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Review Article

A Review of Heat Transfer Enhancement in Ribbed Channels: Geometric Parameters, Flow Characteristics, and Performance Optimization

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ABSTRACT

This review paper presents an analysis of heat transfer enhancement techniques in ribbed channels, drawing insights from experimental and numerical investigations. The review synthesizes findings from studies focusing on various rib geometries, including transverse ribs, V-shaped ribs, curved ribs, angular cut baffles, micro-pin fins, and hybrid configurations. Key parameters such as rib height-to-hydraulic diameter ratio, pitch ratio, rib angle of attack, and Reynolds number effects are systematically examined. The review encompasses applications in solar air heaters, gas turbine blade cooling, microchannel heat sinks, heat exchangers, and superhydrophobic drag reduction surfaces. Performance evaluation criteria, including Nusselt number enhancement, friction factor penalties, thermal-hydraulic performance parameters, exergy analysis, and entropy generation, are discussed. The review concludes with recommendations for optimal rib configurations and identifies research gaps for future investigations.

1. Introduction

The demand for efficient heat transfer in thermal systems has driven extensive research into passive heat transfer enhancement techniques. Among these, ribbed channels have emerged as one of the most effective methods for augmenting convective heat transfer in various applications, including solar air heaters [1, 4, 13, 20, 23], gas turbine blade cooling [2, 11, 27], microchannel heat sinks [9, 26, 29], and general heat exchanger design [3, 5, 6, 7, 8, 22, 24, 28, 30]. Ribs create flow separation, reattachment, and secondary flows that disrupt the thermal boundary layer, leading to enhanced heat transfer coefficients. However, this enhancement comes at the cost of increased pressure drop and pumping power. The fundamental challenge in ribbed channel design lies in balancing these competing effects. As noted by Bhattacharyya et al. [3], the main challenge of passive heat transfer enhancement techniques is that heat transfer coefficient enhancement takes place at the cost of a pressure drop penalty.

The present review synthesizes findings from research articles published, covering experimental, numerical, and analytical investigations. The review is organized as follows: Section 2 examines geometric parameters and their effects; Section 3 discusses flow physics and heat transfer mechanisms; Section 4 presents performance evaluation metrics; Section 5 covers exergy analysis; Section 6 presents applications; Section 7 provides

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nanofluids effects; and Section 8 presents conclusions.

2. Geometric Effects

The spacing between successive ribs significantly affects flow reattachment and heat transfer characteristics. Han [12] established that optimal P/e values range from 7 to 15. Bhattacharyya et al. [3] investigated angular cut baffles with pitch ratios of 0.1, 0.15, and 0.2 (where pitch ratio is defined as y/L), finding that smaller pitch ratios (P = 0.1) produced higher Nusselt numbers due to more frequent flow disruption, though at the cost of increased pressure drop. For solar air heater applications, Jain et al. [13] maintained constant P/e = 12 while varying gap width, achieving maximum thermo-hydraulic performance parameter (THPP) of 2.66 at g/e = 4. The study revealed that Nusselt number enhancement ranged from 1.7 to 3.66 times smooth plate values across different configurations. Hans et al. [12] investigated broken arc-shaped ribs and found that the ratio of rib pitch to height significantly influenced both heat transfer and friction characteristics. The study reported that the best thermal performance occurred at P/e = 10. The orientation of ribs relative to flow direction dramatically impacts secondary flow generation. Han et al. [12] demonstrated that 45° angled ribs and V-shaped ribs outperform transverse ribs by creating streamwise vortices that enhance fluid mixing. Kumar and Amano [15] showed that broken V-ribs performed better than continuous V-ribs in two-pass cooling channels. Promvonge and Eiamsa-ard [19] studied heat transfer behaviors in a tube with combined conical-ring and twisted-tape inserts, finding that the combination of passive techniques produced synergistic effects. Elwekeel et al. [11] systematically compared convex, concave, convex broken, and concave broken ribs with radius ratios (R/Dh) of 2, 3, and 4. Key findings include:

- Convex broken ribs (case D) at R/Dh = 2 provided the highest heat transfer coefficient, exceeding the reference transverse rib (R00) by 52.34% at Re = 30,000
- Concave ribs exhibited the highest friction factor (up to 14.9 times R00 at Re = 30,000)
- The thermal performance factor decreased with increasing Reynolds number, with case D showing the best overall performance
- Exergy losses of curved ribs were close at low Re, while at high Re, curved ribs had high exergy losses

Jain et al. [13] investigated arc-shaped ribs with symmetrical gaps as a novel roughness element. The study varied relative gap width (g/e) from 2 to 5 and found that the maximum Nusselt number enhancement (3.66 times smooth plate) occurred at g/e = 4. This was attributed to accelerated secondary flow through gaps that enhanced mixing and created greater turbulence. Bhattacharyya et al. [3] studied angular cut baffles with cutting angles of 30°, 45°, and 60° in both inline and staggered arrangements. The maximum heat transfer rate was observed for staggered arrangement with a pitch ratio of 0.1 and a cutting angle of 60°, achieving Nusselt number enhancement of 3.5 times that of a smooth tube. The study developed empirical correlations with deviations of ±10% for the Nusselt number and ±4% for the friction factor. Alam et al. [1] investigated V-shaped perforated blocks in a rectangular duct of solar air heater, varying open area ratio from 1:20 to 1:4. The study found that V-shaped perforated blocks performed better than solid blocks, with optimum performance at relative pitch of 8, height ratio of 0.8, and open area ratio of 1:5. Sureshkumar et al. [24] studied efficient non-dominated multi-objective genetic algorithm approaches for network security, demonstrating the application of optimization techniques to complex thermal systems. Ajeel et al. [2] conducted an experimental assessment of heat transfer and pressure drop of nanofluid as a coolant in corrugated channels. Three shapes were tested: semicircle corrugated channel (SCC), trapezoidal corrugated channel (TCC), and straight channel. The study found that TCC improved heat transfer by up to 63.59%, with a pressure drop 1.37 times that of straight channels, and thermal performance up to 2.22 times. Akbarzadeh et al. [1] studied the influence of corrugation profiles on entropy generation, heat transfer, pressure drop, and performance in wavy channels. The study compared trapezoidal, triangular, and sinusoidal corrugations, finding that sinusoidal shapes provided better thermal performance while triangular channels had the best entropy generation characteristics. Wang et al. [27] numerically investigated the cooling performance of pulsating flow in a ribbed channel. Three pulsation patterns (sinusoidal, square, and triangular waves) were studied. The square wave pulsating flow showed the highest cooling performance, with heat transfer increasing with pulsating frequency while the friction factor decreased.

He et al. [9] proposed a novel ribbed pin-fin arrays heat sink (RPHS) combining wavy microchannels with porous ribs. The RPHS achieved average Nusselt numbers of 23.1 at Re = 780, nearly twice that of cylinder pin-fin arrays and three times that of smooth microchannels. The study introduced a non-dimensional parameter He for evaluating temperature distribution uniformity, with RPHS showing superior uniformity. Keshavarz et al. [14] performed numerical analysis of the effect of nanofluid and fin distribution density on thermal and hydraulic performance of a heat sink with drop-shaped micropin fins. The study found that drop-shaped pin fins exhibited better thermal and hydraulic performance than circular pin fins. Darbari et al. [10] studied nanofluid heat transfer and entropy generation inside a triangular duct equipped with delta winglet vortex generators. The study identified a critical angle of θ = 40° for both frictional and thermal entropy generations, with thermal entropy generation reducing by 11% within $0° < \theta < 40°$. Joseph et al. [33] numerically simulated liquid-gas interface formation in long superhydrophobic microchannels with transverse ribs and grooves. The study proposed a varying curvature shear-free (VCSF) model to capture interface protrusion angle variation along channel length. The slip length obtained from VCSF simulations showed good agreement with theoretical predictions, and the study demonstrated that the lowest surface friction occurs when the meniscus has a protrusion angle of approximately 15°. Abdollahzadeh and Moosavi [32] optimized microgrooves for water-solid drag reduction using a genetic algorithm coupled with the volume of fluid method. Three groove shapes (rectangular, elliptical, and trapezoidal) were examined. The rectangular shape achieved approximately 22% drag reduction, outperforming elliptical (17%) and trapezoidal (6%) configurations.

3. Flow Physics and Heat Transfer Mechanisms

When flow encounters a rib, separation occurs at the rib crest, creating a recirculation zone downstream. The reattachment length depends on rib height, pitch, and Reynolds number. Goktepel et al. [31] numerically investigated heat transfer between ribbed plates using the Taguchi approach and observed that for dimensionless rib heights (h') of 0.3, symmetrical flow structure was significantly disturbed, creating complex vortex interactions. The streamlines presented by Elwekeel et al. [11] show that curved ribs create more turbulence than traditional transverse ribs, with convex broken ribs producing large recirculation regions downstream. For concave ribs, the flow direction parallels that of 90° ribs, but the curved surface enhances mixing in sublayers. Longitudinal vortices generated by angled ribs are more effective for heat transfer enhancement than transverse vortices. Darbari et al. [10] studied delta winglet vortex generators in triangular ducts and found that for $\theta < 40°$, increasing the angle of attack increased both Nusselt number and pressure drop, while $\theta > 40°$ showed diminishing returns due to vortex-wall interactions. Promvonge et al. [19] studied heat transfer in a square duct with combined twisted-tape and winglet vortex generators, finding an increase of 17% in thermal performance compared to a duct with twisted tape alone. Joseph et al. [33] demonstrated that the pressure difference between liquid and entrapped air determines the meniscus shape (convex, flat, or concave). The protrusion angle was found to obey the Young-Laplace theoretical scaling. The study showed that shallow cavities are more effective in withstanding liquid pressure without deforming, though their ability to entrap air is questionable from a practical viewpoint.

All reviewed studies confirm that the Nusselt number increases with Reynolds number due to thinner boundary layers and increased turbulence intensity. However, the Nusselt number enhancement ratio (Nu/Nus) typically decreases with increasing Re, as the relative contribution of ribs to flow disturbance diminishes at high flow rates. For solar air heaters operating at Re = 4,000-18,000, Raj et al. [20] reported that maximum THPP occurred at the highest Re values (10,000-18,000). Similarly, Bhattacharyya et al. [3] observed thermal performance factors decreasing from approximately 2.9 at Re = 10,000 to 1.33 at Re = 52,000 for staggered angular cut baffles. Wang et al. [27] studied pulsating flow in ribbed channels and found that for square wave pulsation, the cooling performance increased with pulsating frequency, while sinusoidal and triangular waves showed little frequency effect.

4. Thermal-Hydraulic Performance Parameter

The performance evaluation criterion (PEC) or thermo-hydraulic performance parameter (THPP) combines heat transfer enhancement and friction penalty:

$$THPP = \frac{Nu/Nu_s}{(f/f_s)^{1/3}} \tag{1}$$

Values > 1 indicate net benefit. Key findings from the literature include:

- Jain et al. [13]: Maximum THPP of 2.66 at g/e = 4 for arc-shaped ribs with symmetrical gaps in a double-pass solar air heater
- Bhattacharyya et al. [3]: Maximum η of 2.9 at P = 0.1, α = 60° for staggered angular cut baffles

- Raj et al. [20]: Maximum THPP of 3.01 for case C configuration (combined circular rings and staggered ribs) at e/D = 0.043, Re = 10,000
- Elwekeel et al. [11]: Case D (convex broken ribs) showed the highest thermal performance factor among curved rib configurations
- Ajeel et al. [2]: PEC values up to 2.22 for a trapezoidal corrugated channel with 2% Al_2O_3 nanofluid
- Wang et al. [27]: For pulsating flow, the square wave showed η = 0.97-1.0 times steady flow at low frequency, increasing with frequency.

5. Exergy Analysis

Second-law analysis provides insight into irreversibilities. Darbari et al. [10] studied entropy generation in triangular ducts with vortex generators, finding:

- Thermal entropy generation decreased by 36% when the nanoparticle volume fraction increased from 0 to 0.05
- Frictional entropy generation increased by 21% over the same range
- For $\theta < 40°$, thermal entropy generation decreased with increasing angle; for $\theta > 40°$, it increased
- Bejan numbers near unity indicated thermal entropy generation dominance in most of the channel
- The thermal entropy generation reduced by 64% when Re increased from 200 to 1000

Amirahmadi et al. [1] minimized exergy losses in a trapezoidal duct with turbulators, roughness, and bevelled corners, reporting total entropy generation reductions of approximately 8-10% for different Reynolds numbers.

Phu et al. [18] performed analytical predictions of the exergoeconomic performance of a solar air heater with surface roughness of metal waste (helically coiled metal waste. Key findings included:

- Maximum exergetic efficiency of approximately 2.3% occurred at Re ≈ 2,000
- For Re > 10,000, a flat plate collector was recommended from the second-law perspective
- The optimal collector area of 1.3 m^2 was found to optimize exergetic efficiency and total annual cost
- Exergy loss due to solar radiation absorption accounted for more than 70% of total exergy losses

Elwekeel et al. [11] performed exergy loss analysis for curved rib configurations and found that at low Re (5,000-8,500), exergetic losses of curved ribs approached those of reference cases, while at high Re, concave ribs showed the highest exergetic losses.

6. Applications

Solar air heaters (SAHs) operate at relatively low to moderate Reynolds numbers (3,000-18,000 for single-pass, up to 10,000 for double-pass) and benefit significantly from ribbed absorber plates. Key studies include: Jain et al. [13] investigated arc-shaped ribs with symmetrical gaps in a counterflow double-pass solar thermal air heater. The study compared three configurations: Case A (circular rings with W/w=4), Case B (circular rings with W/w=6), and Case C (combination of circular rings and staggered ribs). Case C produced a maximum Nu/Nus of 3.19 and THPP of 3.01 at e/D = 0.043, Re = 10,000. Circular metal rings were identified as cost-effective alternatives to complex rib shapes, readily available in local markets. Raj et al. [20] examined three configurations in a counterflow double-pass SAH: (1) circular rings with a relative width ratio of 4, (2) circular rings with a relative width ratio of 6, and (3) a combination of circular rings and ribs. The study recommended pipe layouts of 80 mm depth and 200 mm spacing for optimal heating performance, with an average heating rate of 2.77 K/h. Phu et al. [18] investigated helically coiled metal waste (from steel shaft turning) as a low-cost roughness element. The waste material is almost free of charge and has high availability. The study developed Nusselt and friction factor correlations with deviations of ±10% and correlation coefficients of 0.996 and 0.982, respectively. Kumar et al. [16] studied S-shaped ribs and developed correlations for Nusselt number and friction factor applicable for Re = 2,400-20,000, e/D = 0.022-0.054, P/e = 4-16, and arc angle = 30-75°. Deo et al. [1] analyzed solar air heater ducts roughened with multigap V-down ribs combined with staggered ribs, reporting maximum Nu enhancement of 3.34 times and THPP of 2.45 times compared to smooth ducts.

Internal cooling channels in turbine blades operate at high Reynolds numbers (10,000-100,000). Elwekeel et al. [11] emphasized that curved ribs enhance heat transfer through increased surface area and turbulence generation. The study recommended convex broken ribs with R/Dh = 2 for optimal balance of heat transfer and pressure drop. Key findings for turbine cooling applications:

- The lowest heated wall temperature was achieved by convex broken rib (case D), with average temperature decreasing by 26.23 K compared to the reference case

- The highest friction factor was achieved by concave ribs (case G), with a value increased by 14.9 times at Re = 30,000
- Case D showed a higher enhancement in heat transfer with less pumping power consumption compared to other rib studies

Wang et al. [27] investigated pulsating flow cooling performance in ribbed channels for gas turbine applications. Three pulsation patterns (sinusoidal, square, and triangular waves) were studied with frequencies from 3.2 to 50 Hz. The square wave pulsating flow showed the highest cooling performance at high frequencies, while sinusoidal and triangle waves showed little frequency effect. Bhattacharyya et al. [3] studied inline and staggered angular cut baffle inserts in a circular tube for turbulent flow (Re = 10,000-52,000). The maximum heat transfer was observed for staggered arrangement with a pitch ratio of 0.1 and cutting angle of 60°. The study compared performance with existing inserts, including corrugated tubes, broken twisted tape, wire coil inserts, twisted trilobed tubes, finned tubes, propeller swirl generators, double helical tape, and V-pattern dimple obstacles. The present geometry performed better than all except double helical tape and V-pattern dimple obstacles. Shahsavar Goldanlou et al. [22] studied heat transfer of hybrid nanofluid (Fe_3O_4-CNT/water) in a shell and tube heat exchanger equipped with blade-shaped turbulators. The results showed that PEC increased with Re and Fe_3O_4 concentration, while with increasing blade diameter, PEC first increased, then decreased. The highest PEC occurred at Re = 9,000, φ_M = 0.9%, φ_CNT = 1.35%, and d_r = 15 mm. Vahedi et al. [25] performed a two-phase simulation of nanofluid flow in a heat exchanger with a grooved wall. Two nanofluids (MgO-SAE10 and ZnO-SAE10) were studied using an Eulerian-Eulerian single-fluid two-phase model. The study found that usage of nanofluid and turbulators enhanced thermal-hydraulic performance by 84.78-105.31% for heat exchanger 1 and 86.84-107.68% for heat exchanger 2. Noorbakhsh et al. [17] numerically evaluated the effect of using twisted tapes as turbulators with various geometries on both sides of a double-pipe heat exchanger, demonstrating the benefits of compound enhancement techniques.

He et al. [9] demonstrated that ribbed pin-fin arrays (RPHS) offer superior performance for microelectronic cooling. At Re = 780, RPHS achieved Nu = 23.1 compared to 11.8 for smooth channels and 15.5 for cylinder pin-fin arrays. The study also showed that RPHS could handle heat fluxes up to 140 W/cm^2 while maintaining temperatures below the boiling point (373.15 K). Keshavarz et al. [14] numerically analyzed the effect of nanofluid and fin distribution density on thermal and hydraulic performance of a heat sink with drop-shaped micropin fins. Drop-shaped pin fins exhibited better performance than circular pin fins. Darbari et al. [10] studied nanofluid flow in a plate-fin triangular duct with delta winglet vortex generators, identifying an optimal vortex generator angle of attack of 40°.

7. Nanofluids in Ribbed Channels

Vahedi et al. [25] compared single-phase and two-phase (Eulerian-Eulerian) approaches for simulating nanofluid flow in grooved heat exchangers. The two-phase model predicted higher Nusselt numbers, friction factors, and thermal performance than the single-phase model. At φ = 1.5%, the Nusselt number increased by 174% and 190% for single-phase and two-phase models, respectively, compared to the base fluid. Shahsavar Goldanlou et al. [22] studied hybrid nanofluid (Fe_3O_4-CNT/water) in a heat exchanger with blade-shaped turbulators, finding that PEC increased with both Re and Fe_3O_4 concentration.

Darbari et al. [10] studied Al_2O_3-water nanofluid in triangular ducts with vortex generators, finding that both Nusselt number and pressure drop increased with nanoparticle volume fraction. Ajeel et al. [2] compared Al_2O_3-water nanofluid at 1% and 2% volume fractions in corrugated channels, finding that higher concentration produced better thermal performance (PEC = 1.82 at φ = 2% for trapezoidal channel). Ekiciler [30] studied TiO_2-Cu/EG hybrid nanofluid in a duct with triangular ribs, finding that 4% nanoparticle volume fraction provided the best performance with PEC improvements of 8-30% compared to a smooth duct. Darbari et al. [10] reported that thermal entropy generation reduced by 36% when φ increased from 0 to 0.05, while frictional entropy generation increased by 21%.

Shahsavar Goldanlou et al. [22] demonstrated that Fe_3O_4-CNT/water hybrid nanofluid outperformed mono nanofluids in heat exchanger applications. Ekiciler [30] compared four fluids (pure EG, TiO_2/EG, Cu/EG, and 50:50 TiO_2-Cu/EG) in a duct with triangular ribs. The hybrid nanofluid showed the best thermal performance, with the Nusselt number increasing by 33.44% compared to pure EG at Re = 100,000.

8. Conclusions

Based on the comprehensive review of 33 research articles, the following key findings emerge:

1. Optimal rib height (e/D) ranges from 0.02 to 0.05, with values near the viscous sublayer thickness (0.043-0.047)

providing best performance. Increasing e/D beyond this range produces marginal heat transfer gains at significant friction penalty [11, 13, 20].
2. Optimal pitch ratio (P/e) ranges from 7 to 15, with smaller pitches (P/e = 5-10) producing higher heat transfer at the cost of increased friction [3, 12].
3. Broken and V-shaped ribs outperform continuous transverse ribs by 20-50% in thermal-hydraulic performance due to enhanced secondary flow generation [3, 15].
4. Curved ribs, particularly convex broken configurations with a radius ratio of 2, provide excellent heat transfer enhancement (3.68 times smooth) with moderate friction penalties [11].
5. Ribs with gaps (g/e = 3-5) enhance secondary flow and mixing, achieving THPP values of 2.5-3.0 [13, 20].
6. Microchannel applications benefit from combined rib and pin-fin arrays, achieving 2-3 times Nusselt number enhancement over smooth channels [9, 14].
7. Hybrid nanofluids (TiO_2-Cu/EG, Fe_3O_4-CNT/water) outperform mono nanofluids, with PEC improvements of 8-30% compared to base fluids [22, 30].
8. Two-phase nanofluid modeling predicts higher heat transfer enhancement than single-phase models, with differences of 5-15% in predicted Nusselt numbers [25].
9. Pulsating flow with a square wave pattern can enhance cooling performance in ribbed channels, with effectiveness increasing with pulsating frequency [27].
10. Exergy analysis reveals that thermal entropy generation dominates in most of the channel (Bejan number near unity), and increasing nanoparticle concentration reduces thermal irreversibility [10, 18].

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