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Recent Advances in Heat Transfer Enhancement using Ribs and Dimples: A Review

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Abstract

The enhancement of heat transfer plays a vital role in developing efficient thermal systems in industrial applications such as various cooling device, gas turbines, heat exchangers, food processing, and the chemical industry. Surface modifications, such as ribs and dimples, have gained considerable attention due to their simplicity, effectiveness, and adaptability across various applications. The surface modification enhances heat transfer. This review provides a comprehensive analysis of past and present studies focused on heat transfer enhancement of extended surfaces of rib and dimple configurations. The paper discusses various surface geometric parameters, arrangement patterns, and orientations, along with their influence on thermal performance and pressure drop characteristics. The numerical and experimental investigation reveal that combining ribs with dimples or protrusions can increase the Nusselt number by approximately 20% to 90% as compared to smooth surfaces through depending on geometry and flow conditions. Mostly the teardrop-shaped dimples and arc-shaped ribs have superior heat transfer augmentation with enhancements often exceeding 50% while maintaining manageable pressure drops (friction factor increase typically between 10% to 40%). Further, the Curved or angled rib geometries boost turbulence intensity and gives an additional 10-15% heat transfer improvement. Furthermore, the review highlights hybrid techniques combining ribs and dimples. They offer high heat transfer efficiency with reduced pressure drop, making them viable for practical applications. The objective is to identify effective design strategies and outline future directions for research and practical implementation in the present scenario.

Keywords: Dimple, Friction Factor, Heat Transfer Enhancement, Nusselt Number, Rib.

Introduction

Effective thermal management is crucial in many engineering systems such as gas turbines, internal combustion engines, heat exchangers and electronic cooling units (1-3). With the on-going trend toward higher efficiency and system miniaturization, there is a growing need for compact, high-performance heat transfer solutions. Ribs are raised structures on flow surfaces that enhance turbulence by disturbing the boundary layer and generating vortices with an increase in turbulence intensity. The performance of heat transfer depends on geometric parameters of ribs such as orientation, shape, pitch and height. Passive heat transfer enhancement methods that operate without the need for external power are especially appealing due to their straightforward implementation, dependability, and compatibility with existing technologies. Among these, surface modifications like ribs and dimples have been extensively explored. The modified geometries enhance thermal performance (4). The hybrid structures of ribs and dimples shows synergistic effects boosted thermal transfer as compared to the individual. The hybrid combination gives an enhancement of increased friction factor with pressure drop. These structures are used in solar air heaters, rectangular channels and jet impingement cooling with turbulent flow (5). Computational fluid dynamics (CFD) has significantly advanced the understanding of these features by providing detailed insights into flow behaviour and temperature distribution (6, 7). Experimental studies remain vital for validating simulation results and assessing system performance under different thermal conditions (8, 9). The effectiveness of these methods varies with factors like shape, size, alignment, and Reynolds number of the flow. A wide range of research has focused on both the standalone and combined performance of ribs and dimples in terms of thermal efficiency and fluid resistance. While ribs often provide higher levels of heat

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transfer, they are typically associated with greater frictional losses. Dimples tend to strike a more favourable balance, offering moderate improvements with less impact on pressure drop. Recently, hybrid designs incorporating both ribs and dimples have shown promise by combining the advantages of each feature, aiming to enhance thermal performance while limiting the accompanying pressure loss (10-12). Effective cooling of gas turbine blades is achieved through a combination of internal and external cooling methods. The turbine blades are cooled through various parameters such as pressure, leading edge, suction surfaces, and the blade tip region of the film.

The review advances theoretical understanding of flow and heat transfer mechanisms associated with ribs and dimples by explaining boundary layer disruption, secondary flow generation, vortex formation, and turbulence intensification. It further synthesizes the influence of geometric parameters such as shape, orientation, pitch, and depth on these mechanisms, and integrates existing theoretical models and correlations from recent studies.

The paper reviews the current state of research on passive methods for enhancing heat transfer through various techniques such as integration of dimples and ribs. It explores the impact of various geometric configurations, and evaluates heat transfer with pressure drop.

Methodology

In engineering applications like Ventilation, Heating and Air Conditioning (HVAC) systems, electronics cooling, power plants, and industrial processes, "developments in heat transfer techniques" refers to new or improved methods and strategies to increase efficiency, speed and heat transfer.

The dimple-shaped surface promotes local vortex and secondary flows, and the cold fluid contacts the boundary layer. The layer reattachment with unsteady flow structure enhances turbulence near the surface and leads to higher local and average Nusselt numbers. The tear-drop shaped dimples have high heat transfer with a lower recirculation zone upstream as compared to spherical and elliptical dimples. Ribs act as tabulators and distribute the flow to promote the boundary layer of detachment and reattachment. It increases mixing and turbulence of intensity across the channel. The thermal boundary layers extend and boost the Nusselt number, though the friction penalty rises depending on rib geometry.

Heat transfer performance was significantly enhanced by Murara *et al*. through the combined use of dimples, cylindrical protrusions, and square ribs on a single wall of a passage (1). Both experimental and numerical investigations revealed notable spatial variations in local Nusselt numbers, with peak values observed at rib tops and protrusion leading edges. While some discrepancies were noted between experimental and numerical results in terms of absolute values, overall trends were consistent. Among the two cylindrical protrusion configurations, the larger diameter case showed a 20–40% higher mean Nusselt number, despite a 26–32% increase in pressure loss. Thermal effectiveness was greater for the larger protrusion configuration, despite the associated pressure drop.

The potential of compound rib–dimple configurations for enhancing heat transfer within a two-pass square channel was effectively demonstrated (2). Transient liquid crystal thermography was used to analyse several rib geometries with angle shape of 45° and (V, W, and M) shapes in combination with cylindrical dimples. Among the tested configurations 45°-angled and V-shaped rib–dimple arrangements have enhanced thermal-hydraulic performance relative to their individual rib or dimple counterparts. The span-wise averaged Nusselt number distribution further confirmed consistent improvement in the first pass, indicating improved heat transfer along the stream wise direction. Overall, these compound configurations offer a promising approach for efficient thermal management in internal cooling applications.

The protrusion–dimple configurations showed that variations in staggered angle, protrusion diameter, and protrusion–dimple spacing, together with the presence of secondary protrusions, significantly enhance heat transfer within the dimple cavities (3). Notably, configurations in cases 4 and 6 achieved greater $Nu/Nu_0 \approx 2.1–2.2$, with only a modest increase in pressure drop (15%), and friction ratio (f/f_0) between 1.9 and 2.1. The calculated thermal performance factor (TPF) confirmed that channels incorporating secondary protrusions outperformed others, with cases 4 and 6 demonstrating the efficient balance between heat transfer improvements through pressure loss. Various rib geometries, including semicircular, multi-semicircular, and W-shaped ribs, in compound configurations with dimples as well as in rib-only channels, were experimentally investigated to determine the optimal design for turbine blade cooling (4). This study, performed within a Reynolds number of 12,600 to 35,000, demonstrates that the semicircular rib configuration consistently offers superior heat transfer performance relative to other rib shapes. The turbulence model of realizable k–ε provides CFD results closely matching experimental data, confirming the reliability of the numerical approach. Overall, the semicircular rib emerged as the most effective geometry for enhancing thermal performance in ribbed cooling channels.

A numerical investigation was conducted to examine heat transfer enhancement and fluid flow behavior in a solar air heater equipped with an absorber plate containing staggered multiple V-shaped ribs. The effects of Reynolds number, rib height, rib pitch, angle of attack, and stagger distance on thermo-hydraulic performance of Solar air heater model (5). The study demonstrated that staggered configurations significantly improve thermal performance. Compared to inline arrangements, staggered ribs yielded higher average Nusselt numbers and improved thermo-hydraulic performance, with a maximum performance factor of 2.43. The optimized stagger distance facilitated effective gap flow, promoting enhanced heat transfer through competing flow effects. The staggered multiple V-shaped ribs proved to be a superior design for efficient solar air heater applications.

The V-shaped ribs exhibit a higher heat transfer rate compared to W-shaped ribs, due to the stronger secondary flow generated at the rib apex. At Re = 80,000, heat transfer was enhanced by factors for V and W-shaped ribs of 1.94 and 1.8, respectively, relative to Re = 20,000 (6). V-shaped ribs demonstrated greater variation in local Nusselt number with the stream wise and span wise directions, whereas W-shaped ribs show uniform heat transfer. Although both rib types achieved a maximum enhancement ratio (Nu/Nu_0) of 3.9 at Re = 20,000, V-shaped ribs incurred higher friction losses up to 85% as compared to 42% for W-shaped ribs. The study concluded that rib-induced enhancements peaked at Re = 40,000, making this a critical design point for optimizing cooling performance in rectangular channels.

Numerical investigations using Delayed Detached Eddy Simulation (DDES) were conducted to study turbulent flow and heat transfer in channels featuring micro V-shaped ribs, dimples, and hybrid combinations of both, at a Reynolds number of 50,500 (7). Micro V-shaped ribs generate strong longitudinal vortex pairs that significantly enhance convective heat transfer, despite a reduction in turbulent mixing downstream of the leeward rib. Dimples, on the other hand, promote near-wall turbulent mixing with formation of shed and shear-layer vortices. The hybrid micro V-shaped rib-dimple configuration breaks the recirculation zones inside dimples via strong downwash flow from the ribs, with dimples acting as vortex amplifiers, producing stronger longitudinal vortices. The downwash flow induced by the ribs disrupts dimple recirculation zones, allowing the dimples to act as vortex amplifiers. This interaction results in intensified vortex structures and enhanced heat transfer, making the hybrid configuration particularly effective for thermal augmentation in turbulent channel flows.

Simulations were performed over Reynolds numbers from 12,500 to 86,500, considering different rib pitch-to-height ratios (8). The study found that all rib configurations enhanced heat transfer, with Nusselt number ratios (Nu/Nuo) of 1.3 to 2.14. with friction factor ratios of 1.8 to 4.2. Hybrid ribs generally exhibited higher thermal-hydraulic efficiency indices compared to rectangular and semi-circular ribs, indicating superior overall performance. This makes the hybrid rib configuration a promising option for efficient thermal management in rectangular duct systems.

The thermal performance associated with various dimple and protrusion shapes combined with angled ribs was examined (9). The tests were conducted at Reynolds numbers of 30,000, 50,000, and 70,000 on compound configuration of the rib–dimple which enhances heat transfer and increased pressure drop. Among the various rib–protrusion configurations, those using low-profile protrusions demonstrated superior thermal performance. This improvement is attributed to a favorable balance between reduced pressure loss and enhanced heat transfer. Additionally, the rib–oval protrusion arrangement and protrusion installation angle were found to significantly influence heat transfer behavior. Overall, the study highlights that optimized combinations of ribs and surface features can substantially improve cooling performance, provided pressure penalties are managed appropriately.

The effect of rib-induced secondary channels on heat transfer and pressure drop in micro channels was numerically investigated at low Reynolds numbers ranging from 100 to 500 (10). The proposed microchannel design on secondary channels and rectangular ribs (MC-SOCRR) outperformed the conventional microchannel designs. These conventional designs consisted of micro channels featuring either rectangular ribs alone or secondary channels alone. The enhanced performance of the MC-SOCRR is attributed to its larger flow area lowers the pressure drop. Additionally, the strategic placement of ribs promotes flow mixing through secondary channels, further improving thermal performance. The parametric analysis revealed that a secondary channel width , relative rib width and channel angle of 0.666, 0.5, and 45° gives an improved performance factor of 1.98 with Re of 500. Overall, the MC-SOCRR configuration offers a highly effective balance between convective enhanced heat transfer and pressure loss mitigation in micro scale applications.

Heat transfer performance in a circular steel passage simulating gas turbine blade cooling was evaluated (11). The tests were performed at Reynolds numbers of 10,800, 12,900, and 15,700, under a surrounding temperature of 673 K. The k–ε turbulence model of ANSYS-FLUENT is compared for smooth and ribbed passages. It gives enhancement of heat transfer for the ribbed configuration, with the greatest improvement observed at Re = 12,900, where heat transfer increased by 84.3%. Additionally, the ribbed tube exhibited superior thermal performance under turbulent flow conditions, confirming the effectiveness of ribbed surfaces in enhancing heat transfer within circular cooling channels.

Heat transfer in turbulent channels fitted with trapezoidal ribs and twisted tape inserts was analysed using CFD simulations (12). The influences of rib inclination angles between 30° and 60° on thermal performance were simulated. The inclination angle of 60° resulted in the highest Nusselt number and friction factor, whereas the optimal thermal performance factor was achieved at 30°. The simulation results closely matched the Promvonge model, validating the reliability of the numerical approach. This agreement also highlights the effectiveness of trapezoidal rib configurations in enhancing thermal performance under turbulent flow conditions.

Thermal performance in turbine blade cooling passages was improved by the use of truncated ribs in high aspect ratio channels (13). Using Liquid Crystal Thermography (LCT) for experimental measurements and k–ω turbulence modeling for numerical simulations, eight ribbed channel configurations were analysed. The study found that staggered arrangements of truncated ribs significantly enhance flow mixing by creating more complex flow paths, leading to improved heat transfer. Among the tested designs, truncated ribs showed particular promise for turbine blade cooling applications in high aspect ratio channels to achieve 10% enhancement heat transfer. The enhanced heat transfer and pressure drop give an effective design strategy in advanced cooling systems.

The rectangular divergent channel is equipped with various parallel angle ribs of 30°, 45°, 60°, and 90° (14). Ribs were applied to either both opposing walls or only one wall of the channel with a range of Reynolds number of 15,000 to 89,000. The evaluation of thermal performance was carried out under the constraints of constant mass flow rate with pressure drop and pumping power. A smooth, straight circular channel was used as the reference configuration for comparison. The results indicated that ribbed divergent channels significantly enhanced heat transfer, with performance strongly dependent on the rib attack angle and wall configuration. Among the configurations, the 45° parallel rib provided higher thermal performance on a Reynolds number of 60000. The cooling airflow and heat transfer in a single-pass channel with wavy ribs were studied to optimize rib geometry for improved thermal performance (15). The rib parameters were examined at a range of Reynolds number of 10,000 to 40,000, using conventional V-shaped ribs of angle 45°. The wavy ribs feature greater height and a larger radius of curvature, which significantly enhance heat transfer while also reducing pressure drop. Compared to the 45° V-shaped ribs, the optimized wavy ribs achieved a 7–37% increase in Nusselt number and a 28–52% increase in ribbed surface area, all without incurring additional friction losses. These findings confirm that wavy ribs are a highly effective solution for improving heat transfer in internal cooling channels, offering both thermal and hydraulic advantages.

The dimple shapes considered included teardrop, spherical, elliptical, and inclined elliptical forms (16). Both numerical and experimental studies were conducted over a Reynolds number range of 8,500 to 60,000. The teardrop-shaped dimples achieved the highest heat transfer rate, exceeding that of spherical dimples by 18%. The elliptical dimples showed 10% lower heat transfer rate as compared to spherical shapes. Inclined elliptical dimples exhibited heat transfer and pressure drop characteristics comparable to those of spherical dimples. Overall, the study highlights that dimple shape significantly influences thermal performance, with teardrop dimples emerging as the efficient for augmenting heat transfer in cooling channel applications.

The staggered pin fin arrangements on the end wall were studied across a Reynolds number range of 8,500 to 60,000 (17). The dimple placement significantly affects thermal and flow behavior within the channel. When dimples were positioned in the wake region of the pin fins, only a modest improvement in heat transfer of 3.52% was observed with friction factor 1.81% as compared to the baseline pin-finned configuration. These results indicate that optimal dimple positioning is critical to maximizing thermal performance in combined dimple–pin fin cooling designs, as improper placement may yield limited enhancement.

The Nusselt number distribution was observed near the leading edge of the grooves and in the reattachment region downstream of the trailing edge (18). Separation is mainly found at the back of protrusions, which increase heat transfer at the leading edge of adjacent downstream grooves. Among the tested geometries, the rectangular protrusion case exhibited the greatest heat transfer enhancement (Nu/Nu_0) with a higher resistance coefficient (f/f_0), showing a strong sensitivity to Reynolds number. When ribs were added, separation bubble sizes notably decreased on the second and third grooves, and heat transfer was significantly improved. The one-row rib configuration provided the best thermal performance, confirming that rib placement plays a crucial role in convective heat transfer within grooved protrusion channels.

An increase in the number of convex dimples significantly enhanced both the Nusselt number and the thermal performance factor (19). This improvement comes with only a minimal increase in the friction factor, indicating a favorable trade-off. However, the span wise placement of convex dimples resulted in complex, non-linear effects on flow structure and heat transfer, indicating that optimal positioning is crucial for maximizing performance. Overall, the incorporation of convex dimples enhances the heat transfer performance of grooved channel configurations. The tabulators were mounted at an attack angle of 45°, arranged with their tips oriented both upstream (V-up) and downstream (V-down), and tested over a Reynolds number range of 5,300 to 23,000 (20). Among the configurations, the V-up arrangement with a relative pitch (RP) of 1.0 produced the highest Nusselt number and friction factor. This was attributed to strong vortex generation and impinging jet flows created by the punched holes on the absorber plate. The combined configuration significantly enhances thermal performance as compared to smooth duct.

Results

The comparative results of different heat transfer techniques are listed in Table 1. The numerical investigation of integrating dimples on a double wall cooling structure can effectively enhance the target. The thermal performance increased up to 15.8% over the baseline, whereas overly deep or wide dimples could reduce performance by as much as 22.2% (21). The stream wise-elliptical dimple demonstrated enhanced heat transfer with enhanced friction factor. Compared to channels of circular pin fins and dimples, stream wise-elliptical pin fins show a 15.0% improvement in the volume goodness factor and a 109.6% improvement in the area goodness factor (22).

Table 1: Major Findings of Various Heat Transfer Approaches

Geometry used	Parameters	Major Findings	Ref. No.
Curved ribs equilateral triangle, and circle cross-section	Re= 10000 to 50000	Performance factor of *R*3 ranges from 1.5 to 2.65 for the square ribs up to Reynolds number of 20,000	(23)
Tube with Broken V-ribbed twisted tapes	Attack angles of rib 45 ∘ , 60 ∘ , 75 ∘ , and 90 ∘ Re= 6000 to 20000 Twist ratio =3.5 to 4.5	The friction factor was enhanced up to 4.65 times, and heat transfer of Nu/Nu_s was 1.32 to 2.27 times higher than that of a plain tube	(24)
Twisted tape with dimples in double pipe	Diameter of 2, 4, and 6 mm, (D/H) = 1.5, 3 and 4.5. Re of 6000–14,000	A higher Nusselt number was observed at D/H = 3, while a lower friction factor was recorded at D/H = 4.5 for different diameters, with values of 0.1033 (for Re = 13,987) and 0.1437 (for Re = 6,180), respectively	(25)
Dimple/Protrusion and triangular rib (Numerically)	Re - 10,000–50,000	Enhanced Nu/Nu_0 of 1.31 is achieved and the f/f_0 is only 0.96.	(26)
Wire-roughened absorber plate	W/H ratio of 5, h/D of 0.01, p/h = 10 to 40, and α=50 ∘ , Re=3000-8000	Higher efficiency of 1.14 at Re=3000, And lower efficiency of 0.46 at Re=8000.	(27)
Rotating cooling channel	Re=5000 to 25000, Ro = 0.118 ~ 0.590, and q = 5000 ~ 25,000 $W{\cdot}m^{-2}$	Increased Nusselt number 73.77% with performance evaluation 23.77%	(28)
45° V-type collective ring	Re=4000-20000, W_D/W_{VR} = 3.0- 6.0, P_{VR}/H_{VR} =45.33 to 78, and H_{VR}/D_h =0.0238 - 0.0368.	A high friction factor, enhanced thermo hydraulic performance, and peak Nusselt number of W_D/W_{VR} = 5, P_{VR}/H_{VR}=63.33, and H_{VR}/D_h = 0.0325	(29)
Notched baffles	The ratio of notch height-to-baffle height (a/e)= 0.125 to 0.5. Re= 6000 to 24,000	Maximum aero thermal performance factor of 1.17 and greater heat transfer rate observed	(30)
Inline and Staggered dimple arrangements (Numerically)	Dimple diameter = 6 mm, pitch = 8 mm and Re=5000-20,000	A significant TPF value of 9.07 observed at D=6mm, P=8 mm and Re=10000.	(31)
Dimpled surface	Re=5000-20,000	Enhanced heat transfer of 267.04%, 239.67%, 199.18%, and 179.93% for volume concentrations of 1%, 0.75%, 0.33%, and 0.1%, respectively, at Re = 5000	(32)
Hybridized dimpled tube with twisted tape	Dimple diameter =1- 6mm, Pitch= 60-100 mm, Re=12000 to 60000	Heat transfer performance observed up to 14 %.	(33)
V shaped flapped baffles and Chamfered groove	Re= 5300–23,000 pitch ratios (1.0, 1.5 and 2.0)	Thermal Performance Factor(TPF) of 2.68 achieved	(34)
S Shape with Gaps	Re=2000 to 20000 P/e ratios 20, 25, 30.	Thermal efficiency improved by 13% to 48%, with a corresponding pressure drop ranging from 15.8 to 30 Pa. Nusselt number =5.42, friction factor = 5.87	(35)
V-shaped and spherical dimple (Numerically)	Re=8500-50,000 Depth-diameter Ratio=0.14	Increases Nusselt number ratio of 23.6% and 33.7%, and friction factor ratio 37.0% and 72.3%.	(36)
Bionic fish scale tube (Numerically)	Re=11225 to 33675	The maximum value of Performance Evaluation Criteria up to 1.352 for Case 11 at Re =16840.	(37)
V shape, Flat, concave with spare/dense dimple/protrusion and rib-dimple/protrusion. (Numerically)	Re=10,000–50,000	A Nusselt number ratio achieved upto 1.31 with sparse protrusions in concave and V-shaped channels, while the corresponding friction factor ratio (f/f_0) is only 0.96.	(38)
Ellipsoidal U-tubes (Numerically)	Ellipsoidal angle of 0⍰, and 45⍰, Re=5000 – 40000	The ellipsoidal U-tube with 45° dimples achieved a 45.4% improvement in overall	(39)

		performance at Re = 12,000, while the ellipsoidal U-tube with 0° dimples and a larger bend curvature showed a 35.3% improvement at Re = 40,000.	
Elliptical absorbers	Re=15000-80000	Enhanced flow characteristics up to 25%, resulting in improved thermal performance. The pressure drop increased up to 4.5%.	(40)
Horizontal spiral coils with flat tubes with rectangular ribs (Numerically)	Re=3000 to 12000, rib height of 0.04 to 0.08 rib pitch of 0.3 to 0.5	Achieved enhanced heat transfer by 1.73% to 26.58%, with a corresponding increase in pressure loss ranging from 3.6% to 36.34% compared to the baseline configuration. The resulting thermo-hydraulic performance factor ranged from 1.004 to 1.141.	(41)
Detached S-Ribs	Re=5000 to 20000	All the normalized Nusselt number ratios decrease as the Reynolds number increases for both the front and back walls. The friction factor ratios range between 15.1 and 13.	(42)

The performance evaluation criterion (PEC) increases with dimple diameter but decreases with excessive dimple depth. Among the 27 simulated cases, the optimal geometry (depth = 2 mm, diameter = 18 mm, pitch = 4D) achieved a maximum PEC of 3.3 at Re = 2000. These findings suggest that deep dimpled tubes offer a promising solution for improving the efficiency and compactness of industrial heat exchangers, with potential for further performance gains through future studies on cooling mechanisms and two-phase flow behavior (43).

Combining perforated ribs with inclined rib configurations can effectively improve the thermal performance of ribbed channels. Inclined perforated ribs demonstrate an improvement in the overall average Nusselt number, with enhancement ratios ranging from approximately 1.85% to 4.94% compared to straight ribs (44). Dimpled surface with a bleed hole installation angle of -30°to +30° in a converging channel angle of 12.7° improves Nusselt number and the thermal performance (45).

The varying dimple depth ratios were obtained from both numerical simulations and experiments. The friction factor ratios for shallower dimples (δ/d = 0.067 and δ/d = 0.1) remain consistent across a Reynolds number range of 10,000 to 60,000 (46). The numerical approach focused on achieving a balance between heat transfer enhancement and acceptable pressure loss. This was accomplished by strategically placing convergent and divergent slit ribs within the flow channel. The investigation covered a range of Reynolds numbers from 10,000 to 25,000 (47).

The inclined detached ribs were evaluated at various attack angles (θ = 0°, 15°, 30°, 45°, 60°, 75°, 105°, 120°, 135°, 150°, and 165°) to assess thermal performance, friction factor, and heat transfer over a Reynolds number range of 4,000 to 24,000. An attack angle of 60° led to a significant increase in heat transfer, achieving rates up to 1.74 times higher than those observed in smooth channels. In contrast, an angle of 120° produced a thermal performance factor of 1.21, showing improved efficiency compared to other rib configurations (48). The highest heat transfer near the end wall is achieved with fully bridged pin fins. The baseline cases, broken ribs, and full ribs only gain an additional 10% to 20% in heat transfer to the end wall (49).

The dimpled configuration structure shows enhanced heat transfer, accompanied by pressure drop penalties. This results in increased friction factor ratios (f/f_0), ranging from 2 to 6.7 in the laminar regime and 2.5 to 3.6 in the turbulent regime, corresponding to their heat transfer enhancement performance (50). Numerical comparisons between a dimple–pin fin wedge duct and a baseline pin fin wedge duct without dimples revealed a significant improvement in performance. Aligning the dimples with the pin fins resulted in the greatest heat transfer improvement while causing the least penalty in the friction factor (51).

Discussion

The review highlights that rib, dimples and hybrid structure with various geometrical structures. Ribs act as repeated flow obstructions which break the laminar sub-layer, generating turbulence and enhancing convective heat transfer. Ribs disturb and reattach the thermal boundary layer, thereby enhancing heat exchange efficiency. The geometric parameters of the ribs such as height, orientation angle, and pitch-to-height ratio significantly influence both the heat transfer rate and the associated pressure drop.

The dimples induce secondary flows and create localized vortices that increase fluid mixing near the surface. Geometric factors such as the dimple depth-to-diameter ratio, arrangement (inline versus staggered), and shape (elliptical, spherical) significantly influence the heat transfer performance. Recent studies indicate that the hybrid applications of rib and dimple achieve higher Nusselt number ratios as compared to individual configurations, though it comes with increased pressure losses. The geometric parameters play a crucial role for determining performance outcomes. Considering the balance between heat transfer efficiency and flow resistance, micro-channels with hemispherical dimples achieve roughly 27% higher overall thermal performance compared to rhombus-dimpled channels (52). The unsteady inflow effects in designing dimpled surfaces for thermal management in applications such as turbine cooling and internal heat exchangers (53).

The synthesized data enable a clear description of commonly investigated configurations, frequently adopted experimental setups, and typical performance ranges reported in the literature. This descriptive synthesis helps in presenting the current state of research on ribs and dimples, highlighting the breadth of available studies while providing a coherent overview of their reported findings.

Numerical simulations are also supported by experimental validations, to enable precise optimization of these parameters for a specific Reynolds number range. However, balancing heat transfer enhancement with hydraulic penalties continues to be a major design challenge.

Consistent trends such as enhanced heat transfer due to boundary-layer disruption and secondary flow generation are emphasized across both earlier and recent studies. Observed discrepancies are critically analysed and explained in terms of differences in rib and dimple geometry, flow conditions, channel configurations, and experimental or numerical methodologies.

Heat transfer enhancement using ribs and dimples significantly increases pressure drop due to higher flow resistance, leading to increased pumping power and reduced overall efficiency. Their performance shows a trade-off between heat transfer gain and hydraulic loss, with effectiveness strongly dependent on Reynolds number. Additionally, complex geometries increase manufacturing cost, fouling risk, and make flow behavior difficult to predict accurately.

Based on the review findings, ribs and dimples should be implemented primarily in applications where the benefits of enhanced heat transfer justify the associated increase in pressure drop, such as gas turbine blade cooling, compact heat exchangers and heat sinks (54). It is recommended that geometric parameters, including rib height, pitch, dimple depth and arrangement, be carefully optimized to balance thermal enhancement with hydraulic performance. Additionally, the use of advanced manufacturing techniques and proper maintenance practices is advised to minimize fabrication costs, fouling issues, and long-term performance degradation.

Conclusion

This review highlights the crucial role of surface features like ribs; dimples and hybrid structure boost the convective heat transfer across various thermal systems. Ribs enhance performance by increasing turbulence and disturbing the boundary layer, while dimples improve heat transfer by inducing localized flow recirculation and creating vortices. The passive heat transfer enhancement techniques such as ribs and dimples significantly improve thermal performance, with reported Nusselt number enhancements ranging from 20% to 90% compared to smooth surfaces, depending on geometric configuration and flow conditions. Among various dimple geometries, teardrop-shaped dimples are particularly effective, providing a 40–50% increase in heat transfer while causing a moderate friction factor rise of about 15–25%, making them well suited for microchannel cooling applications. Hybrid rib and dimple configurations exhibit synergistic effects, achieving Nusselt number enhancements of up to 90% while limiting friction factor increases to 30–35%, resulting in favorable thermal performance factors between 1.6 and 2.0. Furthermore, the use of nano-fluids in ribbed and dimpled channels offers an additional 20–30% heat transfer enhancement, although this benefit is accompanied by higher friction factors due to increased fluid viscosity.

Despite notable progress in heat transfer enhancement, challenges remain in balancing thermal performance with energy efficiency. Increased pressure drop, higher pumping power, and manufacturing complexity limit practical applicability. Future research should focus on optimizing rib and dimple geometries, developing hybrid passive active systems, and employing advanced numerical methods, smart materials, and additive manufacturing to achieve efficient, adaptive, and wide range thermal regulation.

Abbreviations

α: Angle of approach of flow in degree, CFD: Computational Fluid Dynamics, D/H: diameter-to-depth ratio, h/D: Relative wire roughness height, H_{VR}/D_h : Relative V and ring height, Nu: Nusselt Number, Nu/Nu_0: Nusselt number ratio, p/h: Relative wire roughness pitch, P_{VR}/H_{VR} : Rastio of pitch V and ring to height V and ring, Re: Reynolds Number, Ro : Rotating number, W_D/W_{VR} : Relative V combined ring ratio.

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Author Contributions

Chinta Limbadri: perform research, gathered information, Sachin L Borse: guide to write the research paper, Akhya Kumar Behera: guide to write the research paper, Dipak S Patil: review the manuscript in correct format, Sanjay G Mitkari: review the manuscript in correct format.

Conflict of Interest

We have no conflicts of interest to disclose, all authors declare that they have no conflicts of interest.

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The authors have not used AI and AI Assisted Technologies in the Writing Process.

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