning approaches to correlating Nusselt number, friction factor and THPP as continuous functions of geometric parameters, rather than at a handful of discretely tested points, are increasingly used elsewhere in heat-exchanger design optimisation.

XII. CONCLUSION

Rib roughness is by now a thoroughly validated passive technique for enhancing convective heat transfer in single-phase duct flows, with a research history spanning more than five decades: from the foundational rough-surface theory of Webb and Eckert, through the turbine-cooling-oriented rib-turbulator studies of Han and coworkers, to the solar-air-heater roughness literature that Prasad and Saini set in motion. Across this body of work, V-shaped ribs and their descendants — multi-V, gapped-V, W-shaped and modified-V geometries — consistently deliver higher thermo-hydraulic performance than plain transverse or single inclined ribs, because of the extra secondary-flow vortices they generate. Direct numerical simulation of one-wall ribbed square ducts confirms that this secondary-flow behaviour is strongly three-dimensional and sensitive to rib geometry, angle and blockage ratio, while a growing body of ANSYS Fluent-based CFD work, generally using the RNG k-ε turbulence model, has repeatedly shown numerical simulation to predict Nusselt number, friction factor and thermo-hydraulic performance trends consistent with experiments. Beyond THPP itself, the more recent exergy-based and hybrid-enhancement literature suggests that what counts as the best performance depends somewhat on how the question is framed, and that a complete evaluation ideally reports more than one metric.

NOMENCLATURE

SAH — Solar Air Heater
MVR — Modified V-shaped Ribs
Dh — Hydraulic diameter (mm)
e — Rib height (mm)
p — Rib pitch (mm)
Re — Reynolds number (–)
THPP — Thermo-Hydraulic Performance Parameter (–)
Nu — Average Nusselt number (–)
Nu_s *— Average Nusselt number for smooth plate (–)*
Nu_r *— Average Nusselt number for ribbed plate (–)*
f — Friction factor (–)
f_s *— Friction factor for smooth duct (–)*
f_r *— Friction factor for ribbed duct (–)*
a — V-bar thickness (mm)
b — Rib width (mm)
W — Channel width (mm)
H — Channel height (mm)

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