



Heat Transfer Augmentation in Double-Pipe Heat Exchangers Using Twisted Tape Inserts, Nanofluids and Twisted Tubes: A Review

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ABSTRACT

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Considering the expanding global energy needs and the increasing thermal performance requirements of modern industrial systems, heat exchangers are facing significant challenges, including reduced thermal efficiency and rising energy consumption. This underscores the essential need for effective techniques that increase heat transfer rates without causing substantial increases in hydraulic losses. This investigation plans to analyze and assess the latest advancements in heat transfer enhancement techniques, placing particular emphasis upon nanofluids and twisted tapes/tubes, as they are among the most widely implemented and successful techniques in double-pipe heat exchangers. To achieve this, an exhaustive review of experimental and numerical analyses was conducted, examining the heat-transfer behavior pertaining to nanoparticle-based fluids and the impact of various geometric modifications to twisted strips and tubes on thermal performance. Outcomes reveal improvements in geometric parameters associated with twisted strips, such as reducing twist ratios, adding perforations, or modifying cutting profiles, resulting in a substantial enhancement in heat-transfer performance. Nanofluids, moreover, have strong potential to enhance thermal performance due to their superior thermal conductivity. When both techniques are combined, they provide the highest thermal efficiency with an acceptable increase in pressure drop, making this integration one of the most promising solutions for developing high-efficiency, energy-saving heat exchangers.

1. INTRODUCTION

A heat exchanger is equipment designed to transmit thermal energy between working fluids at varying temperatures without allowing them to mix, usually via a separating heat transfer surface. These devices are widely used in numerous industrial sectors, including electricity generation, petroleum processing, refrigeration, air conditioning, and transport. Common applications include automobile coolant, condensers, evaporators, and other applications [1].

A double-tube heat exchanger is one classified among the commonly employed heat exchanger configurations in industrial and engineering systems. Its widespread use is attributed to its mechanical simplicity, high thermal efficiency in transferring heat between two fluids in concentric tubes, as well as its ability to withstand high pressures and temperatures, ease of maintenance, and low economic cost [2].

Consistent with rising energy use worldwide and material costs, the necessity to develop efficient thermal energy transfer systems has become more pressing. Heat exchangers have attracted significant attention from researchers, particularly

for improving their thermal performance. In this regard, strategies for improving heat transfer are considered fundamental to enhancing the efficiency of heat exchangers. This augmentation is achieved by promoting higher heat transfer rates through mechanisms such as breaking up the thermal boundary layer, increasing surface area, or developing secondary flows. However, these enhancements often come with increased pressure drop in the system, which poses additional challenges related to energy consumption and friction. Therefore, selecting an appropriate enhancement technique requires a careful balance between thermal performance and minimizing undesirable hydraulic losses [3].

The objective of this review is to critically analyze and synthesize recent experimental and numerical studies on heat transfer enhancement techniques in double-pipe heat exchangers, with particular emphasis on twisted tape inserts, twisted tube geometries, and nanofluids. The study aims to evaluate the influence of geometric modifications and nanoparticle-based working fluids on thermal-hydraulic performance, including heat transfer enhancement, pressure drop characteristics, and overall thermal efficiency.

Furthermore, the review seeks to identify optimal configurations and highlight the synergistic potential of combining passive geometric modifications with advanced working fluids to achieve improved energy efficiency and performance in modern heat exchanger systems.

2. SYSTEMATIC REVIEW METHODOLOGY

This review was conducted using a structured literature survey approach to identify and analyze published studies related to heat transfer enhancement in double-pipe heat exchangers. The review focused on peer-reviewed experimental and numerical studies reporting thermo-hydraulic performance parameters, including Reynolds number (Re), Nusselt number (Nu), friction factor (f), thermal performance factor (TPF), and performance evaluation criteria (PEC). Studies were screened based on relevance to passive and hybrid enhancement techniques applied to double-pipe configurations, while works lacking quantitative performance analysis or unrelated to thermal performance improvement were excluded. The selected studies were systematically categorized according to enhancement technique and analyzed comparatively to evaluate their influence on heat transfer characteristics, pressure drop behavior, and overall thermal efficiency, with the aim of identifying performance trends and existing research gaps in the field.

3. CLASSIFICATION OF ENHANCEMENT TECHNIQUES

Enhancement of heat transfer techniques is typically categorized into three major classifications:

(i) Active methods utilize externally supplied energy to promote convection, including mechanical vibration or electrohydrodynamic forcing.

(ii) Passive methods improve thermal performance without additional energy by modifying exchanger geometry or fluid properties, for example, using fins, textured surfaces, coiled wire, twisted tape insertion, or nanofluids.

(iii) Hybrid methods combine both strategies to achieve synergistic effects, as seen in vibrating tubes filled with nanoparticle-laden fluids, as shown in Figure 1.

Twisted tapes (TT) represent helical metallic inserts utilized throughout heat exchangers to improve heat transfer, though

they increase pressure loss. They act as turbulators, increasing flow disruption and fluid mixing. Their geometry induces swirling, enhancing mixing between core and wall fluids [4, 5].

Heeraman et al. [6] examined the influence associated with twisted-strip inserts featuring dimple designs in a double-tube heat exchanger. This study examined the impact of dimple dimension (D) in conjunction with twist ratio on heat-transfer performance and friction factor. The findings demonstrated that incorporating dimples into the twisted tape significantly enhanced thermal performance while maintaining a slight and well-controlled increase in pressure drop.

Majeed and Mushatet [7] investigated how inserting a twisted tape into a double-pipe exchanger can influence and enhance its overall performance. The findings indicated that the twisted tape increases flow turbulence, hence improving heat transfer and elevating thermal effectiveness by as much as 34% relative to a conventional heat exchanger.

Twisted tubes are considered a promising technique for augmenting the heat transfer coefficient of a heat exchanger. Their geometric structure induces secondary swirling flows that increase fluid velocity, enhance the effective Reynolds number, and intensify the thermal gradient. As a result, they improve the thermal efficiency of the system and help minimize total dimensions for heat transfer equipment [8].

Ali and Jalal [9] tested twisted inner pipes to augment heat transfer performance in tube-in-tube heat exchangers. Three elliptical pipes with 3, 5, and 7 twists per meter were tested against a straight pipe. Water was used for testing, which was conducted in parallel and counterflow configurations at Reynolds numbers spanning 5000–26,000. Increasing the twist numbers improved heat transfer; the highest reported Nusselt number was 2.2, while the corresponding performance enhancement factor reached 1.9, and this was with the 7-twist pipe in counterflow. Twisting increased the pressure drop, but heat transfer efficiency overcame it. According to the study, Twisted pipes improve heat exchanger performance.

Nanofluids are nanoparticle-enhanced fluids created by suspending solid nanoparticles, commonly 5 to 100 nanometers in diameter, into standard working fluids, with water, ethylene glycol, and various industrial oils being the most representative examples. Such nanofluids exhibit enhanced thermal and rheological properties, making them highly effective in thermal applications, especially in systems such as heat-exchange equipment and thermal energy storage units [10].

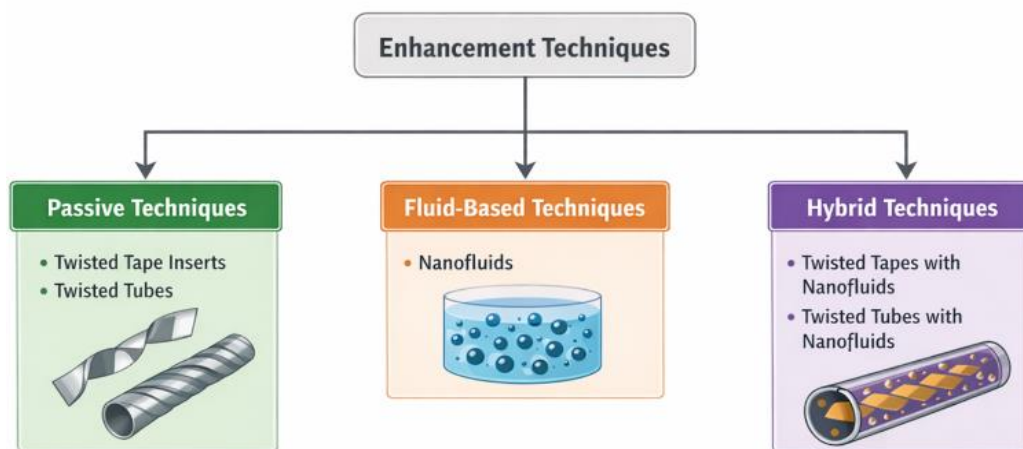


Figure 1. Classification of enhancement techniques

Mousazadeh et al. [11] evaluated the impact associated with employing a MnCoFeO₄-water-based nanofluid on the efficacy of a tube-in-tube heat exchanger. Experimental outcomes demonstrated an increase in nanoparticle concentration, and a marked improvement in heat transfer was observed with cold fluid flow rate. Heat transfer efficiency improved by 40%, and the Nusselt number increased by 37%, along with a modest elevation in the friction factor of 15.4%.

4. TWISTED TAPE PASSIVE AUGMENTATION DEVICES IN DOUBLE-TUBE HEAT EXCHANGER DESIGNS

Ponnada et al. [12] investigated the impact of three different types of twist tape inserts on the thermal performance of a circular tube: plain twisted tape (TT), perforated twisted tape (PTT), and perforated twisted tape with an alternating axis (PATT), using water as the operating medium. The study, conducted over a broad range of Re values (3000–16000) under turbulent flow conditions, entailed an experimental investigation in which the inserts were evaluated at twist ratios of 3, 4, and 5. The perforated tapes include holes spaced at 12.5 mm intervals. In the PATT configuration, the twist axis is alternated every 100 mm to optimize flow behavior and improve the thermal transport. The analysis indicated that PATT achieved the highest heat transfer, was 48.12%, followed by PTT at 44.3% and TT at 33%, relative to the standard tube. The frictional factor increased at 19.1%, 17.6%, and 15.85% for PATT, PTT, and TT, respectively. The peak TPF was obtained by PATT at around 1.433, followed by PTT at 1.396 and TT at 1.24; the details were illustrated in Table 1.

Zhang et al. [13] performed an experimental assessment of a tube-in-tube heat exchanger featuring self-rotating tapes with twists (SRTTs) at twist ratios of 2.2, 3.0, 4.0, and 6.0. Water was an operating medium, and the Re range was 12,000–45,000. The results indicated improved thermal efficiency relative to stationary tapes, with the peak TPF (1.03) attained at $Y = 2.2$. The rotational speed, in addition to the Nu and f , showed a noticeable rise with decreasing twist ratio; however, the twist ratio did not influence the onset of rotation.

Zhang et al. [14] examined a double-tube heat exchanger configuration in which they employed self-rotating perforated twisted tapes (SRTTs) fabricated with a fixed twist ratio (TR = 3.0). Six perforation ratios (PR) were evaluated: 0%, 1.16%, 3.63%, 6.46%, 10.1%, and 14.49%, utilizing water as an operating fluid, and Re spanning (4000–18000), with turbulent flow conditions. The findings indicated that rotation behavior commenced at lower water velocities for tapes with smaller perforation ratios, whereas tapes with larger perforation ratios rotated more slowly. The self-rotating tapes exhibited improved thermal performance relative to stationary tapes, with the Nu growing by 14.5% to 62.3% and the friction factor escalating by 124% to 174%. The maximum thermal performance was reached via a perforation percentage of 10.1%.

Nakhchi et al. [15] investigated the impact of incorporating double cut twisted tape (DCTT) inserts in a tubular heat exchanger through an experimental study. The tape measured 20 mm in width, 2 mm in thickness, and 105 mm in pitch length. A cut depth (b) ranged from 2.5 to 9 mm, with a constant cut width (c) of 10 mm, resulting in cut ratios (b/c) of 0.25, 0.5, 0.75, and 0.9. Water served as the fluid medium for the experiments, with Re of 5,000 and 15,000. The findings

showed that a 177.4% rise in the Nu, while up to a 489% increase in the f , corresponding with a simple tube. Thermal performance was recorded at Re = 5000 with $b/c = 0.9$, yielding a value of 1.63.

Vaisi et al. [16] experimentally investigated the thermal performance of a double-tube heat exchanger utilizing both continuous and discontinuous twisted-tape inserts, which were categorized as perforated or non-perforated. The tests were performed at Re spanning 5500–10000, where warm water passed through the tube while cold water occupied the annular region. The twist ratio of the twisted tapes was 2.16, while the discontinuous tapes incorporated nine perforations in diverse geometric forms, circular, square, rectangular, triangular, and diamond, each engineered with a uniform hydraulic diameter of 8 mm to ensure a consistent geometric foundation for performance evaluation. The results showed that, compared to the continuous type, a discontinuous tape enhanced heat transfer and decreased pressure decline to 8.2% and 9.8%, respectively. Performance was enhanced by the perforated designs; circular holes raised heat transfer to 20.8% and reduced pressure decline to 27.7%. These results highlight the importance of shape-optimized perforations for improving heat exchanger efficiency.

Dhumal and Havaladar [17] performed a computational analysis of a countercurrent tube heat exchanger featuring twisted-helical configurations coupled with external helical fins. This study comprises nine designs, utilizing internal twist ratios (3.38, 4.51, and 6.77) and external helical fin ratios (0.5, 0.67, and 1). Water was the operating medium, with Re of 4000 and 20000. Twisted tapes and helical fins enhanced heat transfer and liquid mixing. According to the investigation, reducing the twist ratio increased the pressure drop but enhanced heat transfer.

Kola et al. [18] carried out a computational investigation of a tube-in-tube heat exchanger incorporating a twisted-tape insert with a curved cross-sectional cut defined by a specific angle and radius to enhance thermal performance. Computational fluid dynamics (CFD) simulations and Response Surface Methodology (RSM) facilitated the identification of such optimal parameters governing thermal performance and flow resistance. Water served as the working medium under a constant twist ratio ($h/d = 3$), and the flow regime was turbulent, with Re spanning (1619–28773). The finding indicated that variation in the cut angle and radius affected the thermal behavior more than the mass flow rate. Optimal values were achieved at a mass flow of 0.05 kg/s, a 5.464 mm cut radius ring, and a 45° twist angle, yielding a heat transfer coefficient of 1965 W/m²K with a corresponding friction factor of 0.077. The RSM model demonstrated remarkable predictive accuracy ($R^2 = 98.4\%$), demonstrating its efficiency in optimizing exchanger design and reducing experimental effort.

Soltani et al. [19] employed turbulent water flow to study alternative geometric arrangements of twisted-tape configurations within the inner pipe for a double-pipe heat exchanger. Six twisted tapes under a constant twist ratio ($\gamma = 3$) were studied: typical, continuous, winglet, and louvered, dimpled, and undimpled. Re spanning (5000 to 9500) inside the inner pipe and remained at 11000 in the annular space. Results indicate that the discontinuous louvered twisted-tape design incorporating surface dimples exhibited a high thermal performance, with $\eta = 1.24$ at Re = 5300. Adding surface dimples to continuous twisted tape improved heat transfer by 5.58%.

Pimsarn et al. [20] performed a laboratory investigation on a single tube. Aiming to enhance aero-thermal efficiency, they used twisted tapes and inclined circular rings. The examined ring inclination angles were 30°, 45°, 60°, and 90°, while the twisted tape numbers were 2, 4, and 6, with twist ratios of 1.0, 2.0, and 3.0. Air constituted the operating fluid, and Reynolds number spanned the interval (5,000–22,000), indicating turbulent tube flow. For $\alpha = 30^\circ$, $H = 2$, and $TR = 3$, a maximum aero-TPF (η) reached 1.66. Notably, the friction factor showed a clear upward trend, resulting in a 155.3% augmentation in the heat transfer relative to a smooth tube. This study demonstrates that twisted tapes and tilted rings enhance single-tube heat transfer.

Safitra et al. [21] investigated an experimental and numerical study of plain and perforated twisted-strip inserts at 3.77% porosity. Water served as a working fluid in the inner tube, at Re spanning (1000–5000). Perforated tape increased heat transfer by 0.31%, resulting in a higher Nu. It further increased the friction factor by 366%, which is lower than the 455% for plain tape. The number of Transfer Units (NTU) increased by 78.42%, and thermal effectiveness rose by 45.86%. Overall, perforated tape performed better thermally.

Dandoutiya and Kumar [22] assessed the thermal efficiency for a tube-in-tube heat exchanger enhanced by W-notched twist-tape inserts through a numerical investigation. Each 10 mm-wide twisted tape had cut depths of 2, 4, and 6 mm and b/W ratios of 0.2, 0.4, and 0.6. The internal pipe conveyed Water maintained at 333 K, while the annular passage received water conditioned at 298 K supplied the. The Reynolds number ranged from 5500 to 15300. relative to a simple pipe, Nu was raised by 3.07 times. and the friction factor is 8.66 times. W-cuts provide a better combination of fluids and swirl motion. Reynolds number 5500 had 1.495 as the maximum TPF.

Dhumal and Havaladar [23] experimentally investigated a double-pipe counterflow heat exchanger with interior twisted tapes and external spiral tapes to enhance heat transfer efficiency. Water served as the operating medium in the turbulent regime, altering the respective Reynolds number on each side of the exchanger. Various twist ratios (3.38, 4.51, and 6.77) were studied to evaluate the effects on heat transport and pressure decrease. Results showed that integrating twisted and helical tapes resulted in Nusselt number rising 219–315% in comparison to the plain pipe; while the associated friction factor exhibited an enhancement of 4.4–8.7fold. An impressive 3.06 was the maximum TPF achieved.

Chuwattanakul et al. [24] analyzed a circular exchanger pipe incorporating an innovative broken V-ribbed tape design (B-VRT) in both forward and backward orientations to achieve enhanced heat transfer efficiency. The rib attack angles (45°, 60°, 75°, 90°), in addition to evaluating twist ratios characterized by y/W values of 3.5, 4.0, and 4.5, were investigated within a uniform thermal flux scenario, with an air-served operating medium and Reynolds numbers ranging from 6000 to 20000. The tape, featuring a 45° rib angle and a twist ratio of 3.5, demonstrated optimal performance, with a 227% growth in the Nusselt number and a 4.65-fold reduction in the corresponding friction factor compared to a smooth tube. This enhancement was attributed to the generation of longitudinal vortices and swirling motion, which improved fluid mixing. The peak aerothermal performance factor (APF) attained was 1.38.

Ali and Shimer [25] experimentally evaluated the thermal performance of a double-tube heat exchanger. A helical airfoil

fit was utilized within the interior tube. In this investigation, pitch ratios were characterized by P/D values of 7, 5, and 3, with volumetric flow rates maintained at 2.0, 2.5, and 3.0 L/min, respectively. Experiments conducted under laminar flow conditions ($Re \leq 2100$), utilising cool water via the inner pipe as warm water at the annulus. optimal thermal performance at a P/D ratio of 3. Heat transfer enhancement varied between 134% and 137% depending on the flow rate, with a friction factor increase of up to 142%. This performance evaluation criterion (PEC) attained a peak of 158% when the volumetric flow rate was 2 L/min.

Kumbhar et al. [26] experimentally investigated copper heat exchangers with conventional and perforated twisted tape inserts. The perforated tapes had widths of 5 mm and 8 mm, and ratios of tape twisting (2.5, 3.33, 5.0). All inserts improved thermal transfer relative to a conventional tube. With a TR at 2.5 and an aperture of 8 mm, the maximum TPF achieved 2.37. Perforated tapes with 5 mm perforations increased heat transfer rates by 148% (TR = 2.5), 172% (TR = 3.33), and 126% (TR = 5.0). Medium-sized perforations were found to be effective for enhancing thermal efficiency.

Sadaqat et al. [27] used Ansys Fluent to analyze a heat exchanger tube employing both simple and perforated twisted tapes with varying blade counts. Four blade numbers (2, 4, 6, and 8) were analyzed at three twist ratios under low Reynolds number conditions ($Re = 200$ and 1000), which fall within the laminar regime. According to the results, the perforated twisted tape with six blades exhibited superior thermal performance, achieving a 15.24% rise in the Nusselt number and a 22.26% decrease in the friction factor relative to a standard twisted tape. There was an 18.07% rise in the thermal performance coefficient. However, increasing its blade count to eight resulted in increased pressure losses without corresponding improvements in heat transfer. Raising the Reynolds number was found to enhance the thermal performance coefficient while reducing the friction factor.

Nashee [28] performed an advanced numerical analysis to model the performance of a heat exchanger pipe incorporating both single-notched and double-notched twisted strips using ANSYS Fluent. The research investigated a range of truncation ratios, considering four distinct a/b configurations (0.30, 0.50, 0.70, 0.90). The analysis showed that the double-cut configuration provided optimal thermal performance at a/b = 0.9, resulting in a 42% growth in the Nusselt number compared to a conventional pipe, while also causing an 18% rise in the friction factor due to heightened turbulence. The highest thermal efficiency (η) at a Reynolds number of 5000 is 1.69, whereas the minimum thermal performance was observed in the single-cut scenario at $Re = 25000$, with a value of 0.96.

Bouregueba et al. [29] numerically analyzed a circular cross-section pipe incorporating various twisted-tape configurations: a standard twisted-tape (TT), a twisted tape with circular perforation (CPTT), and another featuring hexagonal perforation (HPTT), all exhibiting a twist ratio of y/w = 5. The tapes contained hexagonal perforations on each side, measuring 4 mm in length and circular apertures with a diameter of 8 mm. Simulations were conducted using ANSYS Fluent, which is compatible with the finite-volume approach through Reynolds numbers spanning (5000–20,000) and a fixed thermal flux of 1200 W/m². The findings indicated that both the plain and perforated twisted tapes significantly enhanced heat transfer by inducing greater turbulence than the plain tube. For TT, CPTT, and HPTT, the Nusselt number

increased by 62.37%, 65.85%, and 76.27%, respectively. As a result, the friction factors increased by 150.68%, 154.31%, and 176.05% for the three cases. Among all PEC, the CPTT's 1.25 was greatest, indicating optimal thermal–hydraulic equilibrium among the evaluated configurations.

Argunhan et al. [30] tested twisted metallic strips within a tube-in-tube heat exchanger to improve thermal performance. Four strip length ratios (0.25 to 1) were tested for heat transfer and pressure lowering. The inner tube was heated by hot air, and the annular gap was cooled by cold water, with Reynolds numbers ranging from 3400 to 6900. Elongated strips improved heat transport by 78% at the ideal ratio. This enhancement increased pressure by almost 100%. The device allowed parallel and counterflow operation. Longer strips increased heat transfer, but the smallest strip had the best heat gain-to-pressure loss ratio. Twisted strips improve heat exchanger performance passively, according to the study.

Kiros et al. [31] conducted a numerical analysis using ANSYS Fluent 19.2 to analyze the influence of multi-leg twisted-tape configurations on heat transport augmentation and associated flow-induced pressure losses under a laminar condition. Three configurations were analyzed: two-twist, three-leg, and four-leg, each with a twist ratio (length-to-diameter) of 5. Simulations were conducted through Reynolds numbers spanning (800–2000). Water served as the working medium. Aspect 2-twist tape showed the greatest TPF by 1.44. Moreover, the Nusselt number was improved by 134% for the 2-twist tape, 152% for the 3-leg tape, and 153% for the 4-leg tape. In contrast, the increases in the friction factor were 329%, 487%, and 630%. The results indicated that augmented geometric complexity improves thermal performance, but markedly increases hydraulic losses.

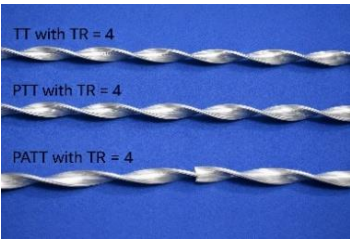

Qiu et al. [32] employed I-RTTW, a twisted tape featuring a central I-shaped rib and 45° twisted winglets, to augment the thermohydraulic behavior of heat exchanger tubes in both computational and experimental investigations. The flow regime was turbulent, and air served as the operating medium, with Reynolds numbers spanning (6000–20000) and an additional twist ratio of 4.0. Three winglet depth ratios were considered, with d/W set at 0.096, 0.13, and 0.16, while three winglet width ratios (w/W) were examined at the same level as 0.096, 0.13, and 0.16, and their combined effects on heat transmission and flow resistance were investigated. Increasing these ratios greatly increased longitudinal and transverse vortices, leading to reduced thermal boundary layers and better

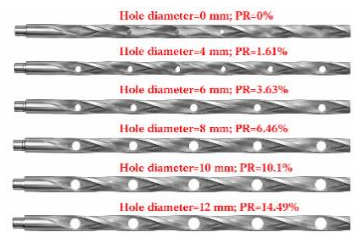
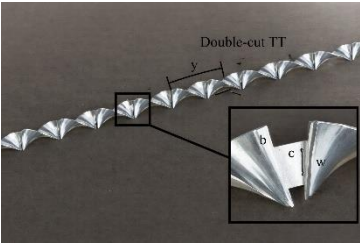
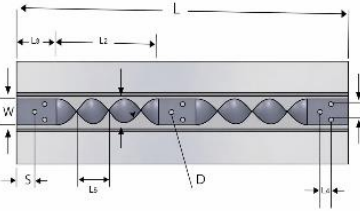

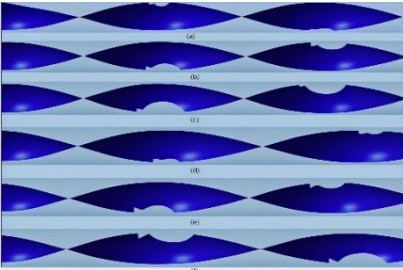

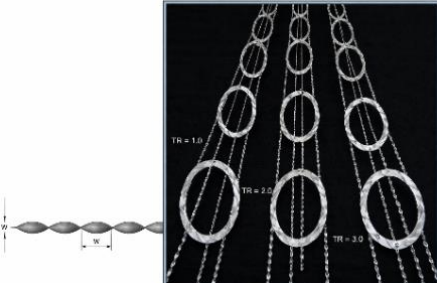

mixing intensity. Compared to the conventional pipe, the thermal performance index (TPI) reached its maximum value, the flow friction factor increased by 4.11 times, and the Nusselt number improved by 1.99 times.

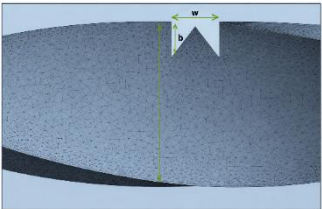
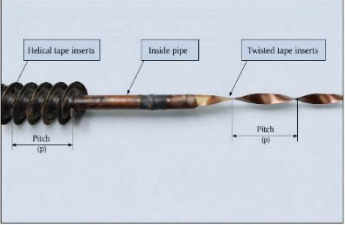
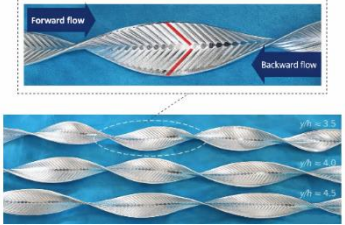

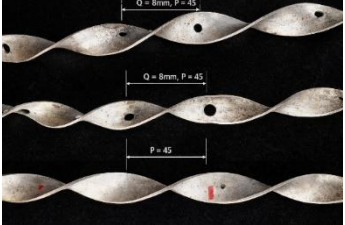

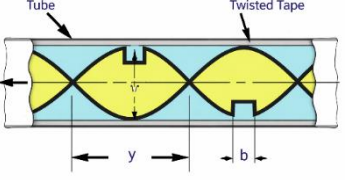
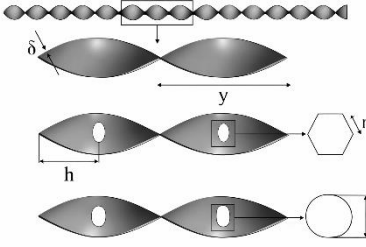
Bhuyan et al. [33] numerically investigated the enhancement of thermal efficiency within the circular tube. They used twisted tape elements with rectangular notches and a twist ratio designated at 5.25. The research examined three rectangular cut types: (8 × 6 × 14), (8 × 10 × 18), and (8 × 12 × 26 mm³). It also included the B. Salam notched specimen, measuring 8 × 8 × 14 mm³. Also, compared all of them to a standard twisted tape arrangement. Water served as the operating medium, with Reynolds numbers spanning (9471–42623). According to the results, cut No. (1), measuring (8 × 6 × 14 mm³), gave the highest heat transfer improvement, showing a 17.66% increase in Nusselt number relative to a standard tube. Overall, B. Salam cut had the greatest thermal effectiveness, reaching a 20.7% improvement. The thermal performance efficiency (η) ranged from 1.98 to 3.17. With the rise in Reynolds' number, the friction coefficient reduced gradually. The study determined that the cut shapes and twist lengths greatly affect heat distribution, vorticity, and overall efficacy of the helical heat exchanger.

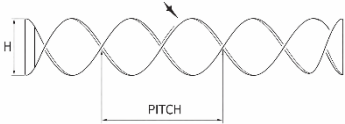
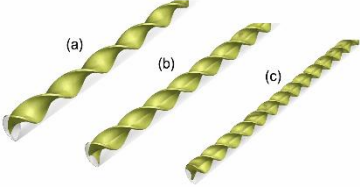
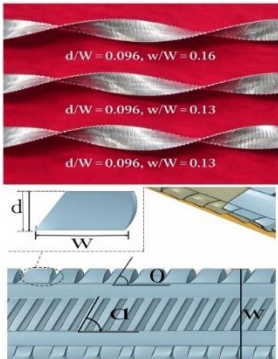

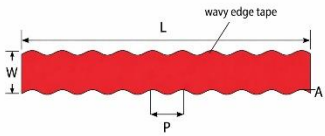
In a comprehensive computational study, Saleh et al. [34] utilised ANSYS Fluent 22 to improve the thermal-hydraulic performance of a concentric-tube heat exchanger incorporating a wavy edge tape (WET) insert, aiming to minimise hydraulic losses while increasing the TPI within the waste thermal recovery system. Hot air served as the operating medium within the interior pipe, while heavy fuel oil (HFO) circulated through the outer tube, with Reynolds numbers for air varying from 6,957 to 187,837. The wavy tape was engineered with varying widths (50%, 75%, 95% of the 101.6 mm inner diameter), with structural lengths of 1000, 1200, and 1400 mm, wave amplitudes of 5, 10, and 15 mm, and wavy-length periods corresponding to 5, 10, and 15 mm, maintaining a uniform thickness of 2 mm. The findings indicated that the ideal configuration, 75% Di diameter, 1200 mm length, 5 mm amplitude, and 15 mm period, attained a TPI of roughly 1.02. This arrangement increased heat transfer by 37% while causing a slight increase in pressure loss (about 10%). The research validates that this design offers an equitable approach to improving thermal efficiency and minimizing energy consumption in industrial heat-recovery applications.

Table 1. Summary of previous studies on twisted tape configurations and heat transfer enhancement

Authors	Configurations	Type of Study	Parameter	Finding (The Best Enhancement)
Ponnada et al. [12]		Experimental	Re (3000–16000), Twist ratio (γ = 3, 4, 5), Hole spacing (12.5 mm), Axis alternation (100 mm)	Perforated twisted tape with an alternating axis (PATT) achieved the highest heat transfer enhancement (48.12%) and thermal performance factor (TPF) (1.433), followed by PTT (44.3%, TPF 1.396) and TT (33%, TPF 1.24)
Zhang et al. [13]		Experimental	Re (12,000–45,000), Twist ratios (Y), with values of 2.2, 3, 4, and 6	Self-rotating tapes with twists (SRTTs) achieved the best TPF = 1.03. at Y = 2.2, with Nu and f increased as Y decreased

Zhang et al. [14]		Experimental	<p>Reynolds numbers spanning (4000–18000), Twist ratio (TR = 3.0), Perforation ratio (PR = 0–14.49%, ratio of hole area to tape area)</p>	<p>SRTT with perforation ratios (PR) = 10.1% achieved optimal thermal performance. Nu increased by 14.5–62.3%, f by 124–174%</p>
Nakhchi et al. [15]		Experimental	<p>Re (5000–15000), Cut depth (b = 2.5–9 mm), Cut width (c = 10 mm), Cut ratio (b/c = 0.25–0.9), Pitch length (105 mm), Tape width (20 mm), Thickness (2 mm)</p>	<p>Double cut twisted tape (DCTT) enhanced Nu by 177.4% and f by 489% vs plain tube. Best performance at Re = 5000 and b/c = 0.9 with $\eta = 1.63$</p>
Vaisi et al. [16]		Experimental	<p>Re (5500–10000), Twist ratio (y = 2.16), Perforation shape (circular, square, rectangular, triangular, diamond), Hole diameter (d = 8 mm)</p>	<p>A discontinuous tape enhanced heat transfer and decreased pressure decline to 8.2% and 9.8%, respectively. Circular perforations gave 20.8% heat transfer and –27.7% pressure drop</p>
Dhumal and Havaladar [17]		Numerical	<p>Re (4000–20000), Internal twist ratio (3.38, 4.51, 6.77), External helical fin ratio (0.5, 0.67, 1)</p>	<p>Twisted-helical configurations coupled with external helical fins enhanced heat transfer and fluid mixing</p>
Kola et al. [18]		Numerical	<p>Re (1619–28773), Twist ratio (h/d = 3), Cut angle (45°), Cut radius (5.464 mm), Flow rate (0.05 kg/s)</p>	<p>Curved-cut twisted tape at 45° and 5.464 mm resulting h = 1965 W/m²K and f = 0.077</p>
Soltani et al. [19]		Experimental	<p>Re (5000–9500 inner, 11000 annulus), Twist ratio (Y = 3), Tape type (typical, continuous, winglet, louvred, dimpled, undimpled)</p>	<p>A discontinuously louvred twisted tape including surface grooves achieved the best TPI ($\eta = 1.24$ at Re = 5300). Adding dimples to continuous tape improved heat transfer by 5.58%</p>
Pimsarn et al. [20]		Experimental	<p>Re (5000–22000), Ring inclination angle ($\alpha = 30^\circ, 45^\circ, 60^\circ, 90^\circ$), Number of twisted tapes (H = 2, 4, 6), Twist ratio (TR = 1.0, 2.0, 3.0)</p>	<p>For $\alpha = 30^\circ$, and H = 2.0, with a twist ratio (TR) of 3.0, the maximum aero-TPF is $\eta = 1.66$. Heat transfer increased by 155.3% over the plain tube</p>
Safitra et al. [21]		Experimental and Numerical	<p>Re (1000–5000), Tape type (plain, perforated), Porosity (3.77%)</p>	<p>Perforated twisted tape increased Nu by 0.31%, Number of Transfer Units (NTU) by 78.42%, and thermal effectiveness by 45.86%. f rose by 366%, lower than 455% for plain tape</p>

Dandoutiya and Kumar [22]		Numerical	<p>Re (5500–15300), Cut depth (b): 2, 4, and 6 mm, The width of tape insert (W): 10 m, notch ratio (b/W): 0.2, 0.4, 0.6</p>	<p>W-notched twist-tape increased Nusselt number by 3.07 times, and the friction factor rose 8.66 times, and the highest TPF = 1.495 at Re = 5500</p>
Dhumal and Havaladar [23]		Experimental	<p>Re (variable, turbulent flow), Twist ratio (3.38, 4.51, 6.77), Helical tape (external)</p>	<p>Combined twisted and helical tapes increased Nu by 219–315% and f by 4.4– 8.7 × vs smooth tube. Maximum TPF = 3.06</p>
Chuwattanakul et al. [24]		Experimental	<p>Re (6000–20000), Rib attack angle (45°, 60°, 75°, 90°), Twist ratio (y/W = 3.5– 4.5), Orientation (forward/backward), Heat flux (constant)</p>	<p>Broken V-ribbed twisted tape (B-VRT) at 45° and y/W = 3.5 gave optimal performance. Nu increased up to 227%, f by 4.65× over the smooth tube. APF = 1.38</p>
Ali and Shimer [25]		Experimental	<p>Re (≤ 2100, laminar flow), pitch ratio (P/D = 7, 5, 3), Flow rate (2–3 L/min)</p>	<p>The spiral airfoil insert at P/D = 3 enhanced heat transfer by 134–137% and f up to 142%. The best performance evaluation criterion (PEC = 158%) at 2 L/min</p>
Kumbhar et al. [26]		Experimental	<p>Twist ratio (TR = 2.5, 3.33, 5.0), Perforation width (5 mm, 8 mm)</p>	<p>TPF = 2.37 for TR = 2.5 and 8 mm perforation. 5 mm perforations increased heat transfer by 148% (TR = 2.5), 172% (TR = 3.33), and 126% (TR = 5.0)</p>
Sadaqat et al. [27]		Numerical	<p>Re (200–1000, laminar), Blade number (2, 4, 6, 8), Twist ratio (3)</p>	<p>Perforated tape with 6 blades gave 15.24% higher Nu, 22.26% lower f, and 18.07% higher thermal performance coefficient (η) vs standard tape</p>
Nashee [28]		Numerical	<p>Re (5000–25000), Cut ratio (a/b = 0.3, 0.5, 0.7, 0.9), Tape type (single, double- cut), Tap pitch (Y) = 108mm</p>	<p>double-notched twisted strips (a/b) of 0.9 gave the best performance. Nu increased by 42% and f by 18% vs plain tube. Maximum η = 1.69 at Re = 5000; minimum η = 0.96 at Re = 25000</p>
Bouregueba et al. [29]		Numerical	<p>Re (5000–20000), Twist ratio (y/w = 5), Perforation type (circular, hexagonal), Hole size (\varnothing = 8 mm, hex side = 4 mm), Heat flux (1200 W/m²)</p>	<p>TT, CPTT, and HPTT increased Nu by 62.37%, 65.85%, and 76.27%, respectively. f rose by 150.68%, 154.31%, and 176.05%. CPTT had the highest PEC = 1.25</p>

Argunhan et al. [30]		Experimental	<p>Re (3400–6900), Strip length ratio (0.25–1), Flow type (parallel/counterflow)</p>	<p>Twisted metallic strips enhanced heat transfer by 78% at the optimal length ratio. Pressure increased by ~100%. Longer strips improved HT, but the shortest strip gave the best heat-to-pressure performance ratio</p>
Kiros et al. [31]		Numerical	<p>Re (800–2000, laminar flow), Tape configuration (2-twist, 3-leg, 4-leg), Twist ratio (5)</p>	<p>2-twisted tape gave the best performance with TPF = 1.44. Nu increased by 134%, 152%, and 153%, and f by 329%, 487%, and 630% for 2-twist, 3-leg, and 4-leg tapes, respectively. Higher complexity improved heat transfer but raised pressure losses</p>
Qiu et al. [32]		Experimental and Numerical	<p>Re (6000–20000, turbulent), Twist ratio (4.0), Winglet depth ratio (d/W): 0.096, 0.13, and 0.16, Winglet width ratio (w/W): 0.096, 0.13, and 0.16</p>	<p>I-RTTW increased Nu by 1.99× and f by 4.11× vs plain tube</p>
Bhuyan et al. [33]		Numerical	<p>Re (9471–42623), Twist ratio (5.25), Cut type ($8 \times 6 \times 14$, $8 \times 10 \times 18$, $8 \times 12 \times 26$, and B. Salam notched specimen, which is $8 \times 8 \times 14$ mm³ in size</p>	<p>Cut No.1 ($8 \times 6 \times 14$ mm³) gave 17.66% higher Nu vs plain tube. B. Salam cut achieved the highest thermal effectiveness (20.7%). Thermal performance efficiency (η) ranged from 1.98 to 3.17. f decreased with increasing Re</p>
Saleh et al. [34]		Numerical	<p>Re (6,957–187,837), Tape width (50–95% of D_i), Tape length (1000–1400 mm), Amplitude (5–15 mm), Wave period (5–15 mm), Thickness (2 mm)</p>	<p>Optimal setup (75% D_i, 1200 mm, 5 mm amplitude, 15 mm period) achieved TPI \approx 1.02. Heat transfer increased by 37% with ~10% higher pressure loss</p>

5. TWISTED TAPE CONFIGURATIONS AND NANOFLUIDS IN DOUBLE-TUBE HEAT EXCHANGER DESIGNS

Nanofluid stability is a key factor affecting their practical use in double-pipe heat exchangers. Although nanofluids enhance heat transfer through improved thermophysical properties, their performance depends on maintaining uniform nanoparticle dispersion. Agglomeration and sedimentation can reduce thermal efficiency, increase pressure drop, and lead to unstable operating conditions. Stability is influenced by nanoparticle type, concentration, base fluid properties, and preparation methods, as reported in Ghaleb et al. [35], who used ANSYS Fluent to evaluate the thermal performance of a counter-current tube-in-tube heat exchanger featuring an overlapped helical tape element in both flow passages. Dual configurations were investigated: co-swirling twisted tapes

(Co-STT) and counter-STT, characterized by a pitch ratio of 5.0, a 10 mm width, and a 1 mm thickness. Simulations were conducted using an Al_2O_3 -water nanofluid at volume fractions reaching 3%, with flow maintained in the laminar regime corresponding to a Reynolds number interval of 250–1000. The Counter-STT configuration increased the Nusselt number by 68.7% and the PEC to 1.40 in the inner pipe and 1.26 in the outer pipe.

Ju et al. [36] conducted a CFD-based study to evaluate the thermo-hydraulic behavior of a tube-type exchanger employing a semi-twisted tape element with an Al_2O_3 /water nanofluid. The research investigated the effect of the number of tapes, nanoparticle concentrations (0–3%), and Reynolds number (250–1000). Raising the tape count from 0 to 4 increased the Nusselt number from about 15 to nearly 28.5, whereas the hydraulic resistance coefficient declined over the range 0.155–0.052. Moreover, the findings indicated that

employing four tapes and a 3% nanoparticle concentration at $Re = 750$ yielded the optimal performance ($PEC = 1.66$) [36].

Hamza and Aljabair [37] performed a comprehensive computational and experimental investigation into a horizontal circular tube. They aimed to improve heat transfer using a dual nanoparticle nanofluid prepared as an aqueous dispersion of Al_2O_3 and CuO nanoparticles, with volume concentrations of 0.6%, 1.2%, and 1.8%. They used both plain and V-cut twisted tapes with a twist ratio valued at 9.25. The Reynolds number spanned the interval (3560–8320), and a constant heat flux was applied. At a nanoparticle volume fraction of 1.8%, a dual nanoparticle nanofluid in the plain tube increased heat transfer by 11.07% compared to water. Utilizing the standard tape resulted in a TPF measured at 1.33, whereas the dual V-notched tape yielded a value of 1.37.

Kumar et al. [38] utilized twisted tape in combination with a perforated conical insert to boost the heat-transfer efficiency of exchanger tubes. CuO/H_2O nanofluids were utilized at concentrations from 0.25% to 1.0%. Geometrical features, including the twist ratio (TL/WT) ranging from 3.33 to 4.38, the inlet-to-ring diameter ratio (DIR/DBR), and the ring pitch ratio (RP/DED), were examined at Reynolds numbers ranging from 6000 to 30000. Results indicate ideal thermo-hydraulic performance ($\eta_{TT} = 1.45$ at $Re = 6000$, with $DIR/DBR = 1.83$, $RP/DED = 1.76$, and $TL/WT = 3.50$). Nanofluid exhibits a 30% elevated Nusselt number with a 20% increased friction factor compared to pure water.

Varma et al. [39] numerically and experimentally investigated the efficiency of a dual-pipe heat exchanger incorporating twisted-tape enhancements, using a ferric oxide nanoparticle fluid. The research varied fluid velocity, nanoparticle concentration, and cut radius. Twisted-tape inserts operated at twist configurations (3, 5, 7), resulting in a marked augmentation of heat transfer. Also, the convection heat-transfer coefficient occurred at 50.29% flow rate and 27.32% nanoparticle concentration. The Nusselt number rose by 50.34% at optimal flow and by 34.25% at optimal concentration. Thermal performance peaked with 79.75% nanoparticle concentration and a 3.83% cut radius.

Ali et al. [40] computationally analyzed the thermal-hydraulic characteristics of a shell-and-tube heat exchanger (STHE) employing a ZnO /water nanoparticle-enhanced fluid. Nanoparticles measuring 30 nm in diameter were employed at volume concentrations (0.2%, 0.35%) at Reynolds numbers spanning (200–1400) under laminar counterflow circumstances. The Nusselt number improved by 10% and 19% at concentrations of 0.2% and 0.35%, respectively, alongside a minor elevation in the friction factor of 0.25–0.47%. The optimal thermal performance gain occurred at a 0.35% concentration, yielding an improvement of roughly 12% relative to the base fluid.

Ali et al. [41] numerically studied entropy reduction in a horizontal circular tube using a helical airfoil wire with ratios of pitch to diameter of 3, 4, and 5 in conjunction with CuO /water nanofluid. Nanoparticle concentrations were 0.15%, 0.39%, 1%, and 2%, under a uniform thermal flux ($25,000 \text{ W/m}^2$) and Reynolds numbers spanning 4,000–14,000. The finding demonstrated that helical wires with smaller pitch ratios reduced entropy and improved thermodynamic efficiency. Higher nanoparticle concentrations further decreased the Bejan number and entropy, enhancing system efficacy. Integrating helical inserts with CuO /water nanofluid improved efficiency by 5.08% to 11.7%.

Ali et al. [42] performed a computational investigation to elevate convection-driven heat transport within a horizontal pipe filled with a cupric oxide-water nanofluid. The study used twisted tapes with twist ratios of 4D, 6D, and 8D. Thermal behavior was analyzed within a Reynolds number spanning (4000–12000) under constant thermal flux at $25,000 \text{ W/m}^2$. The results indicated that reducing the pitch ratio, combined with higher nanoparticle volumetric percentages, considerably increased the heat transfer coefficient. A maximum heat transfer improvement of 228% was recorded at $PR = 4D$ and $Re = 12000$. Higher Reynolds values additionally contributed to improved thermal performance and reduced flow resistance. Twisted tapes with 6D and 8D twist ratios performed well but were not as efficient as the 4D design.

Ali and Tahir [43] reviewed the effect of employing twisted tapes, twisted tubes, in addition to nanofluids, on enhancing heat transfer performance. They proposed experimental studies to analyze geometric designs and ensure fluid stability, optimizing thermal performance efficiency.

Chaurasiya et al. [44] evaluated a tube-in-tube heat exchanger integrating twisted-tape augmentation devices featuring teeth-equipped rectangular V-shaped incisions and SiO_2 nanofluid. With Reynolds numbers spanning (6000–14,000) and an e/c value of 0.14, defined as the ratio between the tooth height and the cut depth. The friction factor increased 6.37-fold, and the heat transfer rate increased 87.73% relative to the standard pipe. An improvement of 18.27% in the Nusselt number was observed with teeth on the V-cut, although the friction factor increased by only 2.97%. At lower Reynolds numbers, tape adjustments enhanced thermal performance by 15.92 times, resulting in the best performance.

Assaf et al. [45] employed CFD simulations to achieve superior thermal behavior in the tubular heat exchanger. In their study, fixed special rings and twisted-tape inserts configured at twist ratios of 5, 10, and 15 were used. A water-based suspension incorporating hybrid Al_2O_3 and CuO nanoparticles up to 0.9% at Reynolds numbers spanning (6000–14000). An improvement in the Nusselt number by 36% with $TR = 5$ relative to a plain pipe. Using the nanofluid increased the TPF value by 3.29. Despite an increase in pressure drop, heat transfer improved significantly.

Karimpooremam et al. [46] utilized wire coil inserts and a 55 nm aluminum oxide nanofluid to achieve better efficient heat exchange in a tube-in-tube heat exchanger. Nanoparticle concentrations at 0.02%, 0.04%, 0.06%, with pitch ratios values at 0, 1, 1.6, 2.4, and Reynolds numbers of 4000 to 14000 were tested. The greatest Nusselt number boost of 135.6% occurred at $\phi = 0.06\%$, $Re = 14000$, and $pitch = 1$, whereas a 7.06% increase in the friction factor was recorded relative to the smooth tube without coils. Viscosity rose 21.16% at 20°C . A perceptron-based artificial neural network (3-22-1) was employed to develop and validate an empirical correlation for the Nusselt number, yielding high predictive accuracy ($R = 0.983$, $MSE = 11.2783$) [46].

Luo et al. [47] numerically studied a double-tube heat exchanger, where the configuration comprised an outer straight pipe with an internal twisted oval pipe, with air serving as the operating medium. Simulation work accounted for laminar and turbulent flow over Reynolds numbers ranging from 1000 to 15000. Three twist ratios (10, 15, and 20) and three aspect ratios (0.4, 0.5, and 0.6) of the inner tube were analyzed. The findings showed substantial improvement in thermal mixing due to secondary flow. A Nusselt number exhibited a 116% peak, accompanied by a 46% in the friction

factor relative to the standard pipe configuration. The highest heat transfer performance factor (JF) with a value of 1.9, occurred at an aspect ratio (0.4), where the twist ratio was 10.

Farnam et al. [48] performed a comprehensive computational and experimental investigation to assess the heat transfer and hydrodynamic behavior of a helical-twisted-pipe heat exchanger. Water functioned as the circulating medium, while the Reynolds number spanned (600–1200). Comparisons were conducted using a reference design in which the helical geometry was defined by a 100 mm helical diameter (hd) and a 20 mm pitch (hp), with the twist pitch (tp) measuring 100 mm. The Nusselt number improved by 14.2% as a result of this design, accompanied by a 7.7% increase in the friction factor. Results demonstrated that decreasing the helical diameter and twist pitch significantly enhances thermal performance. Optimal performance was observed at 50 mm helical diameter (hd) and a 100 mm twist pitch (tp), with Reynolds numbers of 900, yielding a performance index (1.98).

Luo and Song [49] used computational methods to evaluate the heat-transfer performance of a tube-in-tube heat exchanger formed by a pair of oppositely twisted oval conduits that create a unique twisted annulus between them. Water functioned as the circulating medium, and the study examined how aspect and twist ratios affect thermal and hydraulic performance across laminar and turbulent flow regimes. Strong longitudinal vortices improve heat transport, increasing the Nu value by 157% and the f-value by 118. The highest recorded TPF was 1.98.

Li et al. [50] performed a three-dimensional computational investigation to evaluate the thermo-hydraulic behavior on the shell side of dual-pipe heat exchangers featuring twist-shaped oval inner pipes. Simulations were run using air at Reynolds numbers spanning the interval (2700–22000). Geometric factors, including aspect ratio, twist pitch length, and twisting orientation, were examined. Twist-shaped oval pipes improve heat transfer performance by 24% to 39%, especially as the twist pitch length decreases while the inner pipe's dimensional ratio increases. Left- or right twisting had little effect on performance, whereas increasing the outer tube diameter decreased flow resistance and heat transfer.

Luo et al. [51] computationally presented a study of co-spiraled oval tubes featuring varying twist pitches, with air as the operating fluid, under a laminar regime at Reynolds numbers between 800 and 2000. The investigation of twist pitch ratios from 1.0 to 2.0 revealed that 1.5 is the best. At this amount, a 97% enhancement in the Nusselt number was observed, while the flow resistance parameter exhibited an increase of merely 43.7% compared to a conventional circular conduit. In comparison to equivalent twist pitches, Nu rose by 71.4% and f by 19%. At the appropriate twist ratio, a value of 1.75 for the thermal performance (JF) reached its optimal level. The design exhibits robust secondary flow, enhancing thermal mixing between hot and cold fluids. Correlations for Nu, f, and JF were established with variations of $\pm 12\%$, $\pm 6\%$, and $\pm 8\%$, respectively.

Razzaq and Mushatet [52] analyzed a helically twisted circular inner conduit placed within a tube-in-tube heat exchanger using a computational approach. The simulation utilized ANSYS Fluent to study twist ratios of (5, 10, 15) with Reynolds numbers spanning (5000–30000). A counter-flow design was employed, with heated water flowing through the inner conduit and cooling air circulation around the outer passage. Results indicated that the twisted conduit exhibited

enhanced thermal performance relative to the smooth conduit, owing to improved fluid mixing in the annular region. A twist parameter of 5 exhibited the maximum overall thermo-hydraulic effectiveness. And at a flow rate of 0.4962, the efficacy of the exchanger rose by 14.8%, while total performance was enhanced by 13% at a flow rate of 0.082 [52].

Ali and Tahir [53] conducted an experimental study on two double-tube heat exchangers: one incorporating a plain inner pipe and the other with a convoluted inner pipe, to improve heat transfer efficiency. The outer casing was composed of a vinyl-based polymer, but the inner pipe was fabricated from Cu-based alloy, measuring 1000 mm in length. Water served as the working fluid in a counterflow setup. Flow rates between 3 and 5 L/min were assessed to determine thermal performance. The twisted-tube exchanger exhibited enhanced performance, attaining a peak efficiency of 0.33 at 5 L/min and a maximum effectiveness improvement of 65.71% at 3 L/min. The friction factor decreased with increasing flow rate, with the optimal performance evaluation coefficient (PEC) achieved at 3 L/min in the twisted-tube exchanger.

Ali [54] computationally analyzed a concentric heat exchanger incorporating straight-flow conduits and twisted-flow conduits to evaluate its overall behavior. He used water and a nanofluid containing 0.1% CuO nanoparticles. The model included a convoluted inner tube, 1000 mm long, with 59 twists. Each twist was 5 mm in height and separated by 0.8 mm. ANSYS FLUENT was used to model counter-flow and thermal distribution. Results showed that the convoluted tube caused greater pressure loss and an elevated friction factor in comparison with the straight configuration. This influence was notably pronounced with the nanofluid. The convoluted tube's extended flow pathway enhanced thermal performance. A significant elevation in the Nusselt number was observed when the Reynolds numbers increased, reaching a peak of 110 at $Re = 10768$ with the nanofluid. This indicates substantial improvement in heat transfer for the convoluted conduit incorporating nanoparticles.

Investigation by Ghazanfari et al. [55] employed computational methods to analyze the behavior of a helical-coil heat exchanger (HCHE) featuring twisted elliptical flow conduits, rather than conventional circular conduits, over a Reynolds number spanning (10,000 to 100,000). Water functioned as the circulating medium. Twisted tubes improved heat transfer by as much as 35%, and nearly 25% reduced the resistance factor, owing to intensified turbulence and the highest effective heat-transfer area provided by the geometry. Four pitch lengths were subsequently analyzed: 11, 7.2, 5.5, and 3.6 mm, with 5.5 mm providing the most favorable trade-off between thermal efficiency and pumping demand. At reduced Reynolds numbers, the PEC was augmented by 20–33% but decreased to below 10% at elevated Reynolds numbers. A counter-flow arrangement involving twisted pipes resulted in a 10% enhancement of PEC.

Gomaa et al. [56] experimentally evaluated the thermo-hydraulic performance pertaining to the heat exchanger employing a single twisted spiral tube compared to a traditional smooth tube. The research tested three twist pitch ratios ($S/D_{hy} = 0.278, 0.372, 0.586$) and three depth ratios ($H/D_{hy} = 0.043, 0.068, 0.082$), within Reynolds number ranges of 5000–50000 in the inner pipe and 1400–10400 for the annulus. The findings revealed that employing a spiral configuration intensified turbulence mixing and reduced the thermal boundary layer, which consequently led to improved

thermal performance. The counter-flow configuration increased Nuc by 16% relative to the parallel-flow design. At $S/D_{hy} = 0.278$, the Nu increased by 38% alongside a 33.2% rise in the friction factor, whilst $H/D_{hy} = 0.082$ resulted in the most significant Nu enhancement of 44.9%, and 36.4% the friction factor increased. The peak TPFs attained were 1.93 and 2.03, respectively. New empirical correlations were established to accurately predict Nuc and f_c .

Ghazanfari et al. [57] presented a computational analysis of a helical heat exchanger featuring twisted elliptical flow conduits with pitch lengths of 17, 27, and 37 mm, where water serves as the heat transfer medium. The system behavior was examined for a set of Reynolds numbers: 1000, 1500, 2000, and 2500. A 27 mm pitch had the highest efficiency at $Re = 2500$, resulting in a 22% improvement in PEC. Performance decreases at lower Reynolds numbers. The study suggests selecting a 27 mm pitch to achieve an ideal equilibrium between efficiency and pressure drop. In addition, higher nanoparticle concentrations increase fluid viscosity and pumping power, which may offset thermal benefits. Therefore, many studies indicate that low to moderate concentrations provide a better balance between heat transfer enhancement and hydraulic performance. Improving dispersion stability and establishing reliable long-term evaluation methods remain essential for the practical and reliable application of nanofluids in heat exchanger systems.

6. ECONOMICS AND FEASIBILITY ANALYSIS

The application of heat transfer enhancement techniques in double-pipe heat exchangers must be evaluated not only in terms of thermal improvement but also in economic feasibility. Passive techniques such as twisted tape inserts and twisted tubes are generally economically favorable due to their simple implementation, low manufacturing cost, and significant heat transfer enhancement without major system modification. However, increased turbulence may lead to higher pressure drop and pumping power, which should be considered in long-term operation.

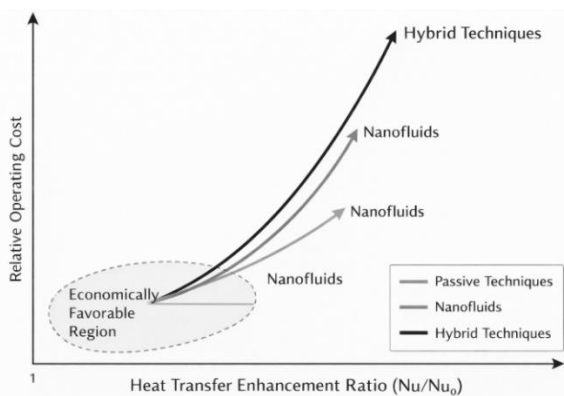


Figure 2. Conceptual relationships between the enhancement level and the relative operating cost for different techniques

Nanofluids enhance heat transfer through improved thermophysical properties, but their economic feasibility depends on nanoparticle cost, stability, and increased fluid viscosity at higher concentrations. Hybrid techniques combining geometric modifications with nanofluids provide the highest thermal performance but may involve higher operational and maintenance costs due to compounded

hydraulic penalties. Therefore, an optimal balance between heat transfer enhancement and pressure loss is required to ensure practical and economical operation, as seen in Figure 2.

7. CONCLUSIONS

This review summarizes recent developments in heat transfer enhancement of double-pipe heat exchangers using twisted tape inserts, twisted tubes, and nanofluids. Passive techniques remain practical and economically attractive due to their simple implementation and consistent improvement in heat transfer through enhanced turbulence and boundary layer disruption, provided that pressure drop penalties are properly controlled. Nanofluids improve thermal performance through enhanced thermophysical properties; however, their effectiveness depends strongly on nanoparticle type, concentration, and stability, with excessive loading often reducing overall efficiency due to increased viscosity.

The analysis indicates that heat transfer enhancement should be evaluated using combined thermo-hydraulic performance criteria rather than heat transfer improvement alone. Hybrid techniques show promising performance potential, but their feasibility depends on balancing thermal gains with hydraulic and operational costs. Future research should focus on optimization-based design approaches, improved nanofluid stability, standardized evaluation methods, and integrated thermo-hydraulic models to support practical and energy-efficient heat exchanger applications.

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