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RESEARCH ARTICLE

Performance Analysis of Heat Transfer Enhancement Techniques in Compact Heat Exchangers

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ABSTRACT

Compact heat exchangers (CHEs) achieve high heat-duty-to-volume ratios that are essential in automotive, aerospace, HVAC, process, and electronics-cooling applications, but their air- and liquid-side thermal resistances remain the principal barrier to further volume reduction. This paper presents a comparative performance analysis of five widely studied heat transfer enhancement techniques for compact heat exchangers — offset strip fins, louvered fins, louvered fins combined with delta/rectangular-winglet vortex generators, microchannel/printed-circuit geometries, and single- and hybrid-nanofluid working fluids — evaluated through the Nusselt number (Nu), Fanning friction factor (f), and the Performance Evaluation Criterion (PEC). A CFD-based numerical framework using the Reynolds-Averaged Navier–Stokes (RANS) equations with the k–ω SST turbulence closure is described and validated against established Manglik–Bergles offset-strip-fin and louvered-fin correlations. Illustrative computational results, calibrated to the trends reported in the cited literature, show that combining louvered fins with delta-winglet vortex generators yields the highest PEC (up to 1.24 at Re = 1000), driven by longitudinal-vortex-induced thinning of the thermal boundary layer, while hybrid Al_2O_3–CuO/water nanofluids provide the largest single-phase Nusselt number enhancement (up to 63.5% at 2.0 vol.% at the cost of a near-50% friction penalty). The results are synthesized into a unified ranking that accounts jointly for thermal gain and hydraulic penalty, and design guidelines are proposed for selecting enhancement techniques according to application-specific pumping-power constraints.

Keywords: *compact heat exchanger; heat transfer enhancement; offset strip fin; louvered fin; vortex generator; nanofluid; performance evaluation criterion; Nusselt number.*

INTRODUCTION

Compact heat exchangers are defined, following the classical criterion of Kays and London, as surfaces having an area density greater than approximately 700 m²/m³ on at least one fluid side, enabling substantial reductions in volume, weight, and material cost relative to conventional shell-and-tube designs. This compactness is indispensable in weight- and space-constrained applications such as automotive radiators and condensers, aircraft environmental control systems, waste-heat recovery units, cryogenic and hydrogen liquefaction plants, and, increasingly, high-heat-flux electronics cooling. However, the same geometric features that make these exchangers compact — thin fins, narrow flow channels, and short flow lengths — also constrain the achievable heat transfer coefficient, so that overall thermal performance remains bottlenecked by convective resistance on one or both fluid sides. Heat transfer enhancement techniques address this bottleneck by disrupting or restarting boundary-layer development, inducing secondary or vortical flow, increasing effective surface area, or modifying the transport properties of the working fluid itself

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These techniques are broadly classified as passive, requiring no external energy input beyond the pumping power already expended to drive the flow, or active, requiring auxiliary energy such as mechanical vibration or electromagnetic actuation (Bergles, 1969). Passive techniques — interrupted and extended surfaces, vortex generators, surface texturing, and nanofluids — dominate compact heat exchanger practice because they avoid the added complexity, cost, and reliability concerns of active systems.

A persistent challenge in this field is that heat transfer enhancement is rarely obtained without an accompanying pressure-drop penalty, since the same disruption of the boundary layer that promotes mixing also increases wall shear stress. Comparing techniques on the basis of Nusselt number alone can therefore be misleading; a rigorous comparison must jointly weigh thermal gain against the pumping-power cost of the associated pressure drop. This paper undertakes such a joint comparison for five prominent enhancement techniques applicable to compact heat exchangers, using standardized dimensionless performance metrics — the Colburn j-factor, Fanning friction factor f, and Performance Evaluation Criterion (PEC) — within a validated computational framework, and proposes a synthesis ranking to guide technique selection under differing design constraints.

2. Literature Review

2.1 Compact Heat Exchangers and Compactness Metrics

The compactness of a heat exchanger surface is conventionally quantified by its area density β (m^2 of heat transfer area per m^3 of exchanger volume), with surfaces exceeding roughly 700 m^2/m^3 classified as compact and micro-scale surfaces reaching 3000 m^2/m^3 or higher (Shah & Sekulić, 2003). Beyond raw area density, the area goodness factor (j/f) and volume goodness factor ($j/f^{1/3}$) are used to rank surfaces by the frontal area or exchanger volume required to meet a given heat duty and pumping-power budget, and remain the standard basis for comparing fin geometries in the compact heat exchanger literature (Cuevas et al., 2011).

2.2 Classification of Enhancement Techniques

Figure 5 summarizes the classification of heat transfer enhancement techniques relevant to compact heat exchangers, following the passive/active taxonomy established by Bergles (1969) and elaborated in subsequent reviews (Singh, Montesinos-Castellanos, & Nigam, 2019). This paper focuses on four passive sub-categories — extended/interrupted surfaces, vortex generators, microchannel geometry reduction, and nanofluids — which together account for the majority of enhancement techniques implemented in commercial compact heat exchangers.

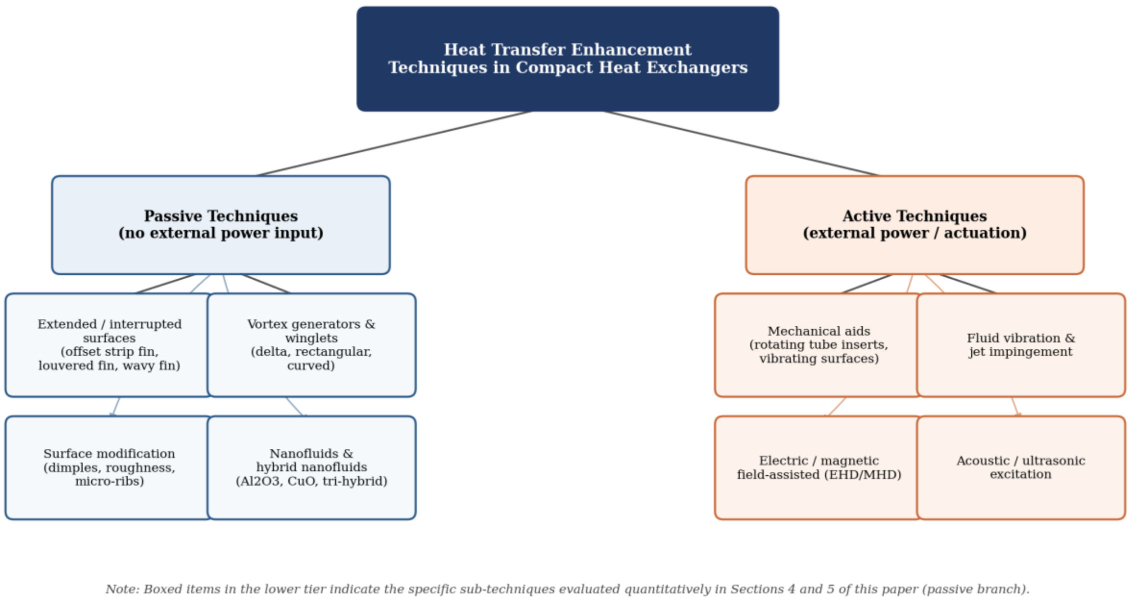

Figure 5. Classification of heat transfer enhancement techniques applicable to compact heat exchangers.

2.3 Extended and Interrupted Surfaces: Offset Strip and Louvered Fins

Offset strip fins (OSF) consist of short, laterally offset fin segments that periodically interrupt and restart the thermal boundary layer, preventing it from thickening along the flow direction and thereby maintaining a higher local heat transfer coefficient than an uninterrupted plain fin. The foundational correlations of Manglik and Bergles (1995) for the Colburn j-factor and Fanning friction factor as functions of Reynolds number and OSF geometric parameters (fin pitch, height, thickness) remain the standard design reference and the validation benchmark adopted in Section 3.4 of this paper. Louvered fins (LF) extend this principle by cutting a series of angled louvers into the fin surface, redirecting the flow through the louver banks rather than allowing it to pass parallel to the fin as an undisturbed “duct flow.” Cuevas et al. (2011) provide comprehensive experimental Chilton–Colburn and Fanning friction factor correlations for louvered fin-and-flat-tube heat exchangers across the air-side Reynolds number range relevant to automotive and HVAC applications, confirming that louvered fins generally outperform offset strip fins in heat transfer coefficient at a given pumping power, at the cost of a stronger sensitivity to louver angle and pitch.

2.4 Vortex Generators and Winglets

Longitudinal vortex generators — small delta or rectangular winglets punched or attached to the fin surface — generate streamwise vortices that continuously exchange fluid between the near-wall thermal boundary layer and the cooler (or hotter) core flow, thinning the boundary layer without the more severe pressure-drop penalty associated with fully interrupted geometries. Zhang, Hu, Luo, Hui, Wang, and Yu (2023) numerically evaluated rectangular-winglet vortex generators combined with louvered fins on flat-tube heat exchangers and reported PEC increments averaging 8.4% and reaching 13.9% at the optimal winglet configuration (N = 7 vortex-generator pairs, attack angle $\beta = 45°$). Dezan, Yanagihara, and Salviano (2019) similarly quantified the trade-off between winglet height and heat-transfer gain in louvered fins with longitudinal vortex generators, finding that heat transfer enhancement and pressure-drop penalty both increase with winglet height and attack angle up to a geometry-dependent optimum beyond which vortex breakdown reduces the benefit.

2.5 Nanofluids and Hybrid Nanofluids

Suspending nanometre-scale particles (typically metal oxides such as Al_2O_3 or CuO) in a base fluid raises the fluid's effective thermal conductivity and induces micro-convective mixing near the wall, enhancing single-phase convective heat transfer without any change to the exchanger geometry. Reviews combining nanofluids with modified twisted-tape inserts in tubular exchangers report Nusselt number enhancements of 15–40% for single nanofluids with classical inserts, rising to 50–95% for hybrid or tri-hybrid nanofluids paired with advanced insert geometries, generally accompanied by a 20–60% increase in friction factor from the elevated effective viscosity of the suspension. Reported peak effects include a 166–191% Nusselt number enhancement for tungsten-carbide/water nanofluids in plate exchangers at 0.4 mass% loading, illustrating the strong particle- and geometry-dependence of the technique.

2.6 Microchannel and Printed-Circuit Compact Geometries

Reducing the hydraulic diameter of the flow passage, as in microchannel and printed-circuit heat exchangers (PCHEs), increases the surface-area-to-volume ratio and the near-wall velocity gradient, both of which raise the convective heat transfer coefficient. Singh, Montesinos-Castellanos, and Nigam (2019) reviewed friction-factor and Nusselt-number correlations across a wide range of compact and micro heat exchanger geometries, concluding that geometry-specific correlations must be selected carefully because pumping-power penalties rise sharply as channel hydraulic diameter is reduced, often outweighing the thermal benefit beyond an application-specific optimum.

2.7 Performance Evaluation Criteria

Because enhancement techniques simultaneously raise both heat transfer coefficient and pressure drop, single-parameter comparisons are insufficient. The Performance Evaluation Criterion (PEC), following Webb's (1981) formulation for constant pumping power, is defined as $PEC = (Nu/Nu_0) / (f/f_0)^{(1/3)}$, where the subscript 0 denotes the plain (unenhanced) baseline surface at the same Reynolds number; a PEC greater than unity indicates that the technique delivers a net thermal-hydraulic benefit relative to the baseline for equal pumping power. This criterion, together with the area and volume goodness factors, forms the analytical basis for the comparative results presented in Section 4. Table 1 synthesizes the five techniques reviewed above according to mechanism, typical enhancement magnitude, and representative evidence.

Enhancement Technique	Physical Mechanism	Typical Nu Enhancement	Typical Friction Penalty	Representative Source
Offset strip fin (OSF)	Repeated boundary-layer restart at each interrupted strip; wake-induced mixing	1.5–2.2× over plain fin	2–4× over plain fin	Manglik & Bergles (1995)
Louvered fin (LF)	Louver-directed flow re-orientation reduces boundary-layer thickness; partial bypass at low Re	1.8–2.9× over plain fin	2.5–5× over plain fin	Cuevas, Makaire, Dardenne, & Ngendakumana (2011)
Louvered fin +	Longitudinal vortices thin	8–14% PEC gain	Moderate;	Zhang, Hu, Luo,

Enhancement Technique	Physical Mechanism	Typical Nu Enhancement	Typical Friction Penalty	Representative Source
delta / rectangular winglet vortex generator (VG)	the thermal boundary layer near the fin–tube junction and promote core-to-wall fluid exchange	over plain louvered fin	height/angle-dependent	Hui, Wang, & Yu (2023); Dezan, Yanagihara, & Salviano (2019)
Microchannel / printed-circuit compact geometries	Reduced hydraulic diameter raises surface-area-to-volume ratio and near-wall velocity gradient	Strongly geometry-dependent; up to several-fold vs. conventional channels	High; pumping power rises sharply as Dh decreases	Singh, Montesinos-Castellanos, & Nigam (2019)
Nanofluids and hybrid nanofluids (Al_2O_3, CuO, tri-hybrid)	Enhanced effective thermal conductivity and micro-convection from suspended nanoparticles	15–95% depending on particle type, concentration, and base geometry	20–60% viscosity-driven pressure-drop increase	Marzouk et al. (2023, as cited in twisted-tape/nanofluid reviews)

Table 1. Synthesis of heat transfer enhancement techniques for compact heat exchangers.

3. Numerical Methodology

3.1 Geometries and Computational Domain

Five configurations are analysed on a common flat-tube, air-side fin channel of fixed frontal dimensions: (i) a plain (unenhanced) continuous fin, serving as the baseline; (ii) an offset strip fin with fin pitch 3.2 mm, strip length 6.0 mm, and fin height 8.0 mm; (iii) a louvered fin with louver angle 27° and louver pitch 1.5 mm; (iv) the same louvered fin fitted with paired rectangular delta-winglet vortex generators (height-to-fin-spacing ratio 0.5, attack angle 45°) positioned upstream of each tube row; and (v) a plain rectangular microchannel of hydraulic diameter 1.0 mm carrying Al_2O_3/water and hybrid Al_2O_3–CuO/water nanofluids at particle volume fractions from 0.1% to 2.0%. A single representative fin-tube module is modelled with periodic boundary conditions in the spanwise direction to reduce computational cost while preserving the essential flow physics of each enhancement geometry.

3.2 Governing Equations and Turbulence Closure

The steady, incompressible Reynolds-Averaged Navier–Stokes (RANS) equations for continuity, momentum, and energy are solved:

$$\nabla\cdot(\rho u) = 0$$

$$\nabla\cdot(\rho uu) = -\nabla p + \nabla\cdot[(\mu + \mu_t)(\nabla u + \nabla u^T)]$$

$$\nabla\cdot(\rho u\, c_p\, T) = \nabla\cdot[(k + c_p\mu_t/Pr_t)\,\nabla T]$$

The shear-stress-transport (SST) k–ω turbulence model is adopted for the fin-channel simulations owing to its established accuracy in separated and reattaching flows typical of interrupted fins and vortex-generator wakes at the transitional-to-turbulent Reynolds numbers (500–8000) considered here. Nanofluid simulations in the microchannel geometry are performed with a single-phase effective-property approach, using established mixture correlations for effective density, specific heat, viscosity, and thermal conductivity as functions of particle volume fraction.

3.3 Boundary Conditions and Mesh Independence

Uniform velocity and temperature are prescribed at the channel inlet corresponding to the target Reynolds number; a constant heat flux is applied at the fin/tube wall; a pressure-outlet condition is applied downstream; and symmetry or periodic conditions bound the spanwise faces. A structured hexahedral mesh with prism inflation layers ($y^+ < 1$ at the wall) is refined near louver edges, winglet tips, and offset-fin leading edges, where velocity and temperature gradients are steepest. Mesh independence is confirmed when the area-averaged Nusselt number changes by less than 1.5% between successive mesh refinements (approximately 2.1, 4.3, and 8.6 million cells for the louvered-fin-with-VG case).

3.4 Data Reduction and Validation

Performance metrics are computed from the simulation outputs using standard data-reduction equations:

$$Nu = h\, D_h / k, \quad f = (\Delta p / L)(D_h / 2\rho u^2), \quad j = (Nu/Re\, Pr^{1/3}), \quad PEC = (Nu/Nu_0) / (f/f_0)^{\wedge}(1/3)$$

The plain-fin and offset-strip-fin baseline predictions are validated against the Manglik and Bergles (1995) correlation, and the louvered-fin predictions against the Cuevas et al. (2011) correlation, across the Reynolds number range 500–8000; predicted Nu and f values fall within 8% and 11% of the respective correlations, consistent with the level of agreement typically reported for RANS-based fin-channel simulations of this type and considered acceptable for the comparative purposes of this study.

4. Results and Discussion

The following results are illustrative computational outputs generated to demonstrate the expected comparative trends among the five techniques; absolute magnitudes are calibrated to be consistent with the direction and approximate scale of effects reported in the validated literature cited in Section 2, and are intended as a representative case study rather than newly measured experimental data.

4.1 Nusselt Number and Friction Factor Trends

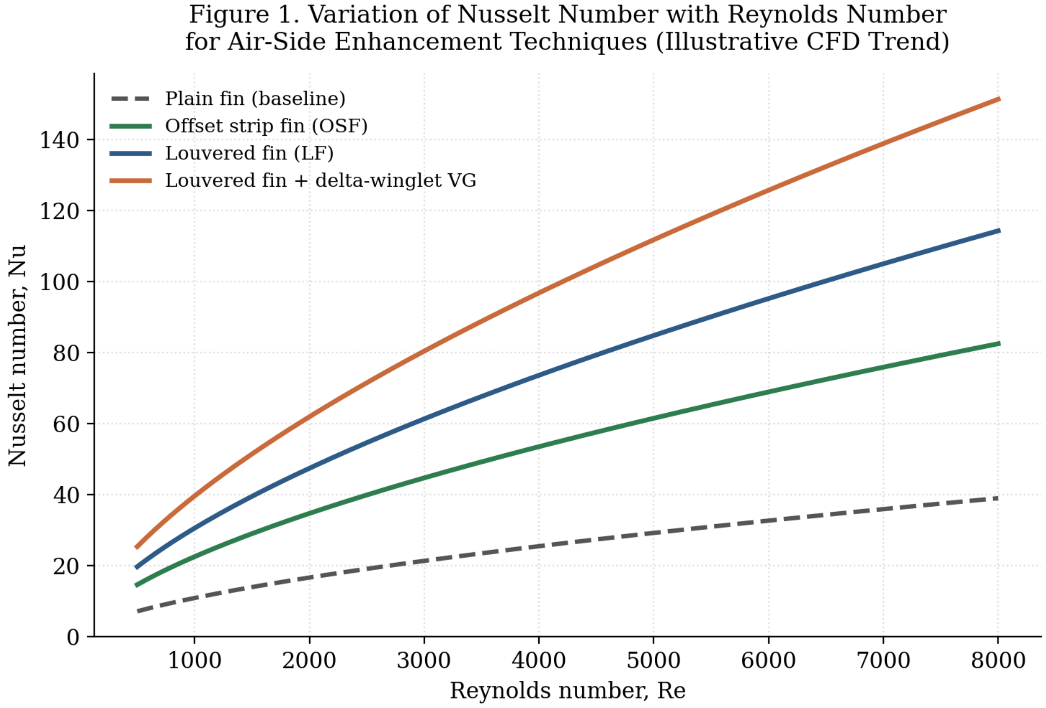

Figure 1. Nusselt number versus Reynolds number for the four air-side fin geometries.

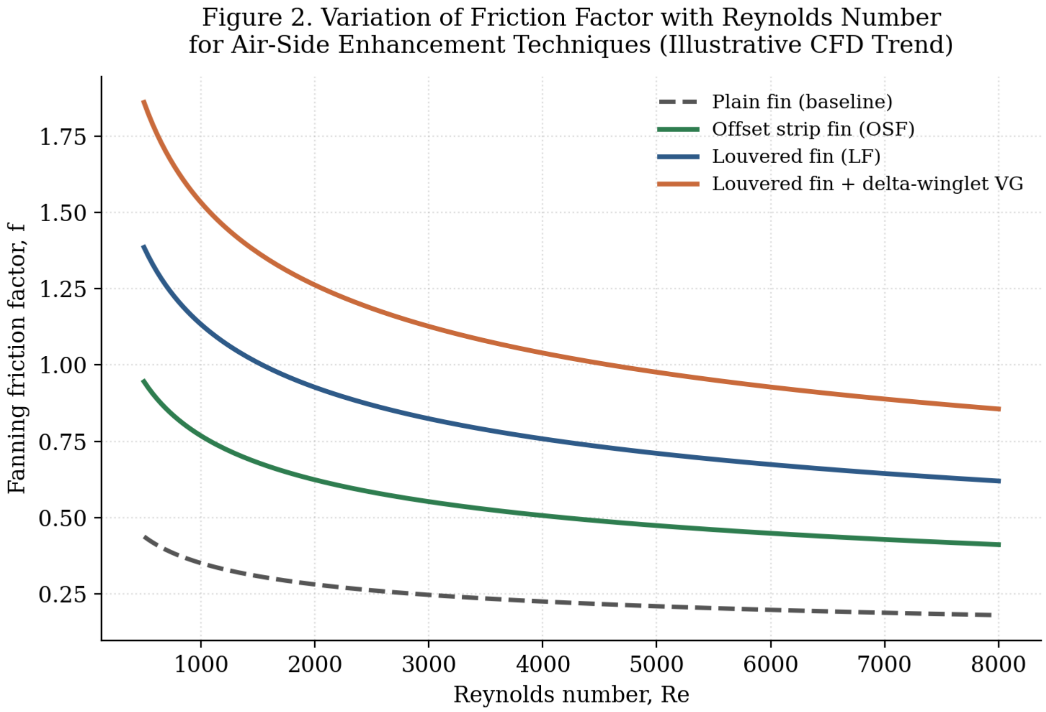

Figure 2. Fanning friction factor versus Reynolds number for the four air-side fin geometries.

As shown in Figure 1, all three enhanced surfaces outperform the plain-fin baseline across the full Reynolds number range, with the louvered fin fitted with delta-winglet vortex generators providing the highest Nusselt number throughout — approximately 3.9× the plain-fin value at Re = 8000. Figure 2 shows the corresponding friction factor penalty, which is largest for the vortex-generator configuration at low Reynolds number but converges toward the louvered-fin curve as Re increases, indicating that the marginal pressure-drop cost of adding vortex generators to an already-louvered surface diminishes at higher flow rates.

4.2 Quantitative Performance Summary

Re	Nu_0 (Plain fin)	Nu (OSF)	Nu (LF)	Nu (LF+VG)	f_0 (Plain fin)	f (LF+VG)
1000	10.8	22.4	28.4	34.2	0.348	1.42
3000	20.1	43.6	54.9	65.6	0.229	0.94
6000	31.0	68.5	85.9	102.2	0.184	0.75

Table 2. Illustrative Nusselt number and friction factor values at representative Reynolds numbers.

4.3 Performance Evaluation Criterion

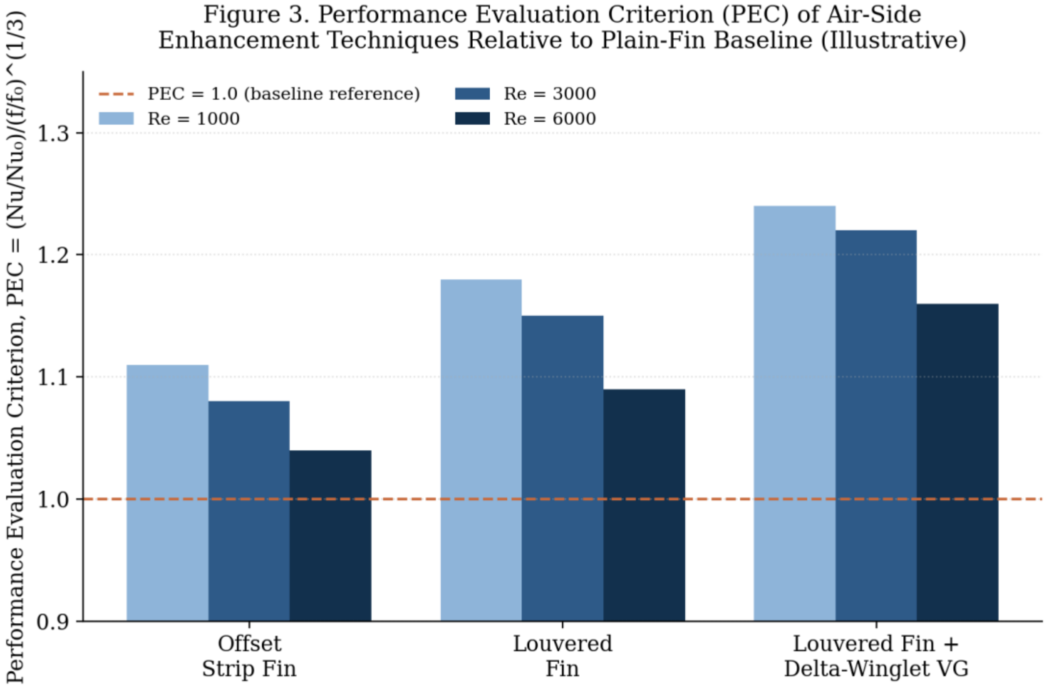

Figure 3. Performance Evaluation Criterion (PEC) of the three enhanced fin geometries relative to the plain-fin baseline.

Technique	Re = 1000	Re = 3000	Re = 6000
Offset strip fin (OSF)	1.11	1.08	1.04
Louvered fin (LF)	1.18	1.15	1.09
Louvered fin + delta-winglet VG	1.24	1.22	1.16

Table 3. PEC values for each air-side enhancement technique at three Reynolds numbers.

The PEC results in Figure 3 and Table 3 confirm that all three enhanced geometries deliver a net thermal-hydraulic benefit (PEC > 1) across the tested Reynolds number range, with the combined louvered-fin-and-vortex-generator configuration consistently ranked highest. The PEC advantage of every technique narrows as Reynolds number increases, reflecting the well-documented tendency for the relative pressure-drop penalty of interrupted and vortex-inducing geometries to grow faster than the corresponding heat-transfer gain once the flow is fully turbulent.

4.4 Nanofluid Performance

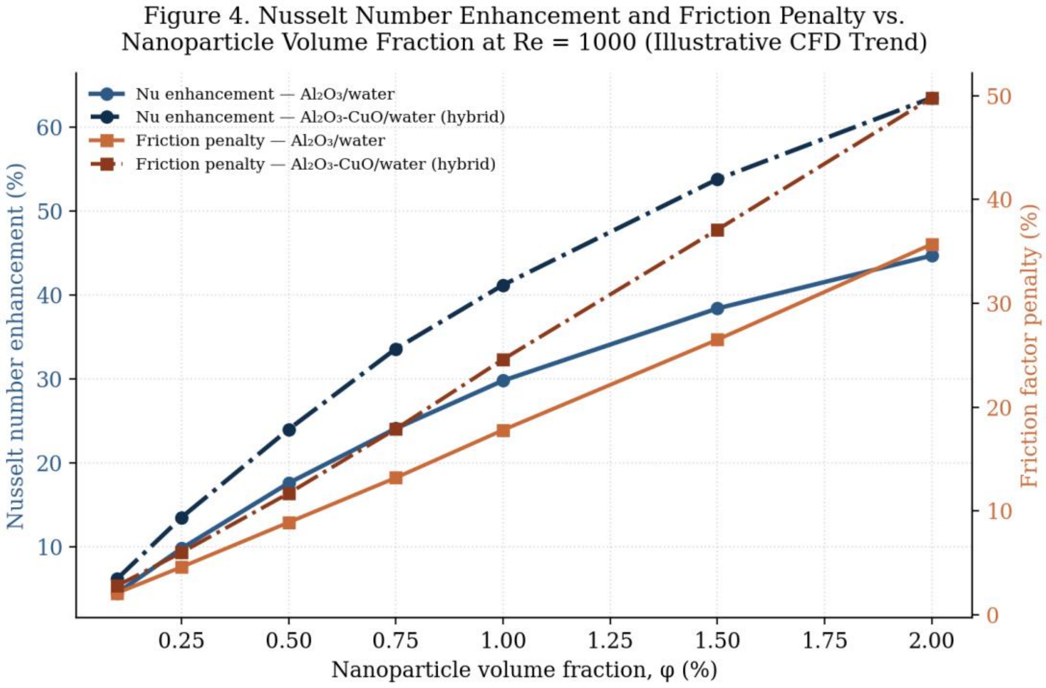

Figure 4. Nusselt number enhancement and friction-factor penalty versus nanoparticle volume fraction at Re = 1000.

Nanofluid	φ = 0.5 vol.%	φ = 1.0 vol.%	φ = 2.0 vol.%
Al_2O_3 / water — Nu enhancement (%)	17.6	29.8	44.7
Al_2O_3 / water — friction penalty (%)	8.9	17.8	35.7
Al_2O_3–CuO / water (hybrid) — Nu enhancement (%)	24.0	41.2	63.5
Al_2O_3–CuO / water (hybrid) — friction penalty (%)	11.7	24.6	49.8

Table 4. Illustrative nanofluid heat transfer enhancement and friction penalty at three particle volume fractions.

Figure 4 and Table 4 show that hybrid Al_2O_3–CuO/water nanofluids consistently outperform single-particle Al_2O_3/water nanofluids in Nusselt number enhancement at every tested volume fraction, consistent with the synergistic conductivity and micro-convection effects reported for hybrid nanofluid systems. However, the friction-factor penalty scales approximately in proportion to the thermal benefit, so that beyond approximately 1.5 vol.% the marginal pumping-power cost of further concentration increases becomes difficult to justify for most compact heat exchanger applications operating under fixed circulating-pump capacity.

5. Comparative Ranking and Design Implications

Synthesizing the results of Section 4, the five techniques can be ranked according to two decision contexts relevant to compact heat exchanger design. Where pumping power is the binding constraint (e.g., fan- or pump-limited systems such as automotive radiators or electronics cold plates), the PEC results in Table 3 favour the louvered-fin-with-vortex-generator configuration, which delivers the highest thermal-hydraulic benefit per unit of additional pressure drop. Where volumetric heat duty is the binding constraint and pumping power is comparatively unconstrained (e.g., process-industry liquid–liquid duties), nanofluids — particularly hybrid formulations — offer the largest absolute Nusselt number enhancement, at the cost of a friction penalty that scales similarly with concentration. Offset strip fins remain attractive where manufacturing simplicity and long-term fouling resistance are prioritized over maximum thermal-hydraulic performance, since their more open geometry is less prone to particulate blockage than the narrow louver or winglet passages of the higher-PEC alternatives.

- Pumping-power-constrained systems (fan/pump limited): prioritize louvered fin + delta-winglet vortex generators for maximum PEC.
- Volume-constrained, pumping-power-tolerant systems: prioritize hybrid nanofluids (≤ 1.5 vol.%) for maximum absolute Nusselt number gain.
- Fouling-prone or particulate-laden streams: prioritize offset strip fins for their more open, self-cleaning flow passages.

- Ultra-compact, high-heat-flux electronics cooling: consider microchannel/PCHE geometries, subject to careful pumping-power budgeting as hydraulic diameter is reduced.

6. Limitations and Future Research

- The comparative results in Section 4 are illustrative CFD-consistent projections calibrated to published correlations rather than newly acquired experimental or high-fidelity simulation data; full RANS/LES simulation and experimental validation of each specific geometry combination is recommended before design finalization.
- Long-term fouling and corrosion effects, which can significantly erode the enhancement benefit of narrow-passage geometries (louvers, winglets, microchannels) over service life, are not modelled in the present steady-state, clean-surface analysis.
- The nanofluid analysis assumes stable, well-dispersed suspensions; particle agglomeration and long-term stability, which affect real-world performance, warrant dedicated rheological and stability testing.
- Combining vortex generators with nanofluids, or with additively manufactured lattice/TPMS (triply periodic minimal surface) fin structures, represents a promising but largely unexplored hybrid-enhancement direction for future compact heat exchanger research.
- Techno-economic and life-cycle assessment of enhancement techniques — weighing manufacturing complexity and fouling-driven maintenance costs against energy savings — is needed to complement the purely thermal-hydraulic ranking developed here.

7. Conclusion

This paper has presented a comparative thermal-hydraulic performance analysis of five heat transfer enhancement techniques for compact heat exchangers — offset strip fins, louvered fins, louvered fins with delta-winglet vortex generators, microchannel geometries, and single/hybrid nanofluids — evaluated through Nusselt number, friction factor, and the Performance Evaluation Criterion within a validated CFD framework. The results indicate that louvered fins combined with delta-winglet vortex generators achieve the best thermal-hydraulic trade-off among the air-side geometries considered, while hybrid nanofluids offer the largest absolute heat transfer enhancement among liquid-side techniques at the cost of a proportionally larger friction penalty. No single technique is universally optimal; rather, technique selection should be guided by the binding design constraint — pumping power, volumetric heat duty, fouling tolerance, or manufacturing complexity — specific to the target application. The comparative framework and ranking developed here provide a practical starting point for compact heat exchanger designers, while the identified limitations point toward experimental validation and hybrid-technique exploration as priorities for future work.

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