

Review

Passive Techniques for Heat Transfer Enhancement in Selected Industrial Heat Exchangers: A Comprehensive Review of Geometric Modifications and Nanofluids

Mohammad Arqam ¹, Shahid Husain ², Sameer Usmani ³  and Stefano Landini ^{1,*} 

¹ School of Engineering, Mathematics and Physics, University of East Anglia, Norwich Research Park, Norwich NR4 7TJ, Norfolk, UK; mohammad.arqam@uea.ac.uk

² Department of Mathematics and Statistics, University of Limerick, V94 T9PX Limerick, Ireland; shahid.husain@ul.ie

³ School of Engineering, The Australian National University, Acton, ACT 2601, Australia; sameer.usmani@anu.edu.au

* Correspondence: s.landini@uea.ac.uk

Abstract

Passive heat transfer enhancement remains the most economical route to compact, energy-efficient heat exchangers because it requires no external power and can be retrofitted into existing hardware. This paper reviews passive enhancement techniques applied to five widely used heat exchanger configurations: plate heat exchangers (PHEs), corrugated-plate heat exchangers, double-pipe heat exchangers, printed-circuit heat exchangers (PCHEs) and flat-plate heat exchangers. This comprehensive review draws on 210 references from the peer-reviewed literature, published mainly over the past two decades, with respect to geometric modifications (twisted tapes, wire coils, corrugations, embossing and shaped fins), nanofluid working media and their combined use. The evidence is synthesised through the thermal performance factor (TPF) so that heat transfer gains are always weighed against the accompanying pressure penalty. Across the collected data, twisted-tape inserts raise the Nusselt number by 20–120% in turbulent flow, with friction factor increases of 30–200% and TPF values typically between 1.0 and 1.5; compound and nanofluid-assisted tapes push the TPF above 2, and in the laminar regime it can reach 4–5, while wire coils outperform twisted tapes in turbulent flow. Nanofluids improve thermal conductivity by 1–52% at volume fractions up to about 8%, but viscosity penalties of 3–210% and long-term stability continue to limit commercial uptake. Corrugated surfaces yield Nusselt-number gains of 10–61% through secondary flow and boundary-layer disruption, while in PCHEs the transition from zigzag to S-shaped and aerofoil fins reduces the pressure drop by up to a factor of 20 at comparable thermal duty. A cross-cutting comparison identifies the best-performing technique for each configuration and exposes four persistent gaps: the scarcity of like-for-like comparisons across heat exchanger types, the limited evidence on long-term nanofluid stability and cost, the under-representation of PCHE and flat-plate passive studies, and the early stage of data-driven optimisation of enhancement geometries. The review provides a consolidated, quantitative basis for selecting enhancement strategies and for directing future work.



Received: 28 August 2026

Revised: 13 October 2026

Accepted: 26 October 2026

Published: 28 October 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article

distributed under the terms and

conditions of the [Creative Commons](#)

[Attribution \(CC BY\)](#) license.

Keywords: heat transfer enhancement; passive techniques; plate heat exchanger; nanofluids; twisted tape; thermal performance factor

1. Introduction

1.1. Background and Motivation

Heat exchangers transfer thermal energy between two or more fluids at different temperatures and are indispensable to power generation, nuclear reactors, chemical processing, refrigeration, air conditioning, waste-heat recovery and domestic heating [1]. Because these devices set the size, cost and efficiency of the systems that contain them, decades of research have been devoted to making them smaller, lighter and more effective while reducing material use and pumping cost [2–5]. Two broad routes are available. The heat transfer surface can be enlarged, or the flow can be made more turbulent so that the thermal boundary layer is disrupted and near-wall mixing is intensified. Both routes lower the thermal resistance, yet both usually raise the pressure drop, so any credible assessment of an enhancement technique has to weigh the thermal gain against the hydraulic penalty rather than reporting the two in isolation.

Enhancement methods are conventionally divided into active and passive techniques [6]. Active techniques rely on external power, for example surface or fluid vibration, electrostatic fields, suction, injection and jet impingement, and although they can be effective, they add complexity, moving parts and a parasitic energy demand that is difficult to justify at scale [7,8]. Passive techniques require no external power. They enhance heat transfer through geometry and working-fluid modifications such as wire coils, twisted tapes, ribs, baffles, corrugated or embossed surfaces, shaped fins and the dispersion of nanoparticles in the base fluid [9,10]. Their simplicity, low cost and ease of retrofit make them the dominant choice in industry and the focus of the present review.

1.2. Passive Enhancement Mechanisms

The geometrical characteristics of an insert, including its width, length, twist ratio and orientation, govern the balance between heat transfer and flow resistance [11]. Twisted tapes are among the most widely studied inserts because the swirl they generate improves mixing in both laminar and turbulent regimes, and their effect can be reinforced by combining them with wire coils [12,13]. For fluids with high Prandtl number, surface-roughness techniques can outperform swirl devices because they act directly on the thin thermal boundary layer near the wall [14]. Corrugated and artificially roughened surfaces destabilise that boundary layer and set up secondary flows, which raises the convective coefficient at a moderate frictional cost [15]. Swirl-flow devices have consequently moved from the laboratory into commercial practice [16]. A complementary passive route is to modify the working fluid itself: suspending metallic or metal-oxide nanoparticles in water or ethylene glycol raises the effective thermal conductivity of the coolant, although it also increases viscosity and pumping power [17].

Beyond inserts, surface modification and nanofluids, two further passive families are now firmly established and are included in the present review. The first is the use of structured and porous media, principally open-cell metal foams but also packed beds and lattice structures, which enlarge the wetted surface area and promote tortuous, well-mixed flow at the expense of an added pressure penalty. The second is the use of phase-change materials in latent-heat storage exchangers, in which the limiting low thermal conductivity of the storage medium is overcome passively by fins, metal foams, extended surfaces, encapsulation or dispersed nanoparticles. Together with geometric inserts, surface corrugation and nanofluids, these define the taxonomy of passive techniques surveyed in this work.

1.3. Performance Evaluation and the Thermal Performance Factor

In thermal design, two analytical frameworks are standard: the log-mean temperature difference (LMTD) method, applied when the terminal temperatures are known, and the effectiveness–number of transfer units (ϵ -NTU) method, preferred when the outlet temperatures are unknown. Both quantify the heat duty and provide the basis for comparing configurations, but neither on its own captures the trade-off that defines a good enhancement technique. For that purpose, the thermal performance factor (TPF), also called the performance evaluation criterion (PEC), is used. It compares the relative gain in heat transfer with the relative rise in friction at constant pumping power and is defined as

$$\text{TPF} = \frac{Nu/Nu_0}{(f/f_0)^{1/3}} \quad (1)$$

where Nu and f are the Nusselt number and Darcy friction factor of the enhanced surface and Nu_0 and f_0 are the corresponding values for the plain reference surface. The exponent $1/3$ enforces the constant-pumping-power condition. A value $\text{TPF} > 1$ indicates that the technique delivers a net thermo-hydraulic benefit, and throughout this review the reported gains are interpreted in this light so that heat transfer improvements are never divorced from their pressure penalty.

1.4. Scope, Novelty and Contributions

Several reviews have addressed individual enhancement techniques or single heat exchanger families, for example twisted tapes [18], passive augmentation in pipe exchangers [9], enhancement in plate heat exchangers [19] and printed-circuit heat exchangers [20,21]. What remains scarce is a consolidated, quantitative treatment that places the same passive techniques side by side across structurally different heat exchangers and interprets them through a common performance metric. The present work addresses that gap. Its contributions are fourfold. First, it assembles quantitative enhancement and penalty data for five heat exchanger configurations from a structured literature search and reports them on a consistent basis. Second, it draws the evidence together in a cross-cutting comparison that identifies the most suitable technique for each configuration. Third, it fills the coverage gap in printed-circuit heat exchangers by reviewing channel-geometry and working-fluid enhancement in that family. Fourth, it distils the open problems into specific, testable research directions. Consistent with this focus, and because the surveyed body of work is overwhelmingly concerned with passive methods, active techniques are introduced only as background and are not reviewed in detail.

1.5. Organisation of the Paper

The remainder of the paper is organised as follows. Section 2 describes the review methodology, including the search protocol, the databases and keywords, and the inclusion and exclusion criteria. Section 3 reviews passive enhancement technique by technique for plate, corrugated-plate, double-pipe, printed-circuit and flat-plate heat exchangers. Section 4 presents the cross-cutting synthesis and the comparative assessment across configurations. Section 5 discusses advancements and future perspectives. Section 6 consolidates the reviewed evidence into a single reference table, and Section 7 states the conclusions and the limitations of the study.

2. Review Methodology

This work is a comprehensive, critical review of passive heat transfer enhancement in selected industrial heat exchangers. The scope was fixed at the outset to five configurations that recur across process, energy and thermal-management duty, namely plate,

corrugated-plate, double-pipe, printed-circuit and flat-plate heat exchangers. These were chosen because they span the compact-to-conventional range, because each admits a distinct family of passive modification (surface corrugation and chevron patterning, in-tube inserts, structured and porous channel media, and nanofluid or phase-change working media), and because together they account for the large majority of the quantitative enhancement literature in common industrial service.

To assemble the evidence base on a transparent and reproducible footing, the literature was identified by structured searches of the Scopus database, supplemented by the peer-reviewed engineering literature of the major publishers (Elsevier, Springer, Wiley, Taylor & Francis and MDPI). Four thematic queries were run against titles, abstracts and keywords, each combining a target configuration or enhancement medium with a thermal-hydraulic performance descriptor and restricted to journal articles. The first paired nanofluid working media with plate, corrugated-plate and chevron geometries and the descriptors Nusselt number, heat transfer coefficient, friction factor and thermal performance (nanofluid* AND ("plate heat exchanger" OR "corrugated plate" OR chevron) AND (Nusselt OR "heat transfer coefficient" OR "friction factor" OR "thermal performance")). The second isolated twisted-tape inserts and the twist-ratio parameter against the same descriptors ("twisted tape" AND "twist ratio" AND (Nusselt OR "friction factor" OR "thermal performance factor")). The third addressed porous and metal-foam media in heat exchangers (("metal foam" OR "porous media" OR "porous medium") AND "heat exchanger" AND (Nusselt OR "heat transfer enhancement" OR "pressure drop")), and the fourth covered phase-change-material units enhanced by fins, foams, nanoparticles or extended surfaces ("phase change material" AND "heat exchanger" AND ("heat transfer enhancement" OR fin OR "metal foam" OR nanoparticle OR "extended surface" OR corrugat*)). The searches were limited to the document type article; the nanofluid and phase-change queries were additionally bounded to the modern period (post-2004 and post-1999, respectively) to concentrate on the era in which quantitative enhancement data became routine, while seminal earlier studies were retained where they underpin the fundamentals of a technique.

The four queries returned 2040 records in total (164, 402, 779 and 695, respectively). After removal of 28 duplicates, matched on digital object identifier where present and otherwise on normalised title, 2012 unique records remained, spanning the late 1960s to the current publishing year. The temporal distribution of the wider field, obtained from a broader Scopus bibliometric query on passive enhancement in heat exchangers, is shown in Figure 1; it demonstrates the pronounced intensification of output after about 2007, driven successively by in-tube inserts, nanofluids and, more recently, porous-medium and phase-change studies.

2.1. Selection Criteria and Screening

The retrieved records were screened against explicit inclusion and exclusion criteria. A study was included when it (i) concerned one of the five target configurations or a passive enhancement medium applicable to them; (ii) employed a passive technique, that is, one requiring no external power input, such as surface corrugation, an in-tube insert, a structured or porous medium, an extended surface, or a nanofluid or phase-change working medium; and (iii) reported quantitative thermal or thermo-hydraulic results, such as Nusselt number, heat transfer coefficient, friction factor, pressure drop or thermal performance factor. Records were excluded when they addressed only active techniques (for example mechanical agitation, electrohydrodynamic or acoustic methods), reported no quantitative performance data, or fell outside the target configurations and media. Conference abstracts, editorials and non-English records were not considered, and duplicates were removed as described above. Title-and-abstract screening against these criteria was followed by full-text

appraisal of the studies carried forward for quantitative comparison; the review ultimately draws on 210 references, the majority reporting experimental or numerical performance data, together with a smaller number of foundational, textbook and review sources cited for context.

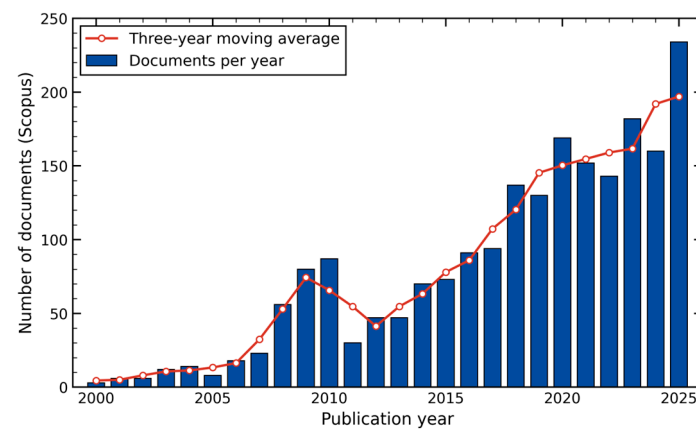


Figure 1. Annual number of documents on passive heat transfer enhancement in heat exchangers indexed in Scopus (2000–2025; 2072 documents), retrieved from the query TITLE-ABS-KEY(("heat transfer enhancement" OR "heat transfer augmentation") AND ("heat exchanger" OR "heat exchangers") AND (passive OR "twisted tape" OR "wire coil" OR corrugat* OR dimple* OR emboss* OR nanofluid* OR "metal foam" OR porous OR "phase change material")). Bars show documents per year; the solid line is a three-year moving average.

2.2. Classification Framework

The screened literature was classified along two axes. The first axis is the actual flow geometry in which enhancement occurs, so that a technique is discussed under the configuration whose flow field it modifies rather than under the exchanger in which it is nominally housed. Twisted tapes, wire coils and similar in-tube inserts, which act on the swirling flow inside a round tube or annular duct, are therefore treated under tubular and double-pipe exchangers, whereas corrugation, chevron patterning and plate-surface structuring are treated under plate and corrugated-plate exchangers. The second axis is the enhancement mechanism; for nanofluid working media the studies are further separated into mono (single-nanoparticle), hybrid (two-nanoparticle) and ternary (three-nanoparticle) suspensions, so that their incremental benefits and penalties can be compared on a consistent basis. It is noted at the outset that ternary suspensions, although emerging rapidly in tubular geometries, remain almost absent from the plate-exchanger literature, a gap identified by the present screening. Throughout, the thermal performance factor is applied with a single, consistent definition (Section 1.3), so that comparisons between configurations are made on a like-for-like basis at matched Reynolds number or pumping power.

3. Heat Transfer Enhancement by Heat Exchanger Type

This section reviews passive enhancement configuration by configuration, and the principal geometric modifications examined are illustrated schematically in Figure 2. For each family the operating principle is stated briefly, the geometric and nanofluid techniques are then examined, and the reported gains are interpreted through the thermal performance factor of Equation (1).

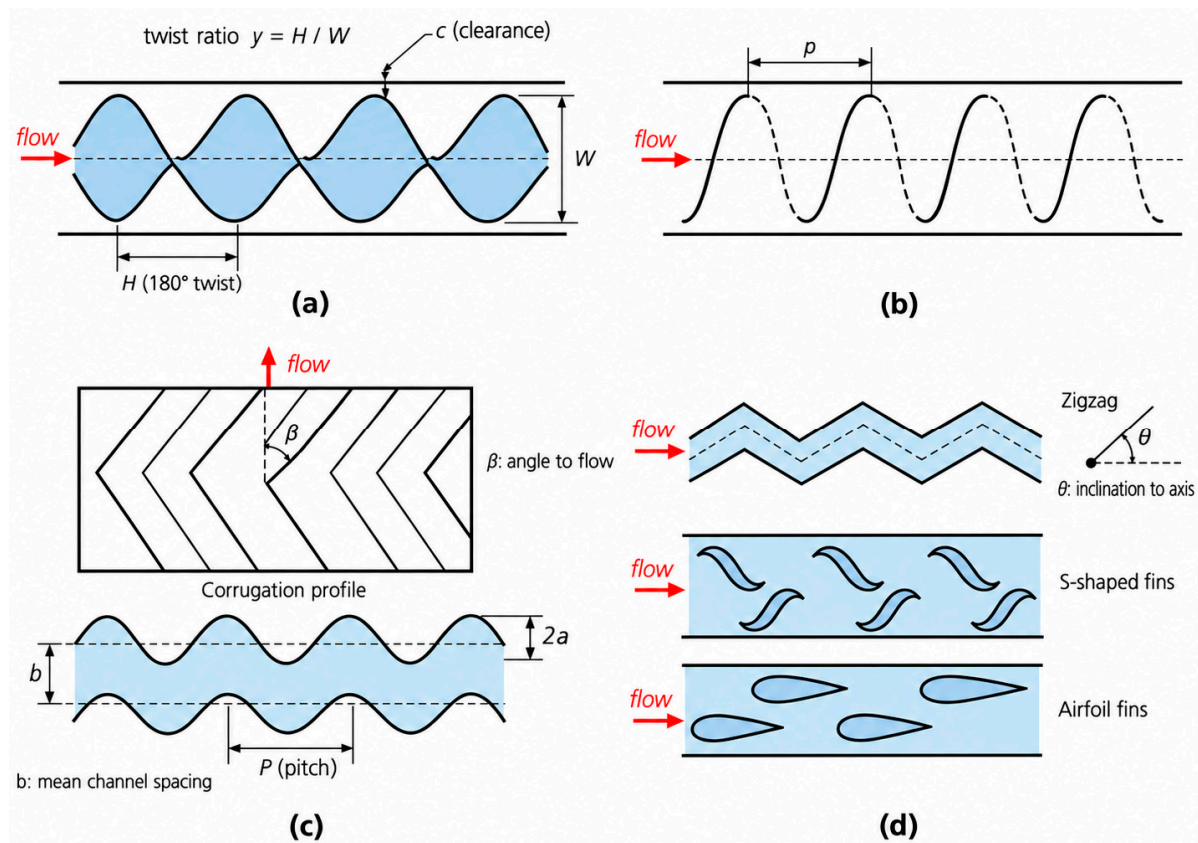


Figure 2. Schematic of the principal passive geometric modifications reviewed in this work: (a) twisted-tape insert, defined by the twist ratio $y = H/W$ (H is the axial length for a 180° twist and W the tape width) and the tube clearance c ; (b) wire-coil insert of coil pitch p ; (c) plate chevron corrugation (top view) set at a chevron angle β to the flow, with the corrugation profile showing the pitch P , the peak-to-valley amplitude $2a$ and the mean channel spacing b ; (d) printed-circuit channel geometries: zigzag (bend inclination θ to the axis), S-shaped fins and aerofoil fins.

3.1. Plate Heat Exchangers

A plate heat exchanger (PHE) is built from a stack of thin corrugated plates clamped in a frame, with gaskets that direct the hot and cold streams into alternate channels so the fluids exchange heat across the plate without mixing [22,23]. The corrugations force the flow to change direction repeatedly, which promotes turbulence at a low Reynolds number and produces a high heat transfer coefficient in a compact volume. In the corrugated construction the chevron patterns of adjacent plates cross to form a dense network of contact points that repeatedly split and recombine the streams, which further intensifies mixing [24]. These features, together with easy maintenance and a small footprint, explain why PHEs are preferred in heating, ventilation, air conditioning, refrigeration and two-phase process duties [25,26].

Enhancement in PHEs operates through two coupled mechanisms that both raise the pressure drop. The first is repeated flow separation and reattachment, which disrupts and renews the boundary layer; the second is the increase in wall shear associated with surface roughness, which intensifies near-wall convection [27]. Because the final performance depends strongly on the initial choice of plate pattern, and because much of the published data emphasise the heat transfer coefficient rather than the accompanying hydraulic cost, a consistent thermo-hydraulic comparison is essential. The two dominant passive routes for PHEs are surface or insert modifications and nanofluid working media, which are treated in turn.

3.1.1. Passive Surface and Insert Techniques

Passive inserts and shaped surfaces increase turbulence and extend the residence time of the fluid near the wall, which lowers entropy generation for a well-designed geometry [10,28]. Sparrow and Hossfeld [29] showed that rounding the protruding edges of a corrugated passage reduces heat transfer more at low Reynolds number ($2000 \leq Re \leq 10,000$) than at high Reynolds number ($Re \geq 30,000$), while Fabbri [30] found that wavy-wall channels are most beneficial at high Reynolds and Prandtl numbers. Durmus et al. [27] confirmed that increasing the interaction area, the mass flow rate and the corrugation severity all raise the heat transfer efficiency at the expense of pressure drop.

Twisted tapes and wire coils are in-tube inserts: they act on the swirling flow inside a round tube or annular duct and cannot be fitted into the corrugated inter-plate channels of a conventional gasketed plate exchanger. They are reviewed here as the dominant insert family for tubular passages, and their quantitative performance (Tables 1 and 2 and Figures 2 and 3) should be read in that tubular context and together with the double-pipe results of Section 3.3. Enhancement within plate exchangers proper is achieved instead by the plate corrugation and chevron geometry described above and in Section 3.2.

Among inserts, twisted tapes and wire coils dominate the literature. Table 1 lists the principal twisted-tape geometries that have been investigated, and Table 2 summarises representative quantitative studies. Twisted tapes are particularly effective in laminar and transitional flow, where the induced swirl greatly improves mixing, whereas wire coils become more effective in fully turbulent flow because they act on the near-wall region and intensify shear [31]. Saleh and Sundar [32] likewise reported that, in turbulent flow, the wire-coil technique offers a better thermo-hydraulic balance than twisted tapes. A consistent picture therefore emerges: for a compact PHE, wire coils suit turbulent duties while twisted tapes suit laminar and transitional duties.

Table 1. Representative twisted-tape geometries investigated for passive enhancement, with a representative reported performance for each. The full quantitative Nu, f and TPF results with their flow conditions are compiled in Table 2.

Design	Description	Reported Performance (Nu/f/TPF)	Reference
Conventional twisted tape	Uniform tape twisted at a fixed twist ratio	Baseline insert; see Table 2	[33]
Left–right (directional) tape	Alternating twist direction to periodically reverse the swirl	Bidirectional swirl raises Nu and f above a helical tape; see Table 2	[34]
Trapezoidal-cut tape	Trapezoidal cuts along the edges to shed additional vortices	See Table 2	[18]
Variable-width tape	Width varied along the length to tune local swirl	See Table 2	[35]
Multiple/grouped tapes	Several short tapes in series to renew the boundary layer	Nu +10–170% vs. smooth channel	[12]
V-cut tape	V-shaped notches to promote secondary flow	Nu and f rise with lower twist ratio and higher depth ratio; see Table 2	[13]
Centre-wing/ alternate-axis tape	Wings and axis offsets to strengthen mixing	TPF up to 1.4; Nu +18–62% over plain tapes	[36]
Helical screw-tape	Continuous helical element for strong swirl in short tubes	See Table 2	[37]

Table 2. Representative experimental and numerical studies of the twisted-tape technique, expanded to include the twist ratio, clearance ratio and working fluid. Nu/Nu_0 and f/f_0 are the maximum reported ratios relative to a plain tube; “NR” denotes a quantity not stated in the source. TPF is the thermal performance factor, reported where given and otherwise computed as $(Nu/Nu_0)/(f/f_0)^{1/3}$.

Study	Working Fluid	Twist Ratio	Clearance	Re Range	Nu/Nu_0	f/f_0	TPF
Wang et al. (2026) [38]	Solar HTF	2, 3, 4	1.5 mm (gap)	1000–10,000	2.66	6.02	1.55
Hosseinalipour et al. (2020) [39]	n/s	2.5–10	0–0.5	1×10^4 – 9.79×10^5	1.7	4.1	1.1
Eiamsa-ard et al. (2009) [40]	Air	2.5, 5.0	0.0–0.3	3000–10,000	NR	NR	NR
Keklikcioglu et al. (2022) [41]	Water	2, 2.5, 3, 3.5	0.0178–0.0718	5000–25,000	NR	NR	1.52
Dalkılıç et al. (2020) [42]	Water	4.48	NR	4250–11,000	NR	NR	0.90
Sontakke et al. (2023) [43]	n/s	2.5, 3.5, 5, 10	NR	7500–30,000	1.72	2.19	1.32
H.M. & Hegde (2022) [44]	Water + Al_2O_3	20, 13.3, 9.8	NR	500–5000	1.29	NR	1.33
Dhumal & Havaladar (2023) [45]	Water	6.77, 4.51, 3.38	NR	(Both sides)	3.15	8.7	3.06
Eiamsa-ard & Wongcharee (2018) [46]	Water + nanofluid	$3.0 > 2.8 > 2.6$ (non-uniform)	NR	n/s	NR	NR	1.46
Eiamsa-ard et al. (2010) [36]	Water	3.0	NR	5200–22,000	NR	NR	1.4
Murthy & Hegde (2020) [47]	Water + GO	20, 13.3, 9.8	NR	500–5000	NR	NR	1.23
Eiamsa-ard et al. (delta-winglet) (2010) [48]	Water	3, 4, 5	NR	3000–27,000	NR	NR	1.24
Bizuneh et al. (2025) [49]	Water + nanofluid	3	NR	4000–20,000	NR	NR	1.42
Kumar & Sarviya (2024) [50]	n/s	3, 4, 5	NR	4000–16,000	NR	NR	1.71
Harish & Manjunath (2022) [51]	n/s	3	NR	n/s	NR	NR	1.5
Salman et al. (2015) [52]	SiO_2 and TiO_2 /water	2.93	NR	Laminar	NR	NR	5.13
Singh et al. (2025) [53]	Water	3–6	NR	10,000–22,000	2.23	NR	1.18
Suseel Jai Krishnan & Nagarajan (2019) [54]	Antifreeze + water + MgO	6, 8, 10	NR	n/s	NR	NR	1.98
Ashnaaf Abajja et al. (2025) [55]	n/s	2.0–4.0	NR	500–2300	1.85	NR	4.68
Patel (2023) [56]	GNP/water	3, 4, 5	NR	6700–33,200	NR	NR	2.03
Hazbehian et al. (2016) [57]	TiO_2 /PVA	2–5	NR	800–30,000	2.3	1.95	1.84
Ponnada et al. (2019) [58]	Water	3, 4, 5	NR	3000–16,000	1.48	1.19	1.4
Rezaei Miandoab et al. (2022) [59]	Nanofluid	2.34 (best)	NR	Up to ~Re	NR	NR	NR
Kumar & Afzal (2025) [60]	n/s	3.0	NR	n/s	NR	NR	1.31

Table 2. Cont.

Study	Working Fluid	Twist Ratio	Clearance	Re Range	Nu/Nu ₀	f/f ₀	TPF
Wongcharee & Eiamsa-ard (2011) [61]	Water	3, 4, 5	NR	830–1990	NR	NR	5.25
Yadav et al. (2023) [62]	Fe ₃ O ₄ nanofluid	3.7	NR	900–1800	NR	NR	2.56
Reddy et al. (2025) [63]	CeO ₂ /water	3	NR	2436–11,626	2.28	NR	NR
Rajan et al. (2026) [64]	Water	3, 4, 5, 6	NR	100–1500	1.53	1.86	1.25

Figure 3 collects the twisted-tape studies of Table 2 on a single heat-transfer-versus-friction map, with contours of constant TPF from Equation (1) superimposed. Almost all configurations lie above the TPF = 1 line, confirming a net thermo-hydraulic benefit, but the most favourable cases are those that combine a large Nusselt gain with a moderate friction rise rather than those that maximise heat transfer alone. This representation makes the design trade-off explicit and provides a rational basis for selecting a tape geometry: leading-edge and short-length tapes, which sit closest to the high-TPF contours, are preferable when pumping power is constrained.

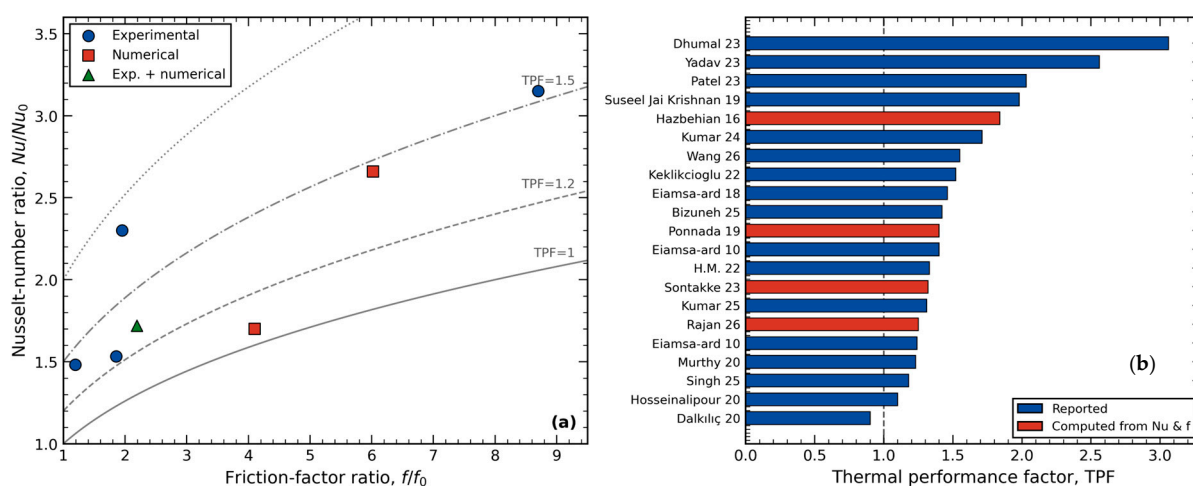


Figure 3. Thermo-hydraulic performance map for twisted-tape inserts compiled from the studies in Table 2: (a) Nusselt-number ratio versus friction-factor ratio relative to a plain tube, with contours of constant thermal performance factor; and (b) thermal performance factor by study, distinguishing values reported in the source from those computed from the reported Nu and f. Points in (a) are shown for the studies that report both ratios. For readability, three laminar-regime studies with off-scale thermal performance factors (Salman et al. [52], TPF $\approx$ 5.1; Wongcharee & Eiamsa-ard [61], TPF $\approx$ 5.3; Ashnaaf Abajja et al. [55], TPF $\approx$ 4.7) are omitted from panel (b).

3.1.2. Nanofluids

Early attempts to raise the thermal conductivity of the working fluid by dispersing micron-sized particles failed in practice because the particles caused clogging, erosion and severe pressure drops [65,66]. The move to nanometre-sized particles overcame most of these problems and produced measurable gains in PHE performance [32]. The behaviour of a nanofluid depends on the particle material, size and volume fraction, so these parameters must be selected for the intended duty [67]. The three properties that matter most for heat exchanger design are the specific heat, the viscosity and the thermal conductivity, and the collected data for each are summarised in Tables 3–5 and visualised in Figures 4–6.

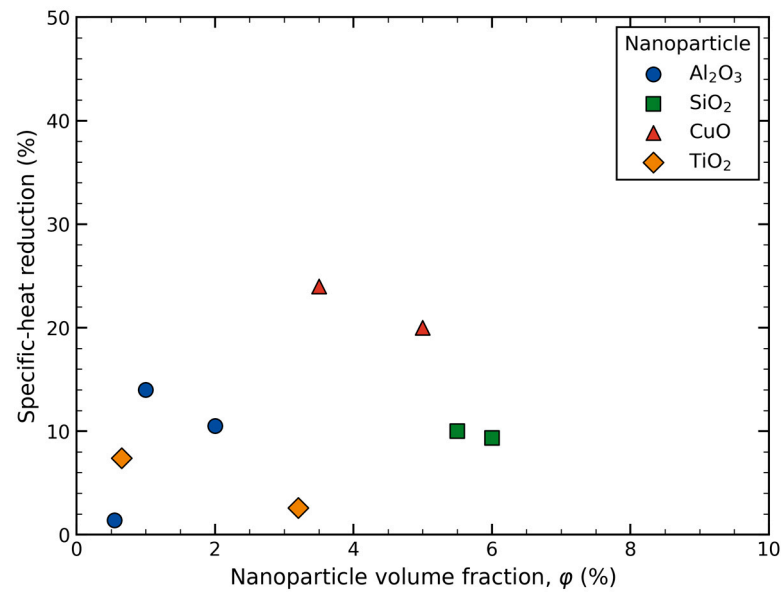


Figure 4. Specific-heat reduction of water-based nanofluids as a function of volume fraction, compiled from Table 3. For clarity, the axis is limited to $\phi \leq 10\%$; the single high-loading point of Zhou and Ni [68] (46% reduction at $\phi = 22\%$) lies off scale.

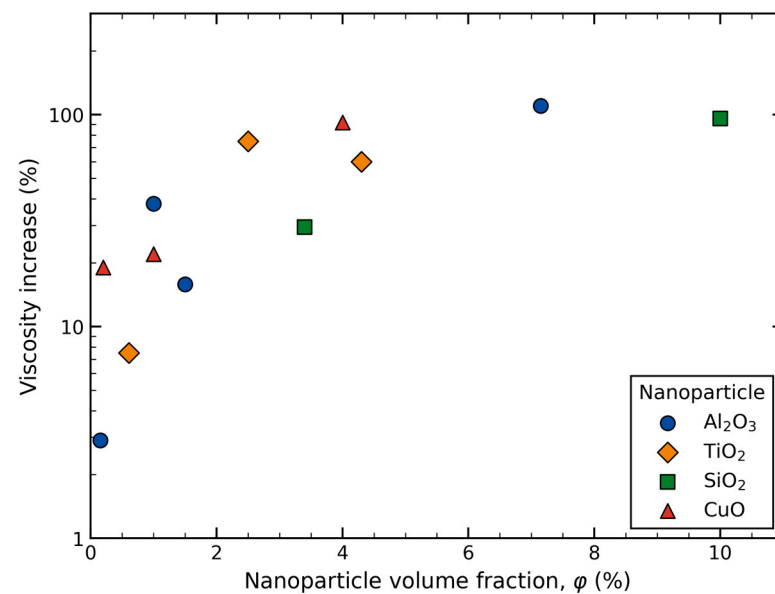


Figure 5. Viscosity increase of water-based nanofluids as a function of volume fraction, compiled from Table 4. Note the logarithmic ordinate.

The specific heat of a nanofluid falls as the volume fraction rises, because the solid particles store less heat per unit mass than the base fluid. Reported reductions range from about 1% to 46%, and the effect is strongest at high loadings, for example the 46% drop measured for alumina at a 22% volume fraction [68,69]. Kulkarni et al. [70] and Vajjha and Das [17] confirmed that the specific heat rises again as the concentration is reduced. As Figure 4 shows, volume fraction is the dominant variable while particle size plays a secondary role.

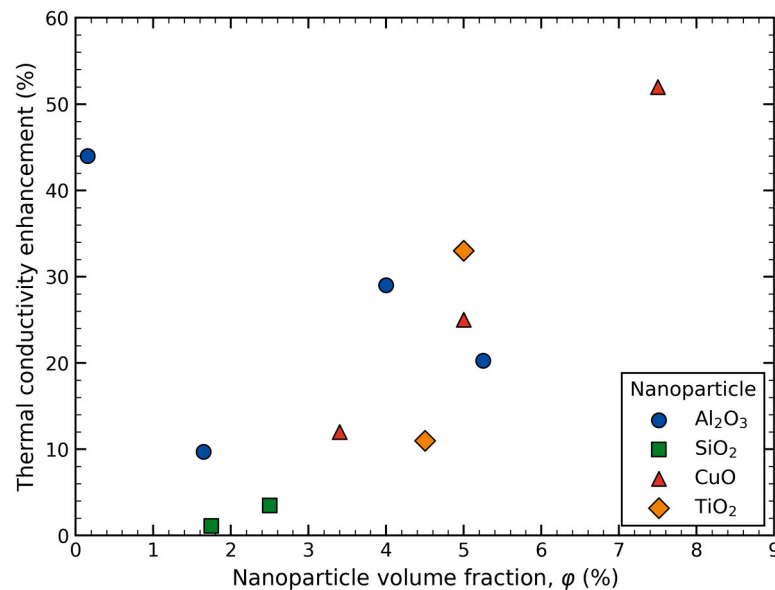


Figure 6. Thermal-conductivity enhancement of water-based nanofluids as a function of volume fraction, compiled from Table 5.

Viscosity, by contrast, increases with volume fraction, and the rise can be steep. Table 4 and Figure 5 show increases from roughly 3% at very low loadings to more than 200% at high concentrations [66,71]. Below about 1% the penalty is modest, typically under 20%, but above 3–5% the flow resistance grows sharply. Metal-oxide fluids such as CuO and Al₂O₃ generally show larger viscosity penalties than SiO₂-based fluids of comparable loading. This viscosity rise is the principal reason nanofluids incur a pumping-power penalty.

Thermal conductivity is the property that motivates the use of nanofluids in the first place. Table 5 and Figure 6 show enhancements from about 1% to 52%, again governed primarily by volume fraction and particle material. Metallic and metal-oxide particles such as CuO and Al₂O₃ outperform SiO₂ because of their higher intrinsic conductivity, and smaller particles contribute a secondary benefit through stronger Brownian motion and interfacial effects.

Heidary and Kermani [72] have reported that the friction penalty from adding nanoparticles in a sinusoidal-wall channel is small, and that the particles reshape the velocity and streamline fields. Khoshvaght-Aliabadi et al. [73] showed that combining copper-based nanoparticles (about 20 nm) with vortex generators in a plate-fin exchanger improves performance when the wing height, pitch and attack angle are tuned, with the Reynolds number strongly shaping the temperature field. Taken together, the data indicate that a higher volume fraction raises the heat transfer coefficient, but the benefit is bounded: several authors report that nanofluids lose their advantage at very high Reynolds number, where the base-fluid turbulence already dominates mixing [67,74–76]. The high cost of nanofluids and the pumping-power penalty from increased viscosity remain the two factors that most restrict commercial adoption [17].

3.2. Corrugated-Plate Heat Exchangers

Corrugating the heat transfer wall is one of the most cost-effective ways to improve a plate or tubular exchanger, because it raises the surface-area-to-volume ratio and sets up secondary flows without a large increase in manufacturing cost. A wide range of corrugation geometries has been studied experimentally and numerically, and the main findings are summarised below.

Table 3. Specific-heat variation of water-based nanofluids with particle type, size and volume fraction.

Particle	Size (nm)	ϕ (%)	Specific-Heat Variation (%)	Ref.
Al ₂ O ₃	45	0–4	3–18 (decrease)	[69]
Al ₂ O ₃	45	22	46 (decrease)	[68]
Al ₂ O ₃	13	1	14 (decrease)	[77]
Al ₂ O ₃	20–50	0.1–1.0	0.15–2.6 (decrease)	[78]
SiO ₂	20–30	1–10	4–14.7 (decrease)	[17,79]
SiO ₂	50	0.003–0.3	–15 to +2	[80]
CuO	29–30	1–8	20–24 (decrease)	[17,81]
TiO ₂	27	3.2	2.6 (decrease)	[82]
TiO ₂	20	0.17–1.13	2.3–12.5 (decrease)	[83]

Table 4. Viscosity augmentation of water-based nanofluids.

Particle	Size (nm)	ϕ (%)	Viscosity Increase (%)	Ref.
Al ₂ O ₃	35	0.01–12.2	2.9–210	[66,71]
Al ₂ O ₃	13	1.5	15.8	[84]
Al ₂ O ₃	20–40	1.0	38	[78]
TiO ₂	27	4.3	60	[85]
TiO ₂	95	0.02–1.2	4–11	[83]
TiO ₂	21	2–3	15–135	[86,87]
SiO ₂	35–190	1.2–5.6	15–44	[88]
SiO ₂	50	10	96	[79]
CuO	29	4	92	[66]
CuO	10	0.2	15–23	[89]

Table 5. Thermal-conductivity augmentation of water-based nanofluids.

Particle	Size (nm)	ϕ (%)	Conductivity Increase (%)	Ref.
Al ₂ O ₃	30	0.01–0.3	44	[71]
Al ₂ O ₃	30	5–5.5	16–24.5	[90]
Al ₂ O ₃	43	0.3–3	9.7	[91]
Al ₂ O ₃	47	4	29	[92]
SiO ₂	12	1.1–2.4	1.1	[85]
SiO ₂	17.5	2.5	3.5	[93]
CuO	23.5	3.4	12	[94]
CuO	29	4–6	14–51	[95,96]
CuO	100	7.5	52	[97]
TiO ₂	21	1–8	2–20	[98]
TiO ₂	15	5	33	[99]

The thermo-hydraulic behaviour of a corrugated channel is governed by four geometric parameters: the corrugation pitch, the corrugation height or amplitude, the chevron or inclination angle, and the channel size expressed through the hydraulic diameter (Figures 6 and 7). Reducing the pitch and increasing the amplitude both strengthen the secondary flows and raise the Nusselt number, but they raise the friction factor more steeply, so an intermediate pitch-to-amplitude ratio generally maximises the thermal performance factor [30,100]. The relative placement and phase of opposing corrugations is equally important: misaligned corrugations and a phase-shift angle near 180° give the highest Nusselt number and the best thermo-hydraulic performance, because the staggered arrangement intensifies eddy formation and boundary-layer renewal [100,101]. The chevron (inclination) angle sets the balance between the flow patterns in a plate channel, and steeper angles (typically 60° compared with 30°) raise both the heat transfer coefficient and the pressure

drop, with the heat transfer gain usually dominating at moderate Reynolds numbers. Decreasing the channel hydraulic diameter raises the heat transfer coefficient through the higher surface-area-to-volume ratio but increases the pumping power, so the channel size must be matched to the duty [102]. The common theme across these parameters is that every geometric change that augments heat transfer also augments friction, which is why corrugated-plate designs are best compared through the thermal performance factor rather than the Nusselt number alone.

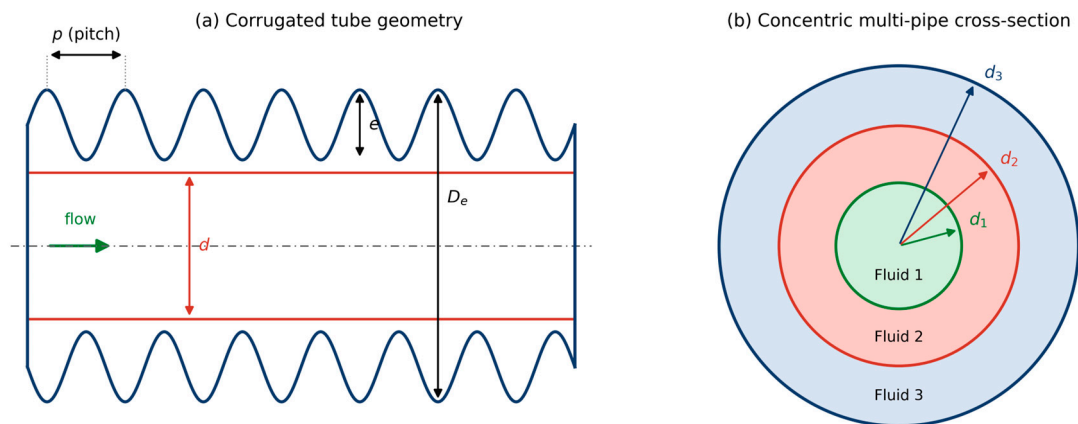


Figure 7. Schematic of (a) a corrugated tube showing the pitch p , envelope diameter D_e , corrugation height e and bore diameter d , and (b) the cross-section of a concentric multi-pipe (triple-tube) heat exchanger with tube diameters d_1 , d_2 and d_3 .

Gurel [103] developed a corrugated-plate exchanger with three plate geometries and thicknesses of 0.4, 0.6 and 0.8 mm, filled with the phase-change materials RT-35 and n-octadecane and using water as the heat transfer fluid at inlet temperatures of 12, 17 and 22 °C. A finite-volume model with an enthalpy–porosity treatment of the phase change showed that the best performance occurred at the lowest inlet temperature with a 0.6 mm steel plate and n-octadecane. Two-phase behaviour in corrugated channels differs fundamentally from that in smooth channels: Buscher [104] demonstrated that the swirling motion generates centrifugal forces strong enough to suppress the slug-flow transitions seen in plain channels and proposed a modified Froude number to characterise the flow.

The relative placement of corrugations strongly affects performance. Cao et al. [100] studied a helical tube-in-tube exchanger with plain, single-corrugated, aligned-corrugated and misaligned-corrugated arrangements and found the maximum Nusselt number for misaligned corrugations on the inner and outer tubes, where the eddies and secondary flows are strongest, with no added weight penalty. Rostami et al. [105] examined a four-start helical corrugation in a tubular exchanger with air–water two-phase flow over liquid and gas Reynolds numbers of 4500–14,500 and 95–500, respectively, and reported that the overall heat transfer coefficient and exergy destruction both rise with the liquid Reynolds number; the corrugation parameters (pitch, envelope diameter and bore diameter) are defined in Figure 7. Although these two studies use tubular geometries, the underlying mechanism, namely corrugation-induced secondary flow, increased area and boundary-layer disruption, transfers directly to corrugated-plate channels.

Further tubular studies reinforce these conclusions and are relevant by analogy. Begag et al. [101] showed by finite-element analysis that concave corrugations at a phase-shift angle of 180° give the best thermo-hydraulic performance in a concentric-tube exchanger, and Han et al. [102] used a hydroforming technique to manufacture circumferentially corrugated double-pipe tubes that increase the area-to-volume ratio and promote heat dissipation. Moya-Rico et al. [106] predicted the heat transfer rate and pressure

change of a triple concentric-tube exchanger with an artificial neural network to within absolute average relative deviations of 1.91% and 3.82%, respectively, while Akbarzadeh and Maghrebi [107] combined porous inserts with sinusoidal wavy walls and found the wave amplitude to have a significant effect on the average Nusselt number.

Nanofluids in Corrugated Exchangers

Combining corrugated geometries with nanofluids gives a compound enhancement. Abbasian Arani and Moradi [108] evaluated an Al_2O_3 nanofluid in a carboxymethyl-cellulose base fluid inside a shell-and-tube exchanger with five corrugated tube shapes and two baffle types and found disc baffles to outperform segmental baffles; comparable shell-and-tube configurations that pair corrugated tubes with different baffle geometries have likewise been examined by Chaoui et al. [109]. Wang et al. [110] tested TiO_2 -water in corrugated tubes of different pitch and reported that heat transfer improves with pitch length and that the corrugated tube outperforms a smooth tube, although the smooth tube retains a higher exergy efficiency. Asadi et al. [111] used CFD to compare hybrid nanofluids of Ag-MoS_2 and $\text{Fe}_3\text{O}_4\text{-SiO}_2$ in a double-tube exchanger fitted with spherical turbulence promoters and identified Ag-MoS_2 as the best option, while Said et al. [112] measured a 7% rise in the overall heat transfer coefficient, an 11.4% rise in convective heat transfer and a 6.8% reduction in required area for a CuO -water nanofluid in a shell-and-tube unit. More recent experiments extend these findings: Painuly et al. [113] reported a 61.3% Nusselt increase for the tightest helical corrugation and a peak thermal performance factor of 1.97 for a SiC-MWCNT hybrid nanofluid, and Anbu et al. [114] obtained an 83.4% Nusselt increase for a 0.5% Al_2O_3 nanofluid combined with a low-pitch spiralled-rod insert in a helically corrugated tube, against an 81.1% friction penalty.

3.3. Double-Pipe Heat Exchangers

A double-pipe, or hairpin, heat exchanger consists of two concentric tubes, with one fluid in the inner tube and the other in the annulus. The design is simple, easy to clean and able to handle high pressures and temperatures, which keeps it popular for chemical processing, refrigeration and HVAC duties despite a lower heat transfer density than plate or printed-circuit units. External enhancement of the inner tube, for example by fins or surface corrugations, is a common way to raise the heat transfer density of this design [115]. Research has concentrated on inserts, corrugations, fins and nanofluids to raise that density while controlling the pressure penalty.

Performance in these exchangers is governed by flow distribution, thermal resistance and energy-recovery strategy rather than by geometry alone. Regenerative and recuperative arrangements improve thermal utilisation [116], and Bejan et al. [117] showed that adding plenums at the inlet and outlet of a counter-flow core reduces thermal resistance under both laminar and turbulent conditions. Reduced-order modelling has been used to expose efficiency limits in high-temperature packed-bed exchangers [118], and numerical studies confirm that a suitable choice of operating parameters markedly improves counter-flow performance [119]. Counter-flow configurations achieve the highest thermal effectiveness because of the favourable temperature gradient along the flow path, which keeps the local temperature difference between the streams more uniform than in a parallel-flow arrangement [1].

Surface modification is decisive. Verma et al. [120] found that helical ribs of about 4 mm pitch and 1.5 mm depth maximise heat transfer over $\text{Re} = 5000\text{--}17,000$, consistent with Gorman et al. [121], who showed that helical corrugations enhance heat transfer in the laminar regime ($\text{Re} = 420\text{--}2000$) through induced secondary flows (Figure 7). More complex geometries extend the area at the cost of added flow complexity: Gomaa et al. [122]

developed correlations for a triple concentric-tube exchanger, and Quadir et al. [123] showed by finite-element analysis that insulating a triple concentric-pipe exchanger improves effectiveness by 10–20% with numerical and experimental profiles agreeing to within about 5%. More recently, Ali et al. [124] showed that partially filling a double-pipe exchanger with metal foam under adaptive sliding-mode control raises the effectiveness while containing the pumping penalty. Gao et al. [125] analysed the transient response of a cross-flow exchanger and found the response time to fall by 20–50% as the mass flow rate increases. Sheikholeslami and Ganji [126] obtained a peak thermal performance factor of 1.59 with perforated turbulators in the annulus, achieved at $Re = 6000$ with a low pitch ratio. Related studies on cross-flow winglets [127], transport-membrane condensers [128] and double-pipe solar storage [129] broaden the design space. Representative experimental studies are summarised in Table 6.

Table 6. Representative experimental studies on double-pipe heat exchangers.

Study	Design	Fluids (Hot/Cold)	Main Outcome
Naphon [130]	Straight and twisted-tape inner tube	Water/water	Twisted tape substantially raises heat transfer with a moderate pressure rise
Singh Yadav [131]	U-type with half-length twisted tapes	Oil/water	Half-length tapes improve the thermal performance factor over full-length tapes
Akpınar [132]	Inner pipe with helical wire coils	Air/water	Friction factor and Nusselt number both increase with the number of turns
Taborek [133]	Longitudinal finned tubes, various flow patterns	Water/water	Cut-and-twist fins give low pressure loss at high heat transfer

Nanofluids and modified tapes give the largest recent gains in this family. Assaf et al. [134] combined a twisted tape of twist ratio 5 with a 0.9% Al_2O_3 –CuO/water hybrid nanofluid and raised the thermal performance factor from 1.38 for the plain tube to 3.29, with only a 6% pressure-drop penalty. Marzouk et al. reported Nusselt enhancements of 158–175% for perforated twisted tape with 0.3% Al_2O_3 /water [135] and 130–153% for twisted tape with 0.3% tungsten-carbide/water in a helically coiled double pipe [136]. Ahirwar and Kumar [137] obtained up to a 111% Nusselt increase with wire-coil inserts at a friction penalty of 348%, giving a peak thermal performance factor of 1.36. A recent review by Kadhim et al. [138] concluded that perforated tapes improve hydraulic behaviour while dimpled and baffled tapes give stronger thermal gains at a higher friction cost.

3.4. Printed-Circuit Heat Exchangers

A printed-circuit heat exchanger (PCHE) is a diffusion-bonded block of thin metal plates into which fine semicircular flow channels are chemically etched, with the hot and cold channels interleaved on adjacent plates [139]. The bonded construction withstands high pressures and temperatures, and the etched channels give a very high surface-area density, which makes PCHEs attractive for supercritical CO_2 power cycles, concentrated solar plants, hydrogen processing and compact energy systems [20,21]. Advances in computer-aided design, computational fluid dynamics and additive manufacturing have allowed increasingly intricate channel shapes to be realised [140]. Passive enhancement in PCHEs is achieved almost entirely through channel geometry and, to a lesser extent, through the choice of working fluid; both are reviewed below.

3.4.1. Passive Channel-Geometry Techniques

The straight semicircular channel is the baseline PCHE geometry. Bending the channel into a zigzag path was the first widely adopted enhancement, because the repeated changes

of direction break the boundary layer and raise the heat transfer coefficient. Kim et al. [141] validated zigzag-channel behaviour against helium test data and produced Nusselt-number and friction correlations, showing that straight-channel correlations mispredict the zigzag thermo-hydraulics. The drawback of the zigzag channel is a large form-drag penalty at the sharp bends, and much of the subsequent work has aimed at recovering the heat transfer benefit while removing that penalty.

Discontinuous fin geometries achieve exactly this. Ngo et al. [142,143] introduced the S-shaped fin and, from three-dimensional simulations anchored to CO₂ experiments, derived Nusselt and friction correlations showing that the S-shaped channel delivers a pressure drop roughly one order of magnitude below the zigzag channel at equal heat duty. Tsuzuki et al. [144] optimised the fin angle, length and spacing and confirmed that the S-shaped fin cuts the pressure drop to about 1/5 of the zigzag value for the same thermal performance, which established it as a high-performance passive geometry. Kim et al. [145] went further with a discontinuous aerofoil (NACA-profile) fin and showed by CFD that the streamlined fin reduces the pressure drop to about 1/20 of the zigzag channel while maintaining essentially the same heat transfer, because the aerofoil shape almost eliminates flow separation. Figure 8 summarises these reported pressure-drop reductions relative to the zigzag baseline at comparable heat duty, making explicit the progressive hydraulic gain from the S-shaped to the aerofoil fin.

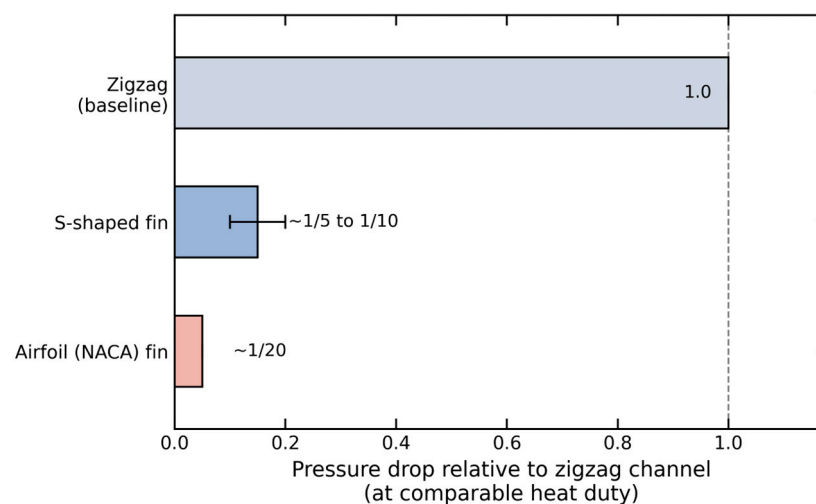


Figure 8. Pressure drop of discontinuous-fin printed-circuit heat exchanger channels relative to the zigzag baseline at comparable heat duty, compiled from the values reported by Ngo et al. [142,143], Tsuzuki et al. [144] and Kim et al. [145]. The S-shaped fin lowers the pressure drop to roughly 1/5 to 1/10 of the zigzag value and the aerofoil fin to about 1/20, while sustaining comparable heat transfer.

Smoothly curved channels offer an intermediate route. Aneesh et al. [146] compared straight, zigzag and sinusoidal (wavy) channels and found that sinusoidal channels give heat transfer comparable to the zigzag design with markedly lower friction, so that bend amplitude and pitch trade the Nusselt number against the pressure drop in a controllable way. Cui et al. [147] showed for a serpentine sCO₂ channel that Dean-type secondary flow near the pseudo-critical point improves the field synergy, with circular cross-sections giving the best heat transfer and elliptical sections the lowest friction. Recent optimisation continues to refine these ideas: Aye et al. [148] identified zigzag bending angles of 6° to 9° as the best compromise between heat transfer and friction for helium flow. Table 7 summarises the principal PCHE channel geometries and their reported thermo-hydraulic behaviour.

Table 7. Passive channel geometries for printed-circuit heat exchangers and their reported thermo-hydraulic behaviour, including the heat-transfer, pressure-drop and thermal-performance-factor ratios relative to the zigzag baseline. “ ≈ 1 ” denotes a value comparable to zigzag; “—” marks a ratio not quantified in the source.

Channel Geometry	Method/Fluid	Key Finding	Nu vs. Zigzag	ΔP vs. Zigzag	TPF vs. Zigzag	Ref.
Zigzag	Helium; experiment + CFD	Boundary-layer breakup raises heat transfer; large bend form-drag penalty	1 (ref.)	1 (ref.)	1 (ref.)	[141]
S-shaped fin	CO ₂ ; experiment + CFD	Pressure drop about one order of magnitude below zigzag at equal duty	≈ 1	$\approx 1/10$	≈ 2.2	[142,143]
Optimised S-shaped fin	CO ₂ ; numerical	Pressure drop about 1/5 of zigzag at equal thermal performance	≈ 1	$\approx 1/5$	≈ 1.7	[144]
Aerofoil (NACA) fin	CO ₂ ; CFD	Pressure drop about 1/20 of zigzag at comparable heat transfer	≈ 1	$\approx 1/20$	≈ 2.7	[145]
Sinu-soidal/wavy	Numerical	Heat transfer comparable to zigzag with markedly lower friction	≈ 1	Lower	>1	[146]
Serpentine	sCO ₂ ; CFD	Dean-vortex secondary flow improves field synergy near pseudo-critical point	—	—	—	[147]
Optimised zigzag angle	Helium; CFD	Bending angles of 6–9° give the best heat-transfer-to-friction balance	—	—	—	[148]

To place these pressure-drop reductions on the same footing as the rest of this review, they can be expressed as a thermal performance factor relative to the zigzag baseline, $TPF = (Nu/Nu_0)/(f/f_0)^{1/3}$, with the zigzag channel as the reference. Where a discontinuous-fin channel delivers heat transfer comparable to the zigzag design ($Nu/Nu_0 \approx 1$) while cutting the friction factor, the relative performance factor follows directly from the friction ratio: a pressure drop reduced to about 1/5 of the zigzag value (the optimised S-shaped fin [144]) corresponds to a relative TPF of about 1.7, and a reduction to roughly 1/20 (the aerofoil fin [145]) to a relative TPF of about 2.7. These figures carry one caveat that the review makes explicit: the cited comparisons are reported at equal thermal duty rather than at a strictly identical hydraulic diameter, and the fin pitch and channel cross-section differ between designs. The values above therefore indicate the substantial advantage of curved and aerofoil fins over the zigzag channel, but a definitive ranking would require a dedicated comparison at matched hydraulic diameter, which the present literature does not yet provide.

3.4.2. Working Fluids and Nanofluid Effects

Because PCHEs are most often deployed in supercritical CO₂ and molten-salt systems, the working fluid strongly conditions the enhancement achievable from a given geometry. Ji et al. [149] tested a trapezoidal-channel PCHE with supercritical CO₂ over $Re = 4800$ – $30,000$ and measured overall heat transfer coefficients up to $2.53 \text{ kW m}^{-2} \text{ K}^{-1}$, noting that trapezoidal channels give the highest heat transfer but also the highest pressure loss relative to the zigzag baseline. Fu et al. [150] analysed a hybrid PCHE that pairs a supercritical CO₂ aerofoil-fin passage with a molten-salt straight passage and showed that the aerofoil fins dominate the local heat transfer, with staggered arrangements giving shorter

fluctuation periods but lower mean coefficients than parallel arrangements. These studies indicate that the strong property variation of supercritical fluids near the pseudo-critical point interacts with the channel geometry, so that fin shape and channel curvature must be selected together with the operating pressure. Unlike in the plate and double-pipe families, dispersed-nanoparticle working fluids have seen little use in PCHEs, mainly because the fine etched channels are prone to particle deposition and clogging; this remains an open and largely unexplored direction.

3.5. Flat-Plate Heat Exchangers

Flat-plate heat exchangers are used widely in power generation, processing, refrigeration and transport because of their compact structure, low cost and simple construction. Improving their thermal performance is central to reducing capital cost, and this is achieved either by geometric optimisation of the plate surface or by using nanofluids. This section focuses on passive surface techniques, which are the most mature route for this family.

Passive surface techniques for flat plates fall into three broad classes: embossed surfaces, secondary-corrugated surfaces and roughened surfaces. Embossing places an array of raised features on the plate, acting much like a finned surface, and both concave and convex forms have been studied in staggered arrangements. Ji et al. [140] investigated a capsule-type embossing and found, from a single-phase k - ω analysis, that it offers slightly higher heat transfer with lower deposition, fouling and pressure drop than conventional chevron corrugation. Dimple-type embossing is particularly effective: Ying et al. [151] reported heat transfer gains of about 10–30% over a smooth plate, and Zhang et al. [19] observed a two- to two-and-a-half-fold rise in the Nusselt number as the flow resistance increases. Representative numerical studies of passive surface techniques are collected in Table 8. Recent work confirms that combining surface features with nanofluids extends these gains: a grooved absorber tube with an Al_2O_3 nanofluid raised efficiency by up to 54% [152], a triangular perforated wavy tape lifted the Nusselt number by about 21% [153], and MWCNT nanofluids raised the thermal efficiency of a flat-plate collector to about 84% [154]. A recent critical review provides a broader map of these methods for flat-plate solar collectors [155].

Table 8. Representative numerical studies of passive surface techniques for flat-plate heat exchangers.

Technique/Analysis	Main Finding	Ref.
Capsule-type embossing	Higher Nusselt number and lower pressure drop than chevron corrugation	[140]
Chevron, elliptic, round embossing	Elliptic embossing gives the best heat transfer performance	[156]
Horse-shoe embossing	Geometry parameters strongly affect thermal performance	[157]
Secondary corrugation (in/anti-phase)	In-phase corrugation gives the maximum Nusselt-number increase	[158]
Transverse and longitudinal corrugation	Compound corrugation lowers both Nusselt number and friction	[159]
Dimple-type embossing	Heat transfer raised by about 10–30% over a smooth plate	[151]
Dimple-type embossing	Two- to two-and-a-half-fold rise in Nusselt number	[19]

4. Cross-Cutting Synthesis and Comparative Assessment

Reviewing each configuration in isolation is useful but incomplete, because the practical question is which passive technique to choose for a given exchanger. This section draws the evidence together. Figure 9 plots the reported Nusselt-number or thermal enhancement

ranges for the main technique–configuration combinations, and Table 9 states, for each configuration, the best-performing technique, the typical thermal performance factor and the principal limitation. The typical thermal performance factor ranges of Table 9 are shown graphically in Figure 10, which places the central performance metric of this review on a single comparative axis.

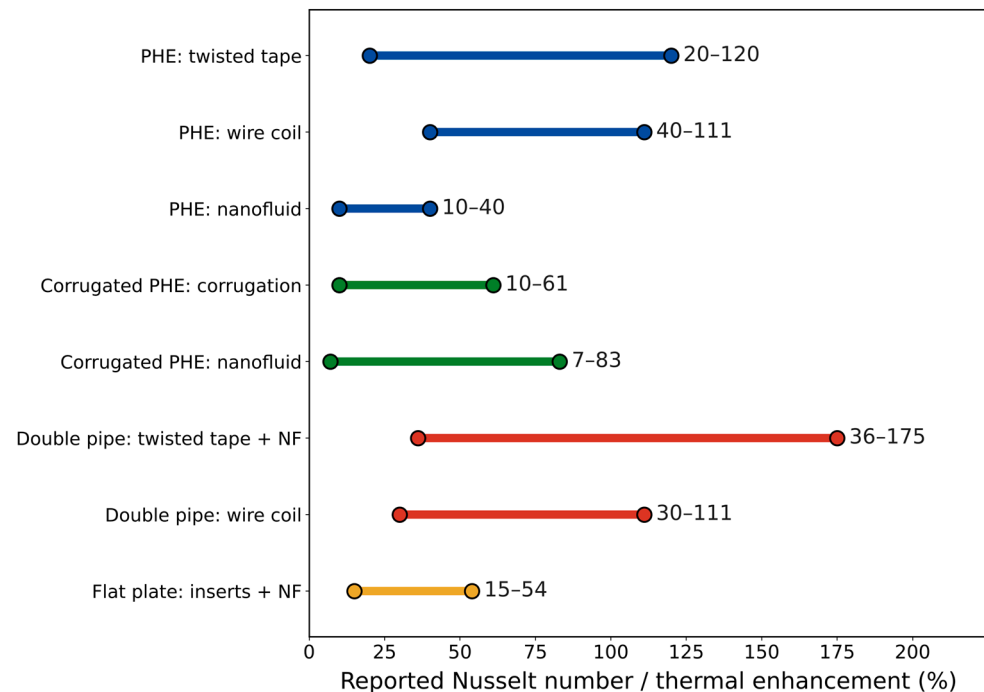


Figure 9. Reported Nusselt-number or thermal enhancement ranges for the principal passive technique and heat exchanger combinations surveyed in this review. Colours group the combinations by heat exchanger family. Circles mark the endpoints (minimum and maximum) of each reported range.

Table 9. Comparative assessment of passive enhancement across the five heat exchanger configurations.

Configuration	Best Passive Technique	Typical TPF	Principal Limitation
Plate	Twisted tape (laminar); wire coil (turbulent)	1.0–1.5	Pressure drop rises steeply at low twist ratio
Corrugated plate	Misaligned corrugation; corrugation + nanofluid	1.2–2.0	Manufacturing tolerance; exergy penalty of nanofluids
Double pipe	Twisted tape + hybrid nanofluid	1.3–3.3	Cost and stability of nanofluid; high friction
Printed circuit	S-shaped/aerofoil fin	Pressure drop ↓ up to 20×	Etched channels prone to fouling; limited nanofluid use
Flat plate	Dimple/capsule embossing; grooves + nanofluid	1.1–1.5	Fewer studies; scale-up not demonstrated

A note of caution applies to the computational part of this evidence base. The swirling, separated and reattaching flows produced by twisted tapes, wire coils, corrugations and printed-circuit channels are demanding to resolve, and the reliability of a reported Nusselt-number gain depends on the numerical framework used to obtain it. Rigorous studies demonstrate mesh independence, resolve the near-wall region adequately (a wall-normal y^+ of order unity with enough inflation layers for a low-Reynolds wall treatment), justify the turbulence closure against the flow physics (the k - ω SST model, or scale-resolving

approaches such as large-eddy simulation, generally capturing adverse-pressure-gradient separation better than a standard k-epsilon model), and validate their predictions against experiment. Not all of the cited numerical works report these checks, and where they are absent the quoted enhancements are best treated as indicative rather than definitive. In drawing the quantitative ranges together, this review therefore gives greater weight to results that are either experimental or numerically validated, and a full study-by-study audit of the computational methods is identified as a useful direction for future work.

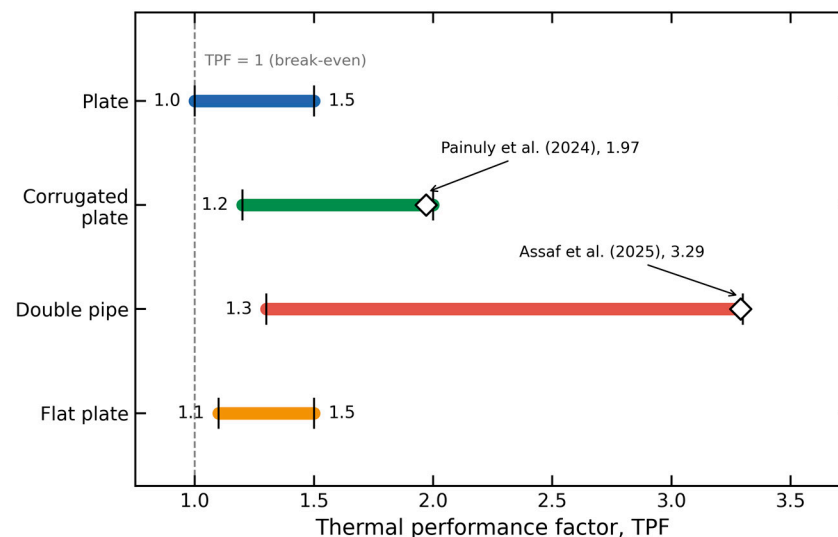


Figure 10. Typical thermal performance factor (TPF) ranges for the reviewed heat exchanger configurations, compiled from the comparative assessment of Table 9. Diamond markers denote the highest reported values from the studies discussed in the text (Assaf et al. [134] for double pipe; Painuly et al. [113] for corrugated plate). Printed-circuit heat exchangers are omitted because their passive benefit is expressed as a pressure-drop reduction (Figure 8) rather than a TPF. The dashed line marks the break-even value $TPF = 1$.

A consistent basis of comparison is essential when thermal performance factors from different studies are placed side by side. Throughout this review the TPF is evaluated at constant pumping power (the exponent of $1/3$ in Equation (1) enforces this condition), and the comparative ranges in Figures 9 and 10 and Table 9 are read at matched Reynolds number wherever the source data allow. This matters because the same technique can show a markedly different TPF at low and high Reynolds number: swirl and insert devices tend to peak in the laminar and transitional regimes, where the heat transfer gain outweighs the friction penalty, whereas in fully turbulent flow the rising friction factor erodes the advantage. Where two studies are compared at different Reynolds numbers, or under constant-flow rather than constant-pumping-power conditions, this is stated so that the comparison is not read as like-for-like, and the most robust conclusions are drawn from studies that report a full TPF-versus-Reynolds-number curve rather than a single peak value.

Several patterns emerge. First, inserts combined with nanofluids in double-pipe exchangers produce the widest and highest enhancement band (36–175%), but they also carry the largest hydraulic and cost penalties, so their high thermal performance factors are realised only at modest concentrations and twist ratios. Second, twisted tapes and wire coils in plate heat exchangers give reliable, well-characterised gains (20–120%) with thermal performance factors that stay comfortably above unity, which explains their industrial dominance. Third, corrugation is the most cost-effective route for plate and tubular geometries, delivering 10–61% gains through secondary flow at a moderate friction cost. Fourth, printed-circuit heat exchangers stand apart: the relevant metric is not the Nusselt

gain but the pressure-drop reduction achieved by moving from zigzag to S-shaped and aerofoil fins, which reaches a factor of 20 at comparable heat transfer, so their entry in Table 9 is framed in those terms. Finally, nanofluids improve every configuration they are applied to, but the viscosity penalty of Figure 5 and the cost of stable suspensions keep the net benefit bounded, particularly at high Reynolds number and high volume fraction.

5. Advancements and Future Perspectives

The field is moving quickly on several fronts. Computational fluid dynamics has become central to design, allowing complex geometries, multiphase flows and conjugate effects to be evaluated with a fidelity that reduces the need for costly experiments, and its coupling with machine learning is beginning to accelerate the search for optimal configurations across large parameter spaces [106]. Additive manufacturing is a second enabler, because it makes intricate channel and fin geometries buildable that conventional methods cannot produce; printed-circuit and compact plate exchangers stand to benefit most [21]. A third direction is the use of hybrid strategies that combine two passive techniques or pair a geometric modification with an advanced working fluid; the twisted-tape-plus-nanofluid and corrugation-plus-nanofluid results reviewed above show clear synergy beyond either technique alone [113,134]. Figure 11 collects the peak Nusselt-number enhancements reported by these recent combined-technique studies, which reach 158 to 175% for a perforated twisted tape paired with an alumina nanofluid in a helically coiled double pipe. A fourth direction is the migration of these techniques into demanding energy applications, including supercritical CO₂ power cycles, concentrated solar plants, industrial waste-heat recovery, hydrogen production and the thermal management of electric-vehicle batteries, all of which need compact exchangers that operate reliably under severe conditions.

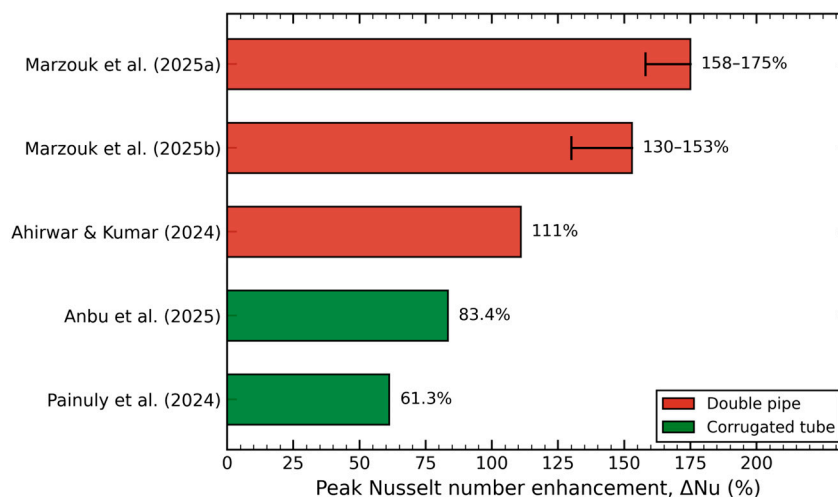


Figure 11. Peak Nusselt-number enhancement reported by recent combined passive-technique studies: Marzouk et al. (2025a) perforated twisted tape with 0.3% Al₂O₃/water [135]; Marzouk et al. (2025b) twisted tape with 0.3% tungsten-carbide/water [136]; Ahirwar and Kumar (2024) wire-coil insert [137]; Anbu et al. (2025) 0.5% Al₂O₃ nanofluid with a spiralled-rod insert in a helically corrugated tube [114]; and Painuly et al. (2024) SiC–MWCNT hybrid nanofluid with a tight helical corrugation [113]. Whiskers denote the range reported across the cited conditions. Colours group the studies by heat exchanger family.

Against these opportunities, four gaps stand out from the synthesis. First, there are very few like-for-like studies that apply the same technique across different heat exchanger types under identical boundary conditions, which prevents a fully controlled ranking. Second, the long-term stability, fouling behaviour and lifecycle cost of nanofluids remain insufficiently

characterised for commercial deployment, and most data are short-duration laboratory measurements. Third, printed-circuit and flat-plate exchangers are under-represented relative to plate and corrugated-plate units, particularly for passive enhancement. Fourth, data-driven optimisation of enhancement geometries is still at an early stage.

Future work should therefore prioritise the following: controlled comparisons of a common technique across configurations under identical conditions; long-duration assessment of nanofluid stability, fouling and cost; the development and testing of hybrid geometry-plus-fluid strategies; the use of high-fidelity CFD coupled with machine-learning optimisation to navigate large design spaces; and dedicated passive-enhancement studies for printed-circuit and flat-plate exchangers in emerging energy systems.

5.1. Mono, Hybrid and Ternary Nanofluids: A Separated Assessment

Because the three nanofluid classes differ markedly in behaviour, their evidence is assessed separately here, complementing the configuration-by-configuration discussion of Section 3. Mono (single-nanoparticle) suspensions remain the best-characterised class in plate and compact exchangers (Table 10); across the screened studies the reported heat transfer coefficient or Nusselt-number gains are typically in the range of 10–35%, for example [160] and [161], with the larger numerical gains obtained when fin-type surface modification is combined with the nanofluid. Hybrid (two-nanoparticle) suspensions (Table 11) aim to combine the high conductivity of one particle with the stability or lower cost of another; the reported gains overlap the upper part of the mono range, for instance a Nusselt-number rise of 12–42% [162], but the coverage is dominated by a small number of research groups and by energetic or exergetic analyses rather than independent thermal-hydraulic measurements. A clear and reportable outcome of the present screening is that true ternary (three-nanoparticle) suspensions, although increasingly studied in tubular geometries, were not found for plate exchangers; the plate-exchanger ternary literature is therefore effectively absent and represents a concrete gap for future work.

Table 10. Representative studies of mono (single-nanoparticle) nanofluids in plate and compact plate heat exchangers. Values are as reported in the source abstracts; “NR” denotes a quantity not stated.

Study	Nanoparticle	Base Fluid	Configuration	Concentration	Reported Nu/HTC Effect
Karatutlu et al. (2026) [160]	Al ₂ O ₃ /Fe ₃ O ₄ /MWCNT/SWCNT/GO	Water	PHE	0.01–0.5 vol%	NR (enhanced)
Sundar et al. (2022) [163]	Ni	Water	PHE	0.1–0.6 vol%	NR
Arya et al. (2018) [164]	MgO	Ethylene glycol	HX (counter-current)	0.1–0.3 wt%	NR
Alikhan et al. (2025) [161]	CuO	Water	Compact PHE + pulsed flow	Low	NR
Khoshvaght-Aliabadi et al. (2018) [165]	Not named	Water	Corrugated/perforated-fin PHE	NR	HTC higher than typical fins
Singh et al. (2022) [166]	MWCNT	Water	Chevron PHE (30°, 60°)	NR	+13.64% (30°), +17.27% (60°) with nanofluid
Zhang et al. (2024) [167]	Cu	Water–glycol	Wavy-walled tube HX	1.5, 3.0 vol%	NR

Table 10. Cont.

Study	Nanoparticle	Base Fluid	Configuration	Concentration	Reported Nu/HTC Effect
Kabeel et al. (2013) [168]	Al ₂ O ₃	Water	Corrugated PHE	1–4 vol%	HTC +3.7–13% (max 13% at 4 vol%)
Mehrarad et al. (2023) [169]	MWCNT	Water/EG	Brazed PHE	0.05 wt% (best stability)	HTC +20.97%, Q +34.3%
Valizadeh Ardalan et al. (2025) [170]	Nanofluid	Water	PHE (chevron)	2 vol% (opt.)	Nu/HT rate rise with NPs (max at 2 vol%); 60°/60° ~100% > 30°/30°
Unverdi et al. (2017) [171]	Al ₂ O ₃	Water	Chevron PHE	0.25–1 vol%	Nu rises with conc and flow
Hassaan (2022) [172]	MWCNT	Water	PHE (HT32)	0.22–1.53 vol%	NR (calculated)

Table 11. Representative studies of hybrid (two-nanoparticle) nanofluids in plate heat exchangers. No true ternary (three-nanoparticle) suspension was identified for plate geometries in the present screening.

Study	Nanoparticle Combination	Base Fluid	Configuration	Concentration	Reported Nu/HTC Effect
Alklaibi et al. (2024) [173]	Fe ₃ O ₄ –SiO ₂	Water	PHE	(Re 245–936)	NR
Roueintan et al. (2024) [162]	(Hybrid)	Water	Pillow/wavy plate HX	NR	Nu +12–42%
Samadi Rikandeh et al. (2026) [174]	SWCNT–Al ₂ O ₃	Water	Pillow-plate heat sink	1, 3, 5 vol%	NR
Bhattad, Sarkar et al. (2018) [175]	Al ₂ O ₃ + MWCNT	Water	PHE	Varied	HTC +39.16% (pump power +1.23%)
Kumar, Tiwari et al. (2016) [176]	Cu + Al ₂ O ₃ (+monos)	Water	PHE (spacing study)	NR	MWCNT/water max HTC at ΔX = 5 mm
Bhattad, Sarkar et al. (2020) [177]	(Hybrid)	Water	Corrugated PHE	Varied	HTC +9.4%, HT rate +1.6% (opt. 2 vol%)
Bhattad (2023) [178]	(Hybrid)	Water	Corrugated PHE	To 0.5 vol%	NR
Bhattad et al. (2021) [179]	Alumina/CuO/silica/titania + Cu	Brines (EG/CaCl ₂ /PG/KAc)	Plate evaporator	Varied	Perf. index +3.96%; HT area –5.9% (CuO–Cu best)
Broumand et al. (2025) [180]	Graphene–TiO ₂	Water	Corrugated PHE	0.05–0.5 vol%	HT rate +18.4% at 2 L/min (0.05%); HTRC +8.5%
Huang, Wu et al. (2016) [181]	Al ₂ O ₃ + MWCNT	Water	Chevron corrugated PHE	MWCNT 0.0111% + Al ₂ O ₃ 1.89% (1:2.5)	HTC slightly > Al ₂ O ₃ /water
Returi, Konijeti et al. (2019) [182]	Al ₂ O ₃ + CuO, Al ₂ O ₃ + TiO ₂ (+monos)	Water	Spiral PHE	2, 4 vol%	HT augmentation +16–27% (4 vol%), +10–16% (2 vol%)
Bhattad, Sarkar et al. (2020) [183]	Al ₂ O ₃ –SiC/AlN/MgO/CuO/MWCNT	DI water	Corrugated PHE	0.1 vol% (4:1)	HTC +31.2% (Al ₂ O ₃ –MWCNT 4:1); perf. index +12.46%

These gains must always be read against the hydraulic penalty. Dispersing nanoparticles raises the effective thermal conductivity of the coolant, but it raises the viscosity more steeply, and because the viscosity enters the pumping power directly, the net thermo-hydraulic benefit is usually modest. A representative illustration is the nickel–water system of [163], in which the thermal conductivity increased by about 34% at 0.6 vol% while the viscosity increased by about 67% at the same loading; the conductivity gain lifts the Nusselt number, yet the larger relative viscosity rise inflates the pumping power, so that the thermal performance factor rises only slowly and is maximised at low particle concentrations. This asymmetry explains why many high-concentration suspensions report thermal performance factors close to, or below, unity despite substantial conductivity gains, and it is the reason the present review reports nanofluid performance in terms of the thermal performance factor rather than the conductivity or Nusselt-number gain alone. A further caveat on comparability is that the studies in Tables 10 and 11 use different base fluids, particle sizes and concentrations, so their headline percentages are not strictly like-for-like; the tables therefore record the base fluid and concentration of every entry so that only comparable cases are set side by side.

5.2. Porous-Media and Metal-Foam Enhancement

Structured and porous media are an established passive route that the present review incorporates alongside inserts, surface modification and nanofluids. Open-cell metal foams dominate the recent literature (Table 12); their high specific surface area and tortuous, well-mixed flow raise the convective coefficient substantially, at the cost of an added pressure penalty governed principally by the porosity and the pore density. Experimental plate and tubular exchangers filled or partially filled with copper foam [184] show that pore density (expressed in pores per inch) and flow velocity set the optimum operating point, while graded-porosity and partially filled arrangements are used to recover part of the pressure penalty. Foams are also increasingly proposed as a direct replacement for conventional fins on the air side of compact exchangers. Because the enhancement and the penalty both scale with the same pore-scale geometry, porous-media designs are best assessed, like the other techniques in this review, through the thermal performance factor at matched pumping power.

Table 12. Representative studies of porous-media and metal-foam enhancement in heat exchangers. “—” denotes not applicable.

Study	Medium	Configuration	Porosity/PPI	Key Finding
Tavakoli et al. (2024) [185]	Porous media	HX (layouts)	Porosity % (stated)	Layout and flow rate raise HT
Ekade et al. (2019) [186]	Octet-truss lattice	HX/sink	Tailorable	Higher effective k vs. stochastic foam
Rahomey et al. (2026) [187]	Porous layer	V-shaped open channel	PL thickness 0–100%	Porous layer enhances HT
Kumar, Ramamoorthy et al. (2023) [188]	Open-porous materials	HX	—	HT from ΔP via L��v��que analogy
Flayh (2025) [189]	Copper foam inserts	Corrugated tube	10 PPI	TEF > smooth tube
Kadhim et al. (2026) [190]	Metal foam (partial)	Double-pipe HX	Partially filled	Partial fill tunes HT vs. ΔP

Table 12. Cont.

Study	Medium	Configuration	Porosity/PPI	Key Finding
Asaei, Siavashi et al. (2026) [191]	Metal foam (Voronoi/Kelvin)	Channel	Porosity 0.75/0.85/0.95	Pore geometry governs ΔP and permeability
Gaur, Sahoo et al. (2024) [192]	Aluminium metal foam	Circular tube	High porosity	Improves hydraulic–thermal, cuts pumping power
Al-Chlahawi, Hasan et al. (2025) [193]	Metal foam blocks	Rectangular channel (solar air)	—	Configuration governs HT
Farid, Aboelsoud et al. (2024) [194]	Porous insert	Channel (air)	Angle param	Angle 14° gives min ΔP
Fakiri et al. (2017) [195]	Porous-media model	Serpentine HX (baffles)	—	Waved baffles: higher Nu and friction
Nilpueng et al. (2020) [184]	Copper foam	PHE (filled)	30–50 PPI	Pore density and velocity set optimum

5.3. Phase-Change-Material Enhancement

Phase-change-material (PCM) latent-heat exchangers are the second contemporary passive family added here (Table 13). Their defining limitation is the very low thermal conductivity of the storage medium, which throttles the charging and discharging rate, and the passive remedies mirror those used elsewhere in this review: extended surfaces and fins, metal foams, dispersed nanoparticles (nano-enhanced PCMs), expanded graphite and encapsulation. Fin-based designs are the most common and the most effective per unit added material; for example, a wedge-fin tube exchanger [196] reduced the melting time by about 13% relative to an annular-fin baseline, and a perforated tree-shaped fin [197] raised the Nusselt number and heat-exchange rate by roughly 10% and 36%, respectively, while using slightly less material. Nanoparticle dispersion and metal-foam impregnation give further gains by raising the effective conductivity of the PCM, again at the cost of added pressure drop or reduced storage density, so the same thermal-against-hydraulic trade-off that frames the rest of this review applies directly to latent-heat designs.

Table 13. Representative studies of passive enhancement of phase-change-material (PCM) latent-heat exchangers.

Study	Enhancement	Configuration	PCM	Key Finding
Safari, Kamkari et al. (2024) [196]	Wedge fins	Tube HX	Paraffin (LHS)	−12.8% (melting time)
Wang et al. (2024) [197]	Tree-shaped perforated fins	Horizontal LHS	PCM	Nu +10.19%, heat exchange +36.51%
Selimefendigil et al. (2025) [198]	Branching fin + ternary nanofluid HTF	Double-vented cavity	Encapsulated PCM	Re 200–1000
Mikkola et al. (2017) [199]	Micro-PCM + nanoparticles	Convection loop	Paraffin micro-PCM	5–10% mass
Qaiser et al. (2021) [200]	Multi-tube + modified shell	Shell-tube LHS	Stearic acid	2–5 tubes

Table 13. Cont.

Study	Enhancement	Configuration	PCM	Key Finding
Khan et al. (2019) [201]	Longitudinal fins, multi-pass	Shell-tube LHS	Commercial paraffin	Charging/discharging power
Alomari et al. (2025) [202]	Nano-encapsulated PCM + porous foam	Corrugated cavity	NEPCM	$Ra\ 1 \times 10^3 - 1 \times 10^5$
Khobragade et al. (2025) [203]	Fins (SCD)	Shell-tube	PCM	Incl. 90–0°
Safari, Abolghasemi et al. (2021) [204]	Straight vs. bifurcated fins	Shell-tube	Paraffin	3 fin arrangements
Khalaf et al. (2026) [205]	Novel fin geometries	Shell-tube	PCM	Melting performance
Emhofer et al. (2025) [206]	Al MPE tubes + Al fins	Immersed-tube HP store	PCM	Desuperheater DHW
Roy, Venkitaraj et al. (2024) [207]	Nanofluid HTF (Al_2O_3 –water)	Shell-tube	PCM	0.1,0.3,0.6 vol%

6. Consolidated Summary of the Reviewed Evidence

To make the review usable as a reference, Table 14 consolidates the surveyed evidence into a single map. For each configuration and technique, it records representative studies, the key quantitative outcome, and a critical remark that connects the result to the central message of the paper, namely that a passive technique is only worthwhile when its heat transfer gain survives the pressure and cost penalty it imposes.

Table 14. Consolidated summary of passive heat transfer enhancement across the reviewed heat exchanger configurations.

Configuration	Technique	Representative Studies	Key Quantitative Outcome	Critical Remark (Relevance to Review Message)
Tubular/double pipe	Twisted tape	[11,18,208]	$\Delta Nu\ 20\text{--}120\%$, $\Delta f\ 30\text{--}200\%$, TPF 1.0–1.5	Best in laminar/transitional flow; low twist ratio raises Nu but the friction penalty grows faster, so TPF peaks at moderate twist.
Tubular/double pipe	Wire coil	[31,32,209]	Superior TPF to twisted tape in turbulent flow	Complements twisted tape rather than replacing it; preferred once flow is fully turbulent.
Plate	Nanofluid	[17,28,210]	k up 1–52%; μ up 3–210%; cp down 1–46%	Conductivity gain is real but bounded by viscosity and cost; benefit fades at high Re and high ϕ .
Corrugated plate	Corrugation geometry	[100,103,105]	$\Delta Nu\ 10\text{--}61\%$ via secondary flow	Most cost-effective single route; misaligned inner/outer corrugation maximises eddy generation.
Corrugated plate	Corrugation + nanofluid	[112–114]	ΔNu up to 83%; TPF up to 1.97	Compound gain, but exergy and pumping penalties rise; disc baffles outperform segmental.

Table 14. Cont.

Configuration	Technique	Representative Studies	Key Quantitative Outcome	Critical Remark (Relevance to Review Message)
Double pipe	Twisted tape + nanofluid	[134–136]	Δ Nu 130–175%; TPF up to 3.3	Highest peak performance of any family, realised only at low concentration and moderate twist.
Double pipe	Wire coil	[132,137]	Δ Nu up to 111%; Δ f up to 348%; TPF 1.36	Strong thermal gain but heavy friction cost; net benefit modest.
Double pipe	Helical rib/corrugation	[4,120,121]	Optimal at Re = 5000–17,000; laminar gains at Re = 420–2000	Pitch and depth must be tuned to the target Re window.
Printed circuit	Zigzag channel	[141,148]	Raises Nu; large bend form-drag; best angle 6–9°	Baseline enhancement; the pressure penalty motivates discontinuous fins.
Printed circuit	S-shaped fin	[142–144]	Δ p cut to 1/5–1/10 of zigzag at equal duty	Removes most of the zigzag penalty; key to compact sCO ₂ cores.
Printed circuit	Aerofoil fin	[145,150]	Δ p cut to 1/20 of zigzag at comparable Nu	Near-elimination of separation; the decisive PCHE passive step.
Printed circuit	Wavy/serpentine	[146,147]	Nu comparable to zigzag at lower friction	Dean-vortex secondary flow aids field synergy near the pseudo-critical point.
Flat plate	Embossing/dimples	[19,140,151]	Δ Nu 10–30%; up to 2–2.5× at higher f	Lower fouling than chevron corrugation; scale-up not yet demonstrated.
Flat plate	Inserts + nanofluid	[152–154]	Efficiency up to 54%; Δ Nu 21%	Promising for solar collectors; long-term nanofluid stability still open.

7. Conclusions

This paper has reviewed passive heat transfer enhancement across five heat exchanger configurations, drawing on 210 references from the peer-reviewed literature and interpreting every result through the thermal performance factor so that thermal gains are always weighed against the accompanying hydraulic penalty. Taken as a whole, the evidence shows that the choice of passive technique is inseparable from the geometry it is applied to and from the flow regime in which the exchanger operates.

For plate heat exchangers, twisted tapes remain the most extensively studied insert and raise the Nusselt number by 20 to 120% with thermal performance factors typically between about 1.0 and 1.5 in turbulent flow. The swirl they generate is most valuable in laminar and transitional flow, where thermal performance factors can rise well above 2, whereas wire coils give a better thermo-hydraulic balance once the flow is fully turbulent, so the two inserts are complementary rather than competing. Dispersing nanoparticles in the working fluid is a parallel route that raises thermal conductivity by 1 to 52% at volume fractions up to about 8%, with alumina and copper-oxide particles the most effective, but the accompanying viscosity rise of 3 to 210% and the associated pumping cost bound the net benefit, particularly at high Reynolds number and high loading.

For corrugated and tubular geometries, corrugation-induced secondary flow and boundary-layer disruption deliver Nusselt gains of 10 to 61% at a moderate friction cost, and these gains are maximised when the corrugations on the inner and outer walls are misaligned. Combining corrugation with a nanofluid is synergistic and pushes the thermal performance factor towards 2.0. In double-pipe exchangers the same logic is amplified: helical ribs, wire coils and twisted tapes used together with nanofluids give the widest enhancement band, up to 175%, and the highest thermal performance factors, up to about 3.3, but they also carry the largest friction and stability penalties, so the operating concentration and twist ratio must be chosen with care. Printed-circuit exchangers behave differently again, because the decisive passive step there is geometric rather than fluid-based: moving from a zigzag channel to S-shaped and then aerofoil fins cuts the pressure drop by up to a factor of 20 at comparable heat transfer, while dispersed nanofluids remain largely unexplored in this family owing to the risk of fouling the fine etched channels.

Across the five families a consistent hierarchy emerges. Corrugation is the most cost-effective single route, insert-plus-nanofluid combinations give the highest peak performance where their penalties can be tolerated, and shaped fins are the key enabler for compact, high-pressure duties. These findings, together with the comparative assessment of Section 4 and the consolidated summary of Table 14, provide a quantitative basis for selecting an enhancement strategy for a given exchanger and duty.

Limitations of the Study

This review is bounded by its scope and by the nature of the available literature. It concentrates on five widely used configurations, so its conclusions may not transfer directly to less common exchanger types. It focuses on passive techniques and does not review active methods in detail. Much of the underlying data come from short-duration experiments and simulations under specific conditions, so care is needed when extrapolating to industrial scale, and the economic analysis of the techniques is necessarily qualitative because consistent cost data are scarce. Finally, as with any review of an active field, the findings represent the state of the literature at the time of writing and will need periodic updating as new studies appear.

Author Contributions: Conceptualization, M.A. and S.H.; methodology, M.A. and S.U.; formal analysis, M.A. and S.L.; investigation, M.A., S.H. and S.U.; writing—original draft preparation, M.A.; writing—review and editing, S.H., S.U. and S.L.; supervision, S.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analysed in this study. Data sharing is not applicable to this article.

Acknowledgments: The authors thank the School of Engineering, Mathematics and Physics, University of East Anglia, Norwich, UK, for the facilities and support that made this review possible.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Bergman, T.L.; Lavine, A.S. *Fundamentals of Heat and Mass Transfer*, 8th ed.; John Wiley & Sons: Hoboken, NJ, USA, 2017.
2. Albadr, J.; Tayal, S.; Alasadi, M. Heat transfer through heat exchanger using Al_2O_3 nanofluid at different concentrations. *Case Stud. Therm. Eng.* **2013**, *1*, 38–44. [[CrossRef](#)]
3. Huang, D.; Wu, Z.; Sunden, B. Pressure drop and convective heat transfer of Al_2O_3 /water and MWCNT/water nanofluids in a chevron plate heat exchanger. *Int. J. Heat Mass Transf.* **2015**, *89*, 620–626. [[CrossRef](#)]
4. Salem, M.R.; Eltoukhey, M.B.; Ali, R.K.; Elshazly, K.M. Experimental investigation on the hydrothermal performance of a double-pipe heat exchanger using helical tape insert. *Int. J. Therm. Sci.* **2018**, *124*, 496–507. [[CrossRef](#)]

5. Sarafraz, M.M.; Hormozi, F. Intensification of forced convection heat transfer using biological nanofluid in a double-pipe heat exchanger. *Exp. Therm. Fluid Sci.* **2015**, *66*, 279–289. [[CrossRef](#)]
6. Raei, B.; Shahraki, F.; Jamialahmadi, M.; Peyghambarzadeh, S.M. Experimental study on the heat transfer and flow properties of g-Al₂O₃/water nanofluid in a double-tube heat exchanger. *J. Therm. Anal. Calorim.* **2017**, *127*, 2561–2575. [[CrossRef](#)]
7. Barzegarian, R.; Aloueyan, A.; Yousefi, T. Thermal performance augmentation using water based Al₂O₃-gamma nanofluid in a horizontal shell and tube heat exchanger under forced circulation. *Int. Commun. Heat Mass Transf.* **2017**, *86*, 52–59. [[CrossRef](#)]
8. Shahrul, I.M.; Mahbubul, I.M.; Saidur, R.; Sabri, M.F.M. Experimental investigation on Al₂O₃-W, SiO₂-W and ZnO-W nanofluids and their application in a shell and tube heat exchanger. *Int. J. Heat Mass Transf.* **2016**, *97*, 547–558. [[CrossRef](#)]
9. Liu, S.; Sakr, M. A comprehensive review on passive heat transfer enhancements in pipe exchangers. *Renew. Sustain. Energy Rev.* **2013**, *19*, 64–81. [[CrossRef](#)]
10. Dewan, A.; Mahanta, P.; Raju, K.S.; Kumar, P.S. Review of passive heat transfer augmentation techniques. *Proc. Inst. Mech. Eng. Part A J. Power Energy* **2004**, *218*, 509–527. [[CrossRef](#)]
11. Manglik, R.M.; Bergles, A.E. Heat Transfer and Pressure Drop Correlations for Twisted-Tape Inserts in Isothermal Tubes: Part I—Laminar Flows. *J. Heat Transf.* **1993**, *115*, 881–889. [[CrossRef](#)]
12. Eiamsa-ard, S. Study on thermal and fluid flow characteristics in turbulent channel flows with multiple twisted tape vortex generators. *Int. Commun. Heat Mass Transf.* **2010**, *37*, 644–651. [[CrossRef](#)]
13. Murugesan, P.; Mayilsamy, K.; Suresh, S.; Srinivasan, P.S.S. Heat transfer and pressure drop characteristics in a circular tube fitted with and without V-cut twisted tape insert. *Int. Commun. Heat Mass Transf.* **2011**, *38*, 329–334. [[CrossRef](#)]
14. Webb, R.L.; Kim, N.-H. *Principles of Enhanced Heat Transfer*, 2nd ed.; Taylor & Francis: New York, NY, USA, 2004.
15. Jin, Z.; Liu, B.; Chen, F.; Gao, Z.; Gao, X.; Qian, J. CFD analysis on flow resistance characteristics of six-start spirally corrugated tube. *Int. J. Heat Mass Transf.* **2016**, *103*, 1198–1207. [[CrossRef](#)]
16. Yu, W.; France, D.M.; Timofeeva, E.V.; Singh, D.; Routbort, J.L. Comparative review of turbulent heat transfer of nanofluids. *Int. J. Heat Mass Transf.* **2012**, *55*, 5380–5396. [[CrossRef](#)]
17. Vajjha, R.S.; Das, D.K. A review and analysis on influence of temperature and concentration of nanofluids on thermophysical properties, heat transfer and pumping power. *Int. J. Heat Mass Transf.* **2012**, *55*, 4063–4078. [[CrossRef](#)]
18. Hasanpour, A.; Farhadi, M.; Sedighi, K. A review study on twisted tape inserts on turbulent flow heat exchangers: The overall enhancement ratio criteria. *Int. Commun. Heat Mass Transf.* **2014**, *55*, 53–62. [[CrossRef](#)]
19. Zhang, J.; Zhu, X.; Mondejar, M.E.; Haglind, F. A review of heat transfer enhancement techniques in plate heat exchangers. *Renew. Sustain. Energy Rev.* **2019**, *101*, 305–328. [[CrossRef](#)]
20. Huang, C.; Cai, W.; Wang, Y.; Liu, Y.; Li, Q.; Li, B. Review on the characteristics of flow and heat transfer in printed circuit heat exchangers. *Appl. Therm. Eng.* **2019**, *153*, 190–205. [[CrossRef](#)]
21. Ma, Y.; Xie, G.; Hooman, K. Review of printed circuit heat exchangers and its applications in solar thermal energy. *Renew. Sustain. Energy Rev.* **2022**, *155*, 111933. [[CrossRef](#)]
22. Prabhakara Rao, B.; Krishna Kumar, P.; Das, S.K. Effect of flow distribution to the channels on the thermal performance of a plate heat exchanger. *Chem. Eng. Process. Process Intensif.* **2002**, *41*, 49–58. [[CrossRef](#)]
23. Gut, J.A.W.; Pinto, J.M. Modeling of plate heat exchangers with generalized configurations. *Int. J. Heat Mass Transf.* **2003**, *46*, 2571–2585. [[CrossRef](#)]
24. Zheng, D.; Wang, J.; Chen, Z.; Baleta, J.; Sunden, B. Performance analysis of a plate heat exchanger using various nanofluids. *Int. J. Heat Mass Transf.* **2020**, *158*, 119993. [[CrossRef](#)]
25. Hu, H.; Li, J. Experimental investigation on heat transfer characteristics of two-phase flow boiling in offset strip fin channels of plate-fin heat exchangers. *Appl. Therm. Eng.* **2021**, *185*, 116404. [[CrossRef](#)]
26. Pelanconi, M.; Zavattoni, S.; Cornolti, L.; Puragliesi, R.; Arrivabeni, E.; Ferrari, L.; Gianella, S.; Barbato, M.; Ortona, A. Application of Ceramic Lattice Structures to Design Compact, High Temperature Heat Exchangers: Material and Architecture Selection. *Materials* **2021**, *14*, 3225. [[CrossRef](#)] [[PubMed](#)]
27. Durmus, A.; Benli, H.; Kurtbas, I.; Gul, H. Investigation of heat transfer and pressure drop in plate heat exchangers having different surface profiles. *Int. J. Heat Mass Transf.* **2009**, *52*, 1451–1457. [[CrossRef](#)]
28. Khoshvaght-Aliabadi, M. Thermal performance of plate-fin heat exchanger using passive techniques: Vortex-generator and nanofluid. *Heat Mass Transf.* **2016**, *52*, 819–828. [[CrossRef](#)]
29. Sparrow, E.M.; Hossfeld, L.M. Effect of rounding of protruding edges on heat transfer and pressure drop in a duct. *Int. J. Heat Mass Transf.* **1984**, *27*, 1715–1723. [[CrossRef](#)]
30. Fabbri, G. Heat transfer optimization in corrugated wall channels. *Int. J. Heat Mass Transf.* **2000**, *43*, 4299–4310. [[CrossRef](#)]
31. Outokesh, M.; Ajarostaghi, S.S.M.; Bozorgzadeh, A.; Sedighi, K. Numerical evaluation of the effect of utilizing twisted tape with curved profile as a turbulator on heat transfer enhancement in a pipe. *J. Therm. Anal. Calorim.* **2020**, *140*, 1537–1553. [[CrossRef](#)]

32. Saleh, B.; Sundar, L.S. Experimental study on heat transfer, friction factor, entropy and exergy efficiency analyses of a corrugated plate heat exchanger using Ni/water nanofluids. *Int. J. Therm. Sci.* **2021**, *165*, 106935. [[CrossRef](#)]
33. Kumar, A.; Prasad, B.N. Investigation of twisted tape inserted solar water heaters—heat transfer, friction factor and thermal performance results. *Renew. Energy* **2000**, *19*, 379–398. [[CrossRef](#)]
34. Jaisankar, S.; Radhakrishnan, T.K.; Sheeba, K.N. Experimental studies on heat transfer and thermal performance characteristics of thermosyphon solar water heating system with helical and Left-Right twisted tapes. *Energy Convers. Manag.* **2011**, *52*, 2048–2055. [[CrossRef](#)]
35. Sarada, S.N.; Raju, A.S.R.; Radha, K.K.; Sunder, L.S. Enhancement of heat transfer using varying width twisted tape inserts. *Int. J. Eng. Sci. Technol.* **2010**, *2*, 107–118. [[CrossRef](#)]
36. Eiamsa-ard, S.; Wongcharee, K.; Eiamsa-ard, P.; Thianpong, C. Thermohydraulic investigation of turbulent flow through a round tube equipped with twisted tapes consisting of centre wings and alternate-axes. *Exp. Therm. Fluid Sci.* **2010**, *34*, 1151–1161. [[CrossRef](#)]
37. Ibrahim, E.Z. Augmentation of laminar flow and heat transfer in flat tubes by means of helical screw-tape inserts. *Energy Convers. Manag.* **2011**, *52*, 250–257. [[CrossRef](#)]
38. Wang, Y.; Liu, C.; Zhai, Y.; Li, Z.; Wang, H. Photothermal MCRT-FVM coupling simulation of an ET-CPC collector equipped with wall-separated twisted tapes in the transitional flow regime. *Int. J. Therm. Sci.* **2026**, *226*, 110856. [[CrossRef](#)]
39. Hosseinalipour, S.M.; Rostami, A.; Shahriari, G. Numerical study of circumferential temperature difference reduction at the absorber tube of parabolic trough direct steam generation collector by inserting a twisted tape in superheated region. *Case Stud. Therm. Eng.* **2020**, *21*, 100720. [[CrossRef](#)]
40. Eiamsa-ard, S.; Wongcharee, K.; Sripattanapipat, S. 3-D Numerical simulation of swirling flow and convective heat transfer in a circular tube induced by means of loose-fit twisted tapes. *Int. Commun. Heat Mass Transf.* **2009**, *36*, 947–955. [[CrossRef](#)]
41. Keklikcioglu, O.; Gunes, S.; Akcadirci, E.; Ozceyhan, V. An experimental study on heat transfer intensification by loose-fit twisted tapes with trapezoidal wings. *Heat Transf. Res.* **2022**, *53*, 39–55. [[CrossRef](#)]
42. Dalkılıç, A.S.; Uluç, B.; Celtek, M.S.; Celen, A.; Jumpholkul, C.; Newaz, K.S.; Wongwises, S. Single phase flow heat transfer characteristics of quad-channel twisted tape inserts in tubes. *Int. Commun. Heat Mass Transf.* **2020**, *118*, 104835. [[CrossRef](#)]
43. Sontakke, S.; Patel, P.; Sharma, A.; Singh, M.; Hardik, B.K. Experimental and numerical investigation of heat transfer enhancement with twisted tape insert. *Heat Transf. Res.* **2023**, *54*, 17–42. [[CrossRef](#)]
44. H.M., S.M.; Hegde, R.N. Investigations on the effect of disturbed flow using differently configured turbulators and Alumina nanofluid as a coolant in a double tube heat exchanger. *Exp. Heat Transf.* **2022**, *35*, 282–307. [[CrossRef](#)]
45. Dhumal, G.S.; Havaldar, S.N. Enhancing heat transfer performance in a double tube heat exchanger: Experimental study with twisted and helical tapes. *Case Stud. Therm. Eng.* **2023**, *51*, 103613. [[CrossRef](#)]
46. Eiamsa-ard, S.; Wongcharee, K. Convective heat transfer enhancement using Ag-water nanofluid in a micro-fin tube combined with non-uniform twisted tape. *Int. J. Mech. Sci.* **2018**, *146–147*, 337–354. [[CrossRef](#)]
47. Murthy, H.M.S.; Hegde, R.N. Investigations on thermal characteristics in a double pipe fitted with circular finned and frequently spaced helical twisted inserts and Graphene oxide nanofluid. *Heat Mass Transf.-Und Stoffuebertragung* **2020**, *56*, 2667–2679. [[CrossRef](#)]
48. Eiamsa-ard, S.; Wongcharee, K.; Eiamsa-ard, P.; Thianpong, C. Heat transfer enhancement in a tube using delta-winglet twisted tape inserts. *Appl. Therm. Eng.* **2010**, *30*, 310–318. [[CrossRef](#)]
49. Bizuneh, Y.E.; Kassie, T.D.; Gebresilassie, E.B.; Bizuneh, A.E. Numerical investigation on heat transfer of CuO-water nano-fluid in a circular pipe with twisted tape inserts. *Int. J. Thermofluids* **2025**, *27*, 101260. [[CrossRef](#)]
50. Kumar, P.; Sarviya, R.M. Experimental investigation on effect of perforated double V-cut twisted tape on thermo-hydraulic characteristics of heat exchanger tube. *Energy Sources Part A Recovery Util. Environ. Eff.* **2024**, *46*, 3228–3244. [[CrossRef](#)]
51. Harish, V.H.; Manjunath, K. Heat and fluid flow behaviors in a laminar tube flow with circular protruded twisted tape inserts. *Case Stud. Therm. Eng.* **2022**, *32*, 101880. [[CrossRef](#)]
52. Salman, S.D.; Kadhum, A.A.H.; Takriff, M.S.; Mohamad, A.B. Comparative studies on thermal performance of conic cut twist tape inserts with SiO₂ and TiO₂ nanofluids. *J. Nanomater.* **2015**, *2015*, 921394. [[CrossRef](#)]
53. Singh, M.; Kumar, A.; Kumar, A. Experimental thermal analysis of heat exchanger tube equipped with triangular perforated nail-head twisted tape inserts under turbulent flow regime. *Therm. Sci. Eng. Prog.* **2025**, *68*, 104252. [[CrossRef](#)]
54. Suseel Jai Krishnan, S.; Nagarajan, P.K. Convective performance and particle effect analysis on aqua-antifreeze based oxomagnesium nanofluids while flowing through a micro-fin tube with twisted tapes. *J. Therm. Anal. Calorim.* **2019**, *138*, 1175–1191. [[CrossRef](#)]
55. Ashnaaf Abajja, K.M.; Selimli, S.; Abdullah Shaneb, A.M.; Eljetlawi, I.A.M. Enhancing heat transfer for laminar flow in heat pipes using perforated and jagged-edged twisted tapes: An experimental study. *Energy* **2025**, *325*, 136141. [[CrossRef](#)]
56. Patel, B.V. Improving hydrothermal performance of a tubular heat exchanger with different types of twisted tapes using graphene nanoplatelets/water nanofluid. *Energy Sources Part A Recovery Util. Environ. Eff.* **2023**, *45*, 12695–12710. [[CrossRef](#)]

57. Hazbehian, M.; Maddah, H.; Mohammadiun, H.; Alizadeh, M. Experimental investigation of heat transfer augmentation inside double pipe heat exchanger equipped with reduced width twisted tapes inserts using polymeric nanofluid. *Heat Mass Transf.-Und Stoffuebertragung* **2016**, *52*, 2515–2529. [[CrossRef](#)]
58. Ponnada, S.; Subrahmanyam, T.; Naidu, S.V. A comparative study on the thermal performance of water in a circular tube with twisted tapes, perforated twisted tapes and perforated twisted tapes with alternate axis. *Int. J. Therm. Sci.* **2019**, *136*, 530–538. [[CrossRef](#)]
59. Rezaei Miandoab, A.; Bagherzadeh, S.A.; Meghdadi Isfahani, A.H. Numerical study of the effects of twisted-tape inserts on heat transfer parameters and pressure drop across a tube carrying Graphene Oxide nanofluid: An optimization by implementation of Artificial Neural Network and Genetic Algorithm. *Eng. Anal. Bound. Elem.* **2022**, *140*, 1–11. [[CrossRef](#)]
60. Kumar, J.; Afzal, M.S. Performance evaluation of a double-pipe heat exchanger using plain and rectangular-cut multi-channel twisted tapes. *Int. J. Therm. Sci.* **2025**, *215*, 109994. [[CrossRef](#)]
61. Wongcharee, K.; Eiamsa-ard, S. Friction and heat transfer characteristics of laminar swirl flow through the round tubes inserted with alternate clockwise and counter-clockwise twisted-tapes. *Int. Commun. Heat Mass Transf.* **2011**, *38*, 348–352. [[CrossRef](#)]
62. Yadav, R.J.; Mahajani, T.; Kore, S.S.; Gadhe, P.M.; Kamble, D.A. Investigation of heat transfer characteristics using Fe₃O₄ nanofluid along with TT inserts in tube with uniform electromagnetic field. *Appl. Nanosci.* **2023**, *13*, 763–785. [[CrossRef](#)]
63. Reddy, G.S.; Kalaivanan, R.; Uday Kumar, R.; Jadhav, P.H. Influence of W-cut twisted tape inserts on heat transfer characteristics of a counter flow heat exchanger using CeO₂ nanofluid—an experimental and numerical investigations. *Numer. Heat Transf. Part A Appl.* **2025**, *86*, 8425–8445. [[CrossRef](#)]
64. Rajan, A.; Kumar, S.; Kumar, V.; Hazra, S.K. Perforated-cut twisted tapes for enhanced laminar flow heat transfer in bio-mechanics applications. *Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci.* **2026**, *240*, 250–263. [[CrossRef](#)]
65. Lin, J.H.; Huang, C.Y.; Su, C.C. Dimensional analysis for the heat transfer characteristics in the corrugated channels of plate heat exchangers. *Int. Commun. Heat Mass Transf.* **2007**, *34*, 304–312. [[CrossRef](#)]
66. Nguyen, C.T.; Desgranges, F.; Roy, G.; Galanis, N.; Mare, T.; Boucher, S.; Angue Mintsu, H. Temperature and particle-size dependent viscosity data for water-based nanofluids—Hysteresis phenomenon. *Int. J. Heat Fluid Flow* **2007**, *28*, 1492–1506. [[CrossRef](#)]
67. Aghayari, R.; Madah, H.; Keyvani, B.; Moghadassi, A.; Ashori, F. The Effect of Nanoparticles on Thermal Efficiency of Double Tube Heat Exchangers in Turbulent Flow. *ISRN Mech. Eng.* **2014**, *2014*, e274560. [[CrossRef](#)]
68. Zhou, S.-Q.; Ni, R. Measurement of the specific heat capacity of water-based Al₂O₃ nanofluid. *Appl. Phys. Lett.* **2008**, *92*, 093123. [[CrossRef](#)]
69. Pandey, S.D.; Nema, V.K. Experimental analysis of heat transfer and friction factor of nanofluid as a coolant in a corrugated plate heat exchanger. *Exp. Therm. Fluid Sci.* **2012**, *38*, 248–256. [[CrossRef](#)]
70. Kulkarni, D.P.; Vajjha, R.S.; Das, D.K.; Oliva, D. Application of aluminum oxide nanofluids in diesel electric generator as jacket water coolant. *Appl. Therm. Eng.* **2008**, *28*, 1774–1781. [[CrossRef](#)]
71. Lee, J.-H.; Hwang, K.S.; Jang, S.P.; Lee, B.H.; Kim, J.H.; Choi, S.U.S.; Choi, C.J. Effective viscosities and thermal conductivities of aqueous nanofluids containing low volume concentrations of Al₂O₃ nanoparticles. *Int. J. Heat Mass Transf.* **2008**, *51*, 2651–2656. [[CrossRef](#)]
72. Heidary, H.; Kermani, M.J. Effect of nano-particles on forced convection in sinusoidal-wall channel. *Int. Commun. Heat Mass Transf.* **2010**, *37*, 1520–1527. [[CrossRef](#)]
73. Khoshvaght-Aliabadi, M.; Hormozi, F.; Zamzamian, A. Effects of geometrical parameters on performance of plate-fin heat exchanger: Vortex-generator as core surface and nanofluid as working media. *Appl. Therm. Eng.* **2014**, *70*, 565–579. [[CrossRef](#)]
74. Arqam, M.; Usmani, S.; Aberoumand, S.; Kumar, V. Recent Advancements in PEM Fuel Cell Technologies for Electrified Transportation [WWW Document]. In *Developing Charging Infrastructure and Technologies for Electric Vehicles*; IGI Global Scientific Publishing: Hershey, PA, USA, 2022. [[CrossRef](#)]
75. Garrick, S.C. Effects of Turbulent Fluctuations on Nanoparticle Coagulation in Shear Flows. *Aerosol Sci. Technol.* **2011**, *45*, 1272–1285. [[CrossRef](#)]
76. Usmani, S. Modelling of a Low Emission Thermally Integrated Gasifier for Clean Gas Production from Agricultural and Forestry Residues. Ph.D. Thesis, University of Technology Sydney, Ultimo, Australia, 2020.
77. Elias, M.M.; Mahbubul, I.M.; Saidur, R.; Sohel, M.R.; Shahrul, I.M.; Khaleduzzaman, S.S.; Sadeghipour, S. Experimental investigation on the thermo-physical properties of Al₂O₃ nanoparticles suspended in car radiator coolant. *Int. Commun. Heat Mass Transf.* **2014**, *54*, 48–53. [[CrossRef](#)]
78. Sonawane, S.; Patankar, K.; Fogla, A.; Puranik, B.; Bhandarkar, U.; Sunil Kumar, S. An experimental investigation of thermo-physical properties and heat transfer performance of Al₂O₃-Aviation Turbine Fuel nanofluids. *Appl. Therm. Eng.* **2011**, *31*, 2841–2849. [[CrossRef](#)]
79. Namburu, P.K.; Kulkarni, D.P.; Dandekar, A.; Das, D.K. Experimental investigation of viscosity and specific heat of silicon dioxide nanofluids. *Micro Nano Lett.* **2007**, *2*, 67–71. [[CrossRef](#)]

80. Starace, A.K.; Gomez, J.C.; Wang, J.; Pradhan, S.; Glatzmaier, G.C. Nanofluid heat capacities. *J. Appl. Phys.* **2011**, *110*, 124323. [[CrossRef](#)]
81. Pantzali, M.N.; Kanaris, A.G.; Antoniadis, K.D.; Mouza, A.A.; Paras, S.V. Effect of nanofluids on the performance of a miniature plate heat exchanger with modulated surface. *Int. J. Heat Fluid Flow* **2009**, *30*, 691–699. [[CrossRef](#)]
82. Pak, B.C.; Cho, Y.I. Hydrodynamic and heat transfer study of dispersed fluids with submicron metallic oxide particles. *Exp. Heat Transf.* **1998**, *11*, 151–170. [[CrossRef](#)]
83. He, Q.; Wang, S.; Tong, M.; Liu, Y. Experimental study on thermophysical properties of nanofluids as phase-change material (PCM) in low temperature cool storage. *Energy Convers. Manag. IREC 2011 Int. Renew. Energy Congr.* **2012**, *64*, 199–205. [[CrossRef](#)]
84. Murshed, S.M.S.; Leong, K.C.; Yang, C. Investigations of thermal conductivity and viscosity of nanofluids. *Int. J. Therm. Sci.* **2008**, *47*, 560–568. [[CrossRef](#)]
85. Masuda, H.; Ebata, A.; Teramae, K.; Hishinuma, N. Alteration of Thermal Conductivity and Viscosity of Liquid by Dispersing Ultra-Fine Particles. Dispersion of Al_2O_3 , SiO_2 and TiO_2 Ultra-Fine Particles. *Jpn. J. Thermophys. Prop.* **1993**, *7*, 227–233. [[CrossRef](#)]
86. Chen, H.; Ding, Y.; He, Y.; Tan, C. Rheological behaviour of ethylene glycol based titania nanofluids. *Chem. Phys. Lett.* **2007**, *444*, 333–337. [[CrossRef](#)]
87. Duangthongsuk, W.; Wongwises, S. Measurement of temperature-dependent thermal conductivity and viscosity of TiO_2 -water nanofluids. *Exp. Therm. Fluid Sci.* **2009**, *33*, 706–714. [[CrossRef](#)]
88. Chevalier, J.; Tillement, O.; Ayela, F. Rheological properties of nanofluids flowing through microchannels. *Appl. Phys. Lett.* **2007**, *91*, 233103. [[CrossRef](#)]
89. Shima, P.D.; Philip, J.; Raj, B. Influence of aggregation on thermal conductivity in stable and unstable nanofluids. *Appl. Phys. Lett.* **2010**, *97*, 153113. [[CrossRef](#)]
90. Wang, X.; Xu, X.; Choi, S.U.S. Thermal Conductivity of Nanoparticle—Fluid Mixture. *J. Thermophys. Heat Transf.* **1999**, *13*, 474–480. [[CrossRef](#)] [[PubMed](#)]
91. Chandrasekar, M.; Suresh, S.; Chandra Bose, A. Experimental investigations and theoretical determination of thermal conductivity and viscosity of Al_2O_3 /water nanofluid. *Exp. Therm. Fluid Sci.* **2010**, *34*, 210–216. [[CrossRef](#)]
92. Chon, C.H.; Kihm, K.D.; Lee, S.P.; Choi, S.U.S. Empirical correlation finding the role of temperature and particle size for nanofluid (Al_2O_3) thermal conductivity enhancement. *Appl. Phys. Lett.* **2005**, *87*, 153107. [[CrossRef](#)]
93. Kang, H.U.; Kim, S.H.; Oh, J.M. Estimation of Thermal Conductivity of Nanofluid Using Experimental Effective Particle Volume. *Exp. Heat Transf.* **2006**, *19*, 181–191. [[CrossRef](#)]
94. Lee, S.; Choi, S.U.-S.; Li, S.; Eastman, J.A. Measuring Thermal Conductivity of Fluids Containing Oxide Nanoparticles. *J. Heat Transf.* **1999**, *121*, 280–289. [[CrossRef](#)]
95. Das, S.K.; Putra, N.; Thiesen, P.; Roetzel, W. Temperature Dependence of Thermal Conductivity Enhancement for Nanofluids. *J. Heat Transf.* **2003**, *125*, 567–574. [[CrossRef](#)]
96. Li, C.H.; Peterson, G.P. Experimental investigation of temperature and volume fraction variations on the effective thermal conductivity of nanoparticle suspensions (nanofluids). *J. Appl. Phys.* **2006**, *99*, 084314. [[CrossRef](#)]
97. Zhang, X.; Gu, H.; Fujii, M. Experimental Study on the Effective Thermal Conductivity and Thermal Diffusivity of Nanofluids. *Int. J. Thermophys.* **2006**, *27*, 569–580. [[CrossRef](#)]
98. Yiamsawasd, T.; Dalkilic, A.S.; Wongwises, S. Measurement of the thermal conductivity of titania and alumina nanofluids. *Thermochim. Acta* **2012**, *545*, 48–56. [[CrossRef](#)]
99. Murshed, S.M.S.; Leong, K.C.; Yang, C. Enhanced thermal conductivity of TiO_2 -water based nanofluids. *Int. J. Therm. Sci.* **2005**, *44*, 367–373. [[CrossRef](#)]
100. Cao, Y.; Ayed, H.; Anqi, A.E.; Tutunchian, O.; Dizaji, H.S.; Pourhedayat, S. Helical tube-in-tube heat exchanger with corrugated inner tube and corrugated outer tube; experimental and numerical study. *Int. J. Therm. Sci.* **2021**, *170*, 107139. [[CrossRef](#)]
101. Begag, A.; Saim, R.; Abboudi, S.; Oztop, H.F. Effect of internal and external corrugated surfaces on the characteristics of heat transfer and pressure drop in a concentric tube heat exchanger. *Int. J. Therm. Sci.* **2021**, *165*, 106930. [[CrossRef](#)]
102. Han, S.W.; Woo, Y.Y.; Lee, T.; Kim, J.; Jeong, J.H.; Moon, Y.H. Manufacturing of a corrugated double-layered tube for the high-performance compact heat exchanger. *Int. J. Adv. Manuf. Technol.* **2021**, *112*, 2065–2080. [[CrossRef](#)]
103. Gurel, B. Thermal performance evaluation for solidification process of latent heat thermal energy storage in a corrugated plate heat exchanger. *Appl. Therm. Eng.* **2020**, *174*, 115312. [[CrossRef](#)]
104. Buscher, S. Visualization and modelling of flow pattern transitions in a cross-corrugated plate heat exchanger channel with uniform two-phase distribution. *Int. J. Heat Mass Transf.* **2019**, *144*, 118643. [[CrossRef](#)]
105. Rostami, S.; Ahmadi, N.; Khorasani, S. Experimental investigations of thermo-exergitic behavior of a four-start helically corrugated heat exchanger with air/water two-phase flow. *Int. J. Therm. Sci.* **2019**, *145*, 106030. [[CrossRef](#)]

106. Moya-Rico, J.D.; Molina, A.E.; Belmonte, J.F.; Corcoles Tendero, J.I.; Almendros-Ibanez, J.A. Characterization of a triple concentric-tube heat exchanger with corrugated tubes using Artificial Neural Networks (ANN). *Appl. Therm. Eng.* **2019**, *147*, 1036–1046. [[CrossRef](#)]
107. Akbarzadeh, M.; Maghrebi, M.J. Combined effects of corrugated walls and porous inserts on performance improvement in a heat exchanger channel. *Int. J. Therm. Sci.* **2018**, *127*, 266–276. [[CrossRef](#)]
108. Abbasian Arani, A.A.; Moradi, R. Shell and tube heat exchanger thermal-hydraulic analysis equipped with baffles and corrugated tubes filled with non-Newtonian two-phase nanofluid. *Int. J. Numer. Methods Heat Fluid Flow* **2021**, *31*, 1214–1244. [[CrossRef](#)]
109. Chaoui, A.; Bouzid, S.; Aidi, M.; Harnane, Y.; Poos, T. Heat Transfer Enhancement in Shell-and-Tube Heat Exchangers with Sinusoidal Tubes and Modified Baffles. *Heat Transf. Eng.* **2025**, 1–19. [[CrossRef](#)]
110. Wang, G.; Qi, C.; Liu, M.; Li, C.; Yan, Y.; Liang, L. Effect of corrugation pitch on thermo-hydraulic performance of nanofluids in corrugated tubes of heat exchanger system based on exergy efficiency. *Energy Convers. Manag.* **2019**, *186*, 51–65. [[CrossRef](#)]
111. Asadi, A.; Zabolli, M.; Mogharrebi, A.R.; Saedodin, S.; Ganji, D.D. Numerical analysis of turbulence-inducing elements with various geometries and utilization of hybrid nanoparticles in a double pipe heat exchanger. *Alex. Eng. J.* **2022**, *61*, 3633–3644. [[CrossRef](#)]
112. Said, Z.; Rahman, S.M.A.; El Haj Assad, M.; Alami, A.H. Heat transfer enhancement and life cycle analysis of a Shell-and-Tube Heat Exchanger using stable CuO/water nanofluid. *Sustain. Energy Technol. Assess.* **2019**, *31*, 306–317. [[CrossRef](#)]
113. Painuly, A.; Mishra, N.K.; Zainith, P. Thermo-hydraulic performance evaluation and comparison of SiC-MWCNT and Al₂O₃-MWCNT non-Newtonian hybrid nanofluids using a heat exchanger equipped with helically corrugated tubes: An experimental study. *J. Therm. Anal. Calorim.* **2024**, *149*, 3965–3980. [[CrossRef](#)]
114. Anbu, S.; Arunkumar, P.; Kamatchi, R.; Chellappan, M. Investigation of convective heat transfer in helically corrugated tubes with inserts using nanofluids. *J. Therm. Anal. Calorim.* **2025**, *150*, 3403–3420. [[CrossRef](#)]
115. Vijayaragavan, B.; Asok, S.P.; Shakthi Ganesh, C.R. Heat transfer characteristics of double pipe heat exchanger having externally enhanced inner pipe. *Acta Polytech.* **2023**, *63*, 65–74. [[CrossRef](#)]
116. Qian, S.; Yu, J.; Yan, G. A review of regenerative heat exchange methods for various cooling technologies. *Renew. Sustain. Energy Rev.* **2017**, *69*, 535–550. [[CrossRef](#)]
117. Bejan, A.; Alalaimi, M.; Lorente, S.; Sabau, A.S.; Klett, J.W. Counterflow heat exchanger with core and plenums at both ends. *Int. J. Heat Mass Transf.* **2016**, *99*, 622–629. [[CrossRef](#)]
118. Albrecht, K.J.; Ho, C.K. Design and operating considerations for a shell-and-plate, moving packed-bed, particle-to-sCO₂ heat exchanger. *Sol. Energy* **2019**, *178*, 331–340. [[CrossRef](#)]
119. Piroozfam, N.; Hosseinpour Shafaghi, A.; Razavi, S.E. Numerical investigation of three methods for improving heat transfer in counter-flow heat exchangers. *Int. J. Therm. Sci.* **2018**, *133*, 230–239. [[CrossRef](#)]
120. Verma, T.N.; Nashine, P.; Singh, D.V.; Singh, T.S.; Panwar, D. ANN: Prediction of an experimental heat transfer analysis of concentric tube heat exchanger with corrugated inner tubes. *Appl. Therm. Eng.* **2017**, *120*, 219–227. [[CrossRef](#)]
121. Gorman, J.M.; Krautbauer, K.R.; Sparrow, E.M. Thermal and fluid flow first-principles numerical design of an enhanced double pipe heat exchanger. *Appl. Therm. Eng.* **2016**, *107*, 194–206. [[CrossRef](#)]
122. Gomaa, A.; Halim, M.A.; Elsaid, A.M. Experimental and numerical investigations of a triple concentric-tube heat exchanger. *Appl. Therm. Eng.* **2016**, *99*, 1303–1315. [[CrossRef](#)]
123. Quadir, G.A.; Badruddin, I.A.; Salman Ahmed, N.J. Numerical investigation of the performance of a triple concentric pipe heat exchanger. *Int. J. Heat Mass Transf.* **2014**, *75*, 165–172. [[CrossRef](#)]
124. Ali, L.F.; AL-Samarraie, S.A.; Humaidi, A.J. Performance of Double Pipe Heat Exchanger–Partially Occupied by Metal Foam–Is Better Enhanced Using Robust Adaptive Barrier Function-Based Sliding Mode Control. *Energies* **2025**, *18*, 4671. [[CrossRef](#)]
125. Gao, T.; Sammakia, B.; Geer, J. Dynamic response and control analysis of cross flow heat exchangers under variable temperature and flow rate conditions. *Int. J. Heat Mass Transf.* **2015**, *81*, 542–553. [[CrossRef](#)]
126. Sheikholeslami, M.; Ganji, D.D. Heat transfer improvement in a double pipe heat exchanger by means of perforated turbulators. *Energy Convers. Manag.* **2016**, *127*, 112–123. [[CrossRef](#)]
127. Wais, P. Influence of fin thickness and winglet orientation on mass and thermal efficiency of cross-flow heat exchanger. *Appl. Therm. Eng.* **2016**, *102*, 184–195. [[CrossRef](#)]
128. Soleimanikutanaei, S.; Lin, C.X.; Wang, D. Modeling and simulation of cross-flow transport membrane condenser heat exchangers. *Int. Commun. Heat Mass Transf.* **2018**, *95*, 92–97. [[CrossRef](#)]
129. Templeton, J.D.; Hassani, F.; Ghoreishi-Madiseh, S.A. Study of effective solar energy storage using a double pipe geothermal heat exchanger. *Renew. Energy* **2016**, *86*, 173–181. [[CrossRef](#)]
130. Naphon, P. Heat transfer and pressure drop in the horizontal double pipes with and without twisted tape insert. *Int. Commun. Heat Mass Transf.* **2006**, *33*, 166–175. [[CrossRef](#)]
131. Singh Yadav, A. Effect of Half Length Twisted-Tape Turbulators on Heat Transfer and Pressure Drop Characteristics inside a Double Pipe U-Bend Heat Exchanger. *Jordan J. Mech. Ind. Eng.* **2009**, *3*, 17–22.

132. Akpınar, E.K. Evaluation of heat transfer and exergy loss in a concentric double pipe exchanger equipped with helical wires. *Energy Convers. Manag.* **2006**, *47*, 3473–3486. [[CrossRef](#)]
133. Taborek, J. Double-Pipe and Multitube Heat Exchangers with Plain and Longitudinal Finned Tubes. *Heat Transf. Eng.* **1997**, *18*, 34–45. [[CrossRef](#)]
134. Assaf, Y.H.; Akroot, A.; Alnamasi, K.; Ismail, M.A. Investigation of heat transfer performance in heat exchangers using hybrid nanofluids and twisted tape inserts with fixed special rings. *Sci. Rep.* **2025**, *15*, 18450. [[CrossRef](#)] [[PubMed](#)]
135. Marzouk, S.A.; Aljabr, A.; Almeahadi, F.A.; Sharaf, M.A. Enhancing heat transfer in a double-tube heat exchanger using perforated twisted tape and nanofluid. *J. Therm. Anal. Calorim.* **2025**, *150*, 3719–3733. [[CrossRef](#)]
136. Marzouk, S.A.; Almeahadi, F.A.; Aljabr, A.; Kaoood, A. Performance analysis of twisted tape inserts and nanofluids in double-pipe helical coil heat exchangers. *J. Therm. Anal. Calorim.* **2025**, *150*, 11197–11211. [[CrossRef](#)]
137. Ahirwar, B.K.; Kumar, A. An in-depth numerical and experimental analysis of wire coil inserts: Enhancing thermal performance and fluid flow characteristics in double pipe heat exchangers. *J. Therm. Anal. Calorim.* **2024**, *149*, 14057–14081. [[CrossRef](#)]
138. Kadhim, S.A.; Hammoodi, K.A.; Ashour, A.M.; Bouabidi, A.; Sathyamurthy, R.; Abd, H.S.; Hussein, A.K.; Rashid, F.L.; Togun, H. Intensification of double-tube heat exchangers performance by modified twisted tapes: Review perforated and dimpled/baffled twisted tape techniques. *J. Therm. Anal. Calorim.* **2025**, *150*, 17157–17184. [[CrossRef](#)]
139. Xu, H.; Duan, C.; Ding, H.; Li, W.; Zhang, Y.; Hong, G.; Gong, H. The optimization for the straight-channel PCHE size for supercritical CO₂ Brayton cycle. *Nucl. Eng. Technol.* **2021**, *53*, 1786–1795. [[CrossRef](#)]
140. Ji, Y.; Xing, K.; Cen, K.; Ni, M.; Xu, H.; Xiao, G. Numerical Study on Flow and Heat Transfer Characteristics of Trapezoidal Printed Circuit Heat Exchanger. *Micromachines* **2021**, *12*, 1589. [[CrossRef](#)] [[PubMed](#)]
141. Kim, I.H.; No, H.C.; Lee, J.I.; Jeon, B.G. Thermal hydraulic performance analysis of the printed circuit heat exchanger using a helium test facility and CFD simulations. *Nucl. Eng. Des.* **2009**, *239*, 2399–2408. [[CrossRef](#)]
142. Ngo, T.L.; Kato, Y.; Nikitin, K.; Tsuzuki, N. New printed circuit heat exchanger with S-shaped fins for hot water supplier. *Exp. Therm. Fluid Sci.* **2006**, *30*, 811–819. [[CrossRef](#)]
143. Ngo, T.L.; Kato, Y.; Nikitin, K.; Ishizuka, T. Heat transfer and pressure drop correlations of microchannel heat exchangers with S-shaped and zigzag fins for carbon dioxide cycles. *Exp. Therm. Fluid Sci.* **2007**, *32*, 560–570. [[CrossRef](#)]
144. Tsuzuki, N.; Kato, Y.; Ishiduka, T. High performance printed circuit heat exchanger. *Appl. Therm. Eng.* **2007**, *27*, 1702–1707. [[CrossRef](#)]
145. Kim, D.E.; Kim, M.H.; Cha, J.E.; Kim, S.O. Numerical investigation on thermal-hydraulic performance of new printed circuit heat exchanger model. *Nucl. Eng. Des.* **2008**, *238*, 3269–3276. [[CrossRef](#)]
146. Aneesh, A.M.; Sharma, A.; Srivastava, A.; Chaudhury, P. Effects of wavy channel configurations on thermal-hydraulic characteristics of Printed Circuit Heat Exchanger (PCHE). *Int. J. Heat Mass Transf.* **2018**, *118*, 304–315. [[CrossRef](#)]
147. Cui, X.; Guo, J.; Huai, X.; Zhang, H.; Cheng, K.; Zhou, J. Numerical investigations on serpentine channel for supercritical CO₂ recuperator. *Energy* **2019**, *172*, 517–530. [[CrossRef](#)]
148. Aye, N.N.; Hemsuwan, W.; Uangpairaj, P.; Thumthae, C. Numerical investigation of zigzag bending-angle channel effects on thermal hydraulic performance of printed circuit heat exchanger. *J. Therm. Sci.* **2024**, *33*, 56–69. [[CrossRef](#)]
149. Ji, Y.; Wang, Z.; Wang, M.; Liu, Y.; Xu, H.; Zhu, P.; Ma, S.; Yang, Z.; Xiao, G. Experimental and numerical study on thermal hydraulic performance of trapezoidal printed circuit heat exchanger for supercritical CO₂ Brayton cycle. *Energies* **2022**, *15*, 4940. [[CrossRef](#)]
150. Fu, Q.; Ding, J.; Lao, J.; Wang, W.; Lu, J. Thermal-hydraulic performance of printed circuit heat exchanger with supercritical carbon dioxide airfoil fin passage and molten salt straight passage. *Appl. Energy* **2019**, *247*, 594–604. [[CrossRef](#)]
151. Ying, P.; He, Y.; Tang, H.; Ren, Y. Numerical and Experimental Investigation of Flow and Heat Transfer in Heat Exchanger Channels with Different Dimples Geometries. *Machines* **2021**, *9*, 72. [[CrossRef](#)]
152. Chilambarasan, L.; Vinoth, T.; Prakash, R. Solar flat plate collector's heat transfer enhancement using grooved tube configuration with alumina nanofluids: Prediction of outcomes through artificial neural network modeling. *Energy* **2024**, *289*, 129953. [[CrossRef](#)]
153. Kumar, A.; Singh, K.D.P.; Agrawal, R. Intensification of thermal characteristics of flat plate solar water heater using triangular perforated wavy tape. *Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci.* **2024**, *238*, 8838–8849. [[CrossRef](#)]
154. Singh, A.K.; Kumar, R. Multi-walled carbon nanotube nanofluids in solar flat plate collectors for advanced heat transfer solution. *J. Therm. Anal. Calorim.* **2025**, *150*, 13535–13549. [[CrossRef](#)]
155. Gaurav, K.; Verma, S.K. Critical review on thermal performance enhancement techniques for flat plate solar collectors. *Proc. Inst. Mech. Eng. Part E J. Process Mech. Eng.* **2024**, *240*, 1116–1144. [[CrossRef](#)]
156. Jeong, J.Y.; Hong, H.K.; Kim, S.K.; Kang, Y.T. Impact of plate design on the performance of welded type plate heat exchangers for sorption cycles. *Int. J. Refrig.* **2009**, *32*, 705–711. [[CrossRef](#)]
157. Villanueva, H.H.S.; De Mello, P.E.B. Heat transfer and pressure drop correlations for finned plate ceramic heat exchangers. *Energy* **2015**, *88*, 118–125. [[CrossRef](#)]

158. Doo, J.H.; Ha, M.Y.; Min, J.K.; Stieger, R.; Rolt, A.; Son, C. An investigation of cross-corrugated heat exchanger primary surfaces for advanced intercooled-cycle aero engines (Part-I: Novel geometry of primary surface). *Int. J. Heat Mass Transf.* **2012**, *55*, 5256–5267. [[CrossRef](#)]
159. Luan, Z.; Zhang, G.; Tian, M.; Fan, M. Flow Resistance and Heat Transfer Characteristics of a New-Type Plate Heat Exchanger. *J. Hydrodyn.* **2008**, *20*, 524–529. [[CrossRef](#)]
160. Karatutlu, Ö.; Genc, G. Experimental investigation of the effect of nanofluids on heat transfer in plate heat exchangers. *J. Therm. Anal. Calorim.* **2026**, *151*, 499–521. [[CrossRef](#)]
161. Alikhan, A.H.D.; Al-Ogaili, K.S.J.; Mery, H.O. Experimental Assessment of Plate Heat Exchanger Performance Enhancement by Compound Pulsating and Low Concentration CuO Nanoadditive Methods. *Int. J. Heat Technol.* **2025**, *43*, 428–436. [[CrossRef](#)]
162. Roueintan, H.; Fattahi, A. On the pillow-plate heat exchanger with wavy walls and filled with a hybrid nanofluid: Numerical simulation and data-assisted prediction. *Case Stud. Therm. Eng.* **2024**, *64*, 105495. [[CrossRef](#)]
163. Sundar, L.S.; Venkata, R.A. Enhanced effectiveness and thermal performance factor of nickel nanofluid flow in a plate heat exchanger. *J. Enhanc. Heat Transf.* **2022**, *29*, 61–92. [[CrossRef](#)]
164. Arya, H.; Sarafraz, M.M.; Arjomandi, M. Heat transfer and fluid flow of MgO/ethylene glycol in a corrugated heat exchanger. *J. Mech. Sci. Technol.* **2018**, *32*, 3975–3982. [[CrossRef](#)]
165. Khoshvaght-Aliabadi, M.; Tatari, M.; Salami, M. Analysis on Al₂O₃/water nanofluid flow in a channel by inserting corrugated/perforated fins for solar heating heat exchangers. *Renew. Energy* **2018**, *115*, 1099–1108. [[CrossRef](#)]
166. Singh, S.; Ghosh, S.K. Influence of chevron angle and MWCNT/distilled water nanofluid on the thermo-hydraulic performance of compact plate heat exchanger: An experimental and numerical study. *Powder Technol.* **2022**, *405*, 117515. [[CrossRef](#)]
167. Zhang, L.; Song, J.; Qu, P.; Wang, S.; Zhang, H.; Wang, H.; Liu, H.; Lu, T. Heat transfer performance study of Cu-ethanol/ethylene glycol/propylene glycol-water nanofluids in a wavy-walled tube heat exchanger. *J. Environ. Chem. Eng.* **2024**, *12*, 112738. [[CrossRef](#)]
168. Kabeel, A.E.; Abou El Maaty, T.; El Samadony, Y. The effect of using nano-particles on corrugated plate heat exchanger performance. *Appl. Therm. Eng.* **2013**, *52*, 221–229. [[CrossRef](#)]
169. Mehrarad, H.; Sarmasti Emami, M.R.; Afsari, K. Thermal performance and flow analysis in a brazed plate heat exchanger using MWCNT@water/EG nanofluid. *Int. Commun. Heat Mass Transf.* **2023**, *146*, 106867. [[CrossRef](#)]
170. Valizadeh Ardalan, M.; Alizadeh, R.; Ameri, A.; Alizadeh, A.; Mohammad Jafari, F. Influence of grooves geometric parameters on the nanofluid flow and thermal efficiency of Chevron plate heat exchangers. *Energy Sources Part A Recovery Util. Environ. Eff.* **2025**, *47*, 1832165. [[CrossRef](#)]
171. Unverdi, M.; Islamoglu, Y. Characteristics of heat transfer and pressure drop in a chevron-type plate heat exchanger with Al₂O₃-water nanofluids. *Therm. Sci.* **2017**, *21*, 2379–2391. [[CrossRef](#)]
172. Hassaan, A.M. An experimental investigation for the use of multi-wall carbon nanotubes based on water nanofluid in a plate heat exchanger. *Heat Transf. Res.* **2022**, *53*, 19–34. [[CrossRef](#)]
173. Alklaibi, A.M.; Mouli, K.V.V.C.; Sundar, L.S. Heat transfer, and friction factor of Fe₃O₄-SiO₂/Water hybrid nanofluids in a plate heat exchanger: Experimental and ANN predictions. *Int. J. Therm. Sci.* **2024**, *195*, 108608. [[CrossRef](#)]
174. Samadi Rikandeh, S.; Khaki Jamei, M.; Abbasi, M. Enhancing thermal efficiency through analysis of nano and hybrid nanofluids in pillow plate heat exchangers: A comprehensive study on optimization techniques and performance evaluation. *Numer. Heat Transf. Part A Appl.* **2026**, *87*, 2539983. [[CrossRef](#)]
175. Bhattad, A.; Sarkar, J.; Ghosh, P. Discrete phase numerical model and experimental study of hybrid nanofluid heat transfer and pressure drop in plate heat exchanger. *Int. Commun. Heat Mass Transf.* **2018**, *91*, 262–273. [[CrossRef](#)]
176. Kumar, V.; Tiwari, A.K.; Ghosh, S.K. Effect of variable spacing on performance of plate heat exchanger using nanofluids. *Energy* **2016**, *114*, 1107–1119. [[CrossRef](#)]
177. Bhattad, A.; Sarkar, J.; Ghosh, P. Energetic and Exergetic Performances of Plate Heat Exchanger Using Brine-Based Hybrid Nanofluid for Milk Chilling Application. *Heat Transf. Eng.* **2020**, *41*, 522–535. [[CrossRef](#)]
178. Bhattad, A. Better performance criteria for plate heat exchanger with hybrid nanofluid: Flow rate or concentration. *J. Therm. Anal. Calorim.* **2023**, *148*, 14295–14304. [[CrossRef](#)]
179. Bhattad, A.; Sarkar, J. Effects of nanoparticle shape and size on the thermohydraulic performance of plate evaporator using hybrid nanofluids. *J. Therm. Anal. Calorim.* **2021**, *143*, 767–779. [[CrossRef](#)]
180. Broumand, B.; Kosari Neia, A.; Ghafouri, A.; Nabhani, N. Experimental study of the effect of using hybrid graphene and titanium oxide nanofluids in corrugated plate heat exchanger. *Int. J. Therm. Sci.* **2025**, *218*, 110125. [[CrossRef](#)]
181. Huang, D.; Wu, Z.; Sunden, B. Effects of hybrid nanofluid mixture in plate heat exchangers. *Exp. Therm. Fluid Sci.* **2016**, *72*, 190–196. [[CrossRef](#)]
182. Returi, M.C.; Konijeti, R.; Dasore, A. Heat transfer enhancement using hybrid nanofluids in spiral plate heat exchangers. *Heat Transf.-Asian Res.* **2019**, *48*, 3128–3143. [[CrossRef](#)]

183. Bhattad, A.; Sarkar, J.; Ghosh, P. Hydrothermal performance of different alumina hybrid nanofluid types in plate heat exchanger: Experimental study. *J. Therm. Anal. Calorim.* **2020**, *139*, 3777–3787. [[CrossRef](#)]
184. Nilpueng, K.; Asirvatham, L.G.; Dalkılıç, A.S.; Mahian, O.; Ahn, H.S.; Wongwises, S. Heat transfer and fluid flow characteristics in a plate heat exchanger filled with copper foam. *Heat Mass Transf.-Und Stoffuebertragung* **2020**, *56*, 3261–3271. [[CrossRef](#)]
185. Tavakoli, M.; Hojaji, M.; Soufivand, M.R.; D’Orazio, A.; Karimipour, A. Presence of a porous medium and the arrangements effects on the performance of an air-cooled heat exchanger: An experimental study for heat transfer and pressure drop. *J. Therm. Anal. Calorim.* **2024**, *149*, 6295–6306. [[CrossRef](#)]
186. Ekade, P.; Krishnan, S. Fluid flow and heat transfer characteristics of octet truss lattice geometry. *Int. J. Therm. Sci.* **2019**, *137*, 253–261. [[CrossRef](#)]
187. Rahomey, M.S.; Abed, I.M.; Said, N.M. Thermal Performance of Heated Cylinders in a V-Shaped Open Channel. *ASME J. Heat Mass Transf.* **2026**, *148*, 21801. [[CrossRef](#)]
188. Kumar, S.; Ramamoorthy, S.; Krishnan, S. Application of L  v  que Analogy to Open Cellular Porous Materials. *IEEE Trans. Compon. Packag. Manuf. Technol.* **2023**, *13*, 1096–1103. [[CrossRef](#)]
189. Flayh, A.M. Heat transfer and pressure drop comparison for corrugated tube and different numbers of copper foam cylindrical inserts in laminar flow. *Heat Transf.* **2025**, *54*, 1052–1069. [[CrossRef](#)]
190. Kadhim, I.F.; Al-Jassani, A.J.J.; Al-Bugharbee, H.R. CFD-based thermal-hydraulic analysis of double-pipe heat exchangers equipped with structured metal-foam inserts. *Math. Model. Eng.* **2026**, *12*, 332–355. [[CrossRef](#)]
191. Asaei, A.; Siavashi, M.; Pourrahmani, H. Comprehensive comparison of conjugate heat transfer in Kelvin and Voronoi structures. *Energy Convers. Manag. X* **2026**, *31*, 102161. [[CrossRef](#)]
192. Gaur, S.K.; Sahoo, R.R.; Sarkar, J. Performance optimization of triple tube heat exchanger using aluminum metal foam: A comprehensive numerical investigation. *Int. Commun. Heat Mass Transf.* **2024**, *158*, 107953. [[CrossRef](#)]
193. Al-Chlaihaw, K.; Hasan, M.; Ekaid, A. Optimizing heat transfer within a rectangular channel through intermittent metal foam block configurations: A numerical study. *Heat Transf.* **2025**, *54*, 716–748. [[CrossRef](#)]
194. Farid, R.; Aboelsoud, W.; Ibrahim, S.M.A. Active cooling heat transfer coefficient enhancements in porous compact heat exchanger. *J. Al-Azhar Univ. Eng. Sect.* **2024**, *19*, 75–91. [[CrossRef](#)]
195. Fakiri, F.; Rahmoun, K. Unsteady numerical simulation of turbulent forced convection in a rectangular pipe provided with waved porous baffles. *J. Therm. Eng.* **2017**, *3*, 1466–1477. [[CrossRef](#)]
196. Safari, V.; Kamkari, B.; Gharbi, A. Wedge-shaped fins to enhance thermal performance of shell and tube heat exchangers containing phase change material: An experimental study. *Therm. Sci. Eng. Prog.* **2024**, *49*, 102474. [[CrossRef](#)]
197. Wang, Z.; Wang, Y.; Yang, L.; Cui, Y.; Song, L.; Yue, G. Multi-objective optimization of heat charging performance of phase change materials in tree-shaped perforated fin heat exchangers. *Energy* **2024**, *294*, 130839. [[CrossRef](#)]
198. Selimefendigil, F.;   ztop, H.F. Branching Fin Influence on Phase Transition and Hybrid Nanofluid Forced Convection in A Double Vented Heat Exchanger Unit Equipped with Encapsulated PCM and Field Reconstruction by Using POD. *Int. J. Thermophys.* **2025**, *46*, 105. [[CrossRef](#)]
199. Mikkola, V.; Puupponen, S.; Saari, K.; Ala-Nissila, T.; Sepp  l  , A. Thermal properties and convective heat transfer of phase changing paraffin nanofluids. *Int. J. Therm. Sci.* **2017**, *117*, 163–171. [[CrossRef](#)]
200. Qaiser, R.; Khan, M.M.; Khan, L.A.; Irfan, M. Melting performance enhancement of PCM based thermal energy storage system using multiple tubes and modified shell designs. *J. Energy Storage* **2021**, *33*, 102161. [[CrossRef](#)]
201. Khan, Z.; Khan, Z.A. Thermodynamic performance of a novel shell-and-tube heat exchanger incorporating paraffin as thermal storage solution for domestic and commercial applications. *Appl. Therm. Eng.* **2019**, *160*, 114007. [[CrossRef](#)]
202. Alomari, M.A.; Hassan, A.M.; Al-Salami, Q.H.; Alyousuf, F.Q.A.; Ismael, M.A.; Alqurashi, F.; Flayyih, M.A. Numerical analysis of Soret/Dufour MHD convection in a NEPCM-filled cavity with partial porous foam: Double pipe heat exchanger application. *Heat Transf.* **2025**, *54*, 788–830. [[CrossRef](#)]
203. Khobragade, S.; Devanuri, J.K. Numerical study on latent heat storage systems with and without fins during simultaneous charging and discharging process. *Proc. Inst. Mech. Eng. Part E J. Process Mech. Eng.* **2025**, *239*, 2026–2037. [[CrossRef](#)]
204. Safari, V.; Abolghasemi, H.; Kamkari, B. Experimental and numerical investigations of thermal performance enhancement in a latent heat storage heat exchanger using bifurcated and straight fins. *Renew. Energy* **2021**, *174*, 102–121. [[CrossRef](#)]
205. Khalaf, A.A.; Togun, H. Heat transfer enhancement in thermal energy storage using novel fin designs: A numerical study. *J. Energy Storage* **2026**, *163*, 122054. [[CrossRef](#)]
206. Emhofer, J.; Barz, T.; Buruzs, A.; Both, S.; Beier, S.; Scsepka, P.; Nitsch, B.; Reichl, C. Model-based design and experimental analysis of a compact PCM thermal storage for integration in heat pump cycles. *Appl. Therm. Eng.* **2025**, *267*, 125674. [[CrossRef](#)]
207. Roy, A.; Venkataraj, K.P.; Vigneshwaran, P.; Saboor, S.; Cuce, E.; Saxena, K.K. Enhanced convective heat transfer with Al₂O₃-water nanofluid in a PCM-based thermal energy storage system. *J. Energy Storage* **2024**, *97*, 112853. [[CrossRef](#)]
208. Saha, S.K.; Dutta, A. Thermohydraulic Study of Laminar Swirl Flow Through a Circular Tube Fitted with Twisted Tapes. *J. Heat Transf.* **2001**, *123*, 417–427. [[CrossRef](#)]

-
209. Rathod, P.; Valmiki, S. Heat Transfer Enhancement in Pipe Flow using Wire Coil Inserts in Forced Convection. *Int. J. Eng. Res. Technol. (IJERT)* **2017**, *6*, 88–91. [[CrossRef](#)]
210. Marzouk, S.A.; Aljabr, A.; Almeahmadi, F.A.; Alqaed, S.; Sharaf, M.A. Numerical study of heat transfer, exergy efficiency, and friction factor with nanofluids in a plate heat exchanger. *J. Therm. Anal. Calorim.* **2023**, *148*, 11269–11281. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.