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Enhancing Thermal Performance in Double Pipe Heat Exchangers Using Combined Twisted Tape and Helical Tape Inserts: A Comprehensive Review and Research Framework

Harsh Narayan Shukla[1], Rakesh Kumar Patel[2], Bhrant Kumar Dandoutiya[3], Abhay Agarwal[4]
[1]*M.Tech Scholar, Rewa Engineering College, Rewa*
[2, 3, 4]*Assistant Professor, Rewa Engineering college, Rewa*

Abstract: This research explores the potential of systematic review and research framework to improve how efficiently heat is transferred in double pipe heat exchangers (DPHEs) using combined passive techniques—internal twisted tape inserts placed inside the pipe and helical tapes wrapped around the outside. Despite extensive studies on individual enhancement methods, a significant research gap exists in understanding their synergistic effects. This review synthesizes key findings from numerical and experimental studies on twisted tape geometries, thermal performance factors (TPF), and entropy generation. It identifies critical gaps, including the lack of empirical correlations for combined inserts and insufficient analysis of thermodynamic efficiency. The proposed research aims to evaluate how the Nusselt number and friction factor change with different Reynolds numbers develop empirical correlations for design optimization, and conduct entropy generation analysis to minimize irreversibility. The findings will contribute to the design of energy-efficient DPHEs for real-world industrial uses.
Keywords: Twisted tape inserts, Helical tapes, Thermal behavior and entropy generation in a double pipe heat exchanger performance factor

I. INTRODUCTION

Heat exchangers play a vital role in many thermal systems.in industries like power generation, chemical processing, and refrigeration. Simple add-on devices, such as twisted and helical tapes, that passively improve heat transfer improve thermal performance by disturbing the boundary layer and creating a swirling flow that enhances heat transfer. Although several studies have investigated these inserts separately, the combined impact of using internal twisted tape (TT) and external helical tape (HT) in double pipe heat exchangers (DPHEs) has not been thoroughly explored. This paper aims to bridge that gap by examining their combined influence on thermal performance and flow characteristics.

1) Reviews advancements in TT/HT-enhanced heat transfer.
2) Identifies gaps in combined insert configurations.
3) Proposes a research framework to optimize DPHE performance.

A comprehensive literature review has been undertaken to explore recent advancements in helping the system transfer heat more effectively. Over the years, the development of heat transfer enhancement techniques has progressed steadily, with significant a useful for designing and improving the efficiency of heat exchangers.This review primarily aims to investigate innovative approaches in heat exchanger design, with a particular emphasis on reducing system size and cost while improving thermal performance.

These advancements are critically evaluated in the broader context of energy conservation and efficiency improvement. The demand for energy-efficient thermal systems has driven significant interest in the enhancement of heat transfer mechanisms, especially within heat exchangers. Over the decades, researchers and engineers have explored a range of passive, active, and compound techniques aimed at improving thermal performance. This literature review synthesizes recent developments in this field, focusing on innovative strategies to lower the size and cost of heat exchangers while boosting their thermal efficiency The overarching goal is to identify technologies that contribute to energy conservation and sustainable thermal system design.

Heat exchangers are widely used in industries like power generation, HVAC, chemical processing, and automotive systems to manage thermal energy efficiently. transfer thermal energy between fluids at different temperatures. As energy efficiency and system compactness become increasingly important in engineering design, the demand for more efficient heat exchanger solutions continues to grow. The application of these enhancement techniques enables the designed to be more space-efficient and financially viable which contributes to material savings, lower energy consumption, and reduced manufacturing and operational costs. In addition, improved thermal performance can also lead to better system reliability and longer equipment lifespan.

Therefore, the integration of heat transfer augmentation technologies not only meets the growing thermal management demands but also aligns with economic and environmental goals. This paper explores various enhancement methods, their working principles, and their effectiveness in real-world applications.

II. NUMERICAL ANALYSIS

Xiong et al. [6] carried out a thorough investigation numerical investigation into the effects of conical and the impact of fusiform turbulators on heat transfer efficiency within double-pipe heat exchangers (DPHEs). The study evaluated 21 different configurations involving circular and rectangular inner tubes, over a wide range of Reynolds numbers through simulations carried out in ANSYS Fluent.

The results highlighted that circular inner pipes consistently yielded higher convective showed higher heat transfer coefficients than rectangular designs. Among the various enhancement techniques..geometries, fusiform turbulators outperformed conical designs, both considering heat transfer performance and the associated pressure losses This performance gain is attributed to the smoother and more stable vortex generation offered by fusiform inserts, which promotes better mixing and thermal boundary layer disruption.

The most effective configuration identified was the circular inner pipe with 12 mm fusiform turbulators, which delivered the highest performance index across all conditions tested. However, a particularly interesting result was observed with fusiform inserts with a 9 mm cross-section placed inside a rectangular pipe (aspect ratio = 0.72) at Reynolds number 4000. This setup outperformed a plain rectangular pipe by 4.58% and a turbulator-free circular pipe by 4.68% in terms of heat transfer coefficient, proving that under certain conditions, enhanced rectangular geometries can compete with optimized circular designs.

These findings highlight the effectiveness of carefully optimized turbulators in enhancing thermal performance. shapes and strategic geometric configurations to significantly improve thermal efficiency in small-scale heat exchanger setups The comprehensive review encompasses a range of enhancement techniques, including triangular fins, double-sided delta-wing tapes, helically twisted tapes, and twisted-ring turbulators. Each method exhibits distinct effects on convective heat transfer and frictional behavior. These findings offer valuable insights into the performance of heat exchangers equipped with inserts and helical tapes, thereby supporting the effective design and optimization of thermal systems for improved energy efficiency.

Several computational studies have been carried out to assess laminar flow behavior and heat transfer enhancement through various insert configurations within ducts and tubes. In one such study, researchers investigated laminar flow in a square duct fitted with twisted tape inserts. The analysis used a curvilinear formulation of the Complete Pressure Correction algorithm on a non-staggered, non-orthogonal grid. The simulation results showed a periodic axial development in both flow and thermal characteristics. Based on these findings, empirical correlations were established for the friction factor and Nusselt number, with the friction factor closely matching experimental data. Interestingly, the square duct demonstrated superior thermo-hydraulic performance compared to circular ducts with twisted tapes—especially at higher Prandtl numbers and lower twist ratios—even when air was used as the working fluid across specific Reynolds number ranges [5].

Xiong et al. [6] conducted a numerical investigation to evaluate how conical and fusiform turbulators affect thermal performance in double-pipe heat exchangers (DPHEs). Using 21 different configurations applied to both circular and rectangular tube geometries across a range of Reynolds numbers, the study employed CFD simulations via ANSYS Fluent. The results showed that circular inner pipes fitted with 12 mm fusiform turbulators achieved the highest convective heat transfer coefficients and thermal performance indices. Notably, a rectangular inner pipe with an aspect ratio of 0.72, equipped with 9 mm fusiform inserts at a Reynolds number of 4000, outperformed plain rectangular tubes by 4.58% and circular tubes without turbulators by 4.68% in terms of overall performance.

Further research focused on a microplate heat exchanger featuring a unique dimple pattern, diverging from conventional herringbone designs. Using both laboratory experiments and CFD simulations under single-phase water flow conditions, the study established direct boundary conditions for validating numerical models. Among the three turbulence models examined, the Reynolds Stress Model provided the most accurate heat transfer predictions. The results showed a proportional heat transfer coefficient, varying from 9,740 to 21,990 W/m²K, showed a strong dependence on Reynolds numbers in the range of 1170 to 4170 [7].

In another investigation, 3D numerical simulations were performed to analyse laminar convective heat transfer in a round tube heat exchanger using different double-V baffle designs to improve thermal performance These inserts were designed to create vortex and impinging flows that disrupt the thermal boundary layer, thereby enhancing both the convective heat transfer coefficient and overall efficiency. The simulations demonstrated a marked improvement in thermal performance due to the strategic deployment of the DVBs.

The implementation of double-V baffles (DVBs) in circular tube heat exchangers has also been numerically investigated for their influence on flow structure and convective heat transfer. The study demonstrated that DVBs significantly perturb The double-V baffles (DVBs) enhanced heat transfer by disrupting the thermal boundary layer through the generation of vortex and impinging flows. This active disturbance promoted better fluid mixing and surface interaction, resulting in significantly improved thermal performance. The study reported a maximum thermal enhancement factor of 3.55 and a Nusselt number ratio of 22.42, clearly demonstrating the effectiveness of DVBs in boosting heat transfer efficiency in the system [8].A comprehensive analysis based on the four E's—Energy, Exergy, Economic, and Environmental perspectives—was conducted on a compact air heat exchanger equipped with various twisted turbulator inserts and charged with ternary hybrid nanofluids (THNFs). The study examined the use of three types of turbulator inserts: Twisted Tape Insert (TTI), Perforated Twisted Tape Insert (PTTI), and Double Twisted Tape Insert (DTTI) within plain tube configurations. The results indicated a substantial improvement in thermohydraulic performance due to the synergistic effect of turbulator geometry and nanofluid composition. Among all configurations, DTTI in combination with THNF-6 exhibited the most favourable performance characteristics, including reduced operating costs and minimized equivalent CO_2 emissions, making it the most sustainable option [9].

Another numerical investigation focused on evaluating the the heat transfer efficiency of double-pipe heat exchangers integrated with W-cut twisted tape inserts. The study explored inserts with varying depth-to-width ratios ranging from 0.2 to 0.6, employing the Realizable k-ε turbulence model for simulation. The results indicated that the W-cut geometry influenced the flow field by creating distinct near-wall and core flow zones. A linear increase in the An increased heat transfer rate was recorded when using rising Reynolds numbers, reaching maximum enhancement at Re = 15,300. However, The implementation of W-cut twisted tapes led to a significant rise in the friction factor, despite a decreasing trend at higher Reynolds numbers. It was also noted that increasing the cut depth enhanced the an indicator that reflects the combined effect of thermal enhancement and pressure drop, particularly at lower Reynolds numbers, indicating an ideal trade-off between improved heat transfer and acceptable pressure losses [10]

III. COMPREHENSIVE LITERATURE REVIEW

Table 2.1 Outline of Literature Review on Twisted Tape

Author	Augmentation Technique	Flow Type	Nu	(f)	Remark
S. Jaisankar [11]	Helical Twisted Tape (Y = 3, 4, 5, 6)	Laminar	5.35%	8.80%	Higher twist ratios reduce swirl, leading to decreased heat transfer and friction.
P. Murugesan [12]	Square-Cut Twisted Tapes (Y = 2, 4.4, 6.0)	Turbulent	1.03–1.14 times	1.05–1.25 times	Square-cut tapes outperform plain twisted tapes in heat transfer.
P. Ferroni [13]	Short-Length Twisted Tapes (1.6 ≤ Y ≤ 6)	Turbulent	—	—	Compared to full-length tapes, the pressure drop decreased by a minimum of 50%
Khalid S. Syed [14]	Triangular Fins	Laminar	177.56%	40.27%	Increased fin count significantly affects system performance.
Smith Eiamsa-Ard [15]	Double-Sided Delta-Wing Tape (Alternative Axis)	Turbulent	165%	14.8 times	T-WA design surpasses T-W in both heat transfer and friction factor.
S. Eiamsa-ard [16]	Helically Twisted Tape (Y = 2, 2.5, 3)	Turbulent	127%	187%	Heat transfer and friction increase with lower twist and helical pitch ratios.

C. Thianpong [17]	Twisted-Ring Turbulators (Y = 1, 1.5, 2)	Turbulent	13.6%	109%	Best performance factor (1.24) achieved at low twist ratio with twisted tape.
Xiaoyu Zhang et al. [18]	Multiple regularly spaced twisted tapes	Laminar	182%	4.06 times	Significant increase in heat transfer enhancement
aZan Wu et al. [19]	Nanofluid (Alumina)	Laminar/Turbulent	--	--	Use of alumina nanofluids
M. Chandra Sekhara et al. [20]	Helical coil inserts + nanofluid	Turbulent	13.85%	--	Combined effect of coil inserts and nanoparticles Developed correlations for Nu and f
Heydar Maddah [21]	Modified twisted tapes with Al_2O_3	Turbulent	1.03–4 times	10.69%	Developed correlation for Nu and f
Rambir Bhadouriya [22]	Twisted square duct (Y=10.6, 15)	Laminar/Turbulent	10.6%–1.2%	--	Supports development of compact heat exchangers
John M. Gorman [23]	Helically corrugated pipe	Laminar	--	--	Strong swirl due to helical twist
Ranjith et al. [24]	Both side twist	Turbulent	1.5 times	--	--
Xiao Wei Zhu [25]	Wavy-tape insert	Turbulent	21.7–77.1% 1.01–0.39	3.5 times	Significant fin effect from twisted tape No significant improvement in enhancement factor in some configurations
M.R. Salem [26]	Segmental perforated baffles	Laminar/Turbulent	10.2% – 81.5%	--	Significant enhancement in both laminar and turbulent flow
Anas El Maakoul [27]	Helical fins on annulus	Turbulent	10.8% – 63.1%	24%	Inserts enhance thermal performance index.
M.R. Salem et al. [28]	Helical tape inserts (ratios: 0.33–1)	Turbulent	69.4% – 164.4%	6.7 times; 48.6–113.1%	Compact and lightweight, significant HTPI on annulus side
Wijayanta et al. [29]	Double-sided delta wing tape	Turbulent	--	177%	Nu, f, and TEF increase with wing width ratio
Akyürek et al. [30]	Wire coil turbulators + Al_2O_3 nanofluid	Turbulent	11.6 times	168.26%	Suitable for advanced heat transfer applications
Wei Wang et al. [31]	Outward helically corrugated tube	Turbulent	95.47%	--	Reduced shell diameters led to enhanced heat transfer, albeit with greater pressure losses.
C. Gnanavel et al. [32]	Twisted tape w/ rectangular cut + nanofluid	Laminar/Turbulent	--	--	Energy savings with combined nanofluid and twisted tape
Ahmad Vaisi et al. [33]	Perforated twisted tapes	Turbulent	--	--	Best thermal performance with perforated twisted turbulators
J.I. Corcoles [34]	Inner corrugated tubes	Turbulent	29%	4.15 times	Significant heat transfer improvement was observed with minimal pressure loss

Table 2.2 Literature Review with Geometry and its Findings

Authors	Geometry Used	Principal Findings
Maddah et al. [35]	Helical threads with TR = 5	Overall Nusselt number (Nu) increased by 32.91%; further boosted by 1.38× using 0.03% nanofluid.
Naik et al. [36]	Smooth tube + TT with TR = 5	Heat transfer coefficient (hc) improved by 27.95% with 0.5% CuO nanofluid; further enhanced to 76.06% with TT insert.
Naik et al. [37]	Ribbed tube + TT with TR = 2.7	Peak heat transfer efficiency (ηp) reached 1.57 with 0.7% CuO/H_2O nanofluid at Re = 6200.
Wongcharee & Eiamsa-ard [38]	Ribbed tube + TT with TR = 2.7	Peak ηp of 1.57 achieved using 0.7% CuO/H_2O nanofluid at Re = 6200.
Wongcharee & Eiamsa-ard [39]	Ribbed tube + TT with TR = 2.7	Same as above – ηp = 1.57 at Re = 6200 with 0.7% CuO/H_2O nanofluid.
Prasad et al. [40]	Helical strings with TR = 5	Nu improved by 32.91%; 1.38× enhancement using 0.03% nanofluid.
Suresh et al. [41]	Smooth tube with TT and Al_2O_3/H_2O nanofluid (y/D = 1.78–3)	Nu enhancement for H_2O: 156.3%, 122.2%, 89.3% at TR = 1.78, 2.44, 3. For Al_2O_3/H_2O: 166.9%, 128.7%, 89.3% at y/D = 1.78, 2.44, 3 respectively.

IV. EXPERIMENTAL INVESTIGATIONS

W. Date et al. [42] conducted a detailed experimental investigation to examine the pressure drop and heat transfer behavior of water flowing through a spirally grooved tube equipped with twisted tape inserts. The study covered a broad range of Reynolds numbers, encompassing both laminar and fully turbulent flow regimes. The spiral grooves were oriented clockwise, matching the direction of fluid flow. The researchers explored how groove orientation and twisted tape inserts with twist ratios of 10.15, 7.95, and 3.4 influenced the thermal performance of the system. The results demonstrated that the thermo-hydraulic performance was highly influenced by the twist direction—whether clockwise or counterclockwise. Under conditions of constant pumping power, the spirally grooved tube without twisted tape achieved a remarkable heat transfer enhancement of up to 400% in the laminar flow regime and 140% in the turbulent regime when compared to a smooth tube. When twisted tape inserts were added to the grooved tube, the combined configuration further amplified the heat transfer, reaching up to a 600% increase in the laminar region while maintaining the same 140% enhancement under turbulent conditions. These outcomes highlight the synergistic interaction between surface grooving and induced swirl flow generated by the twisted inserts, leading to substantial improvements in thermal performance. Promvonge [43] investigated the combined effect of wire coil inserts and twisted tapes on enhancing heat transfer and managing flow resistance within a circular tube exposed to a uniform heat flux, using air as the working fluid. Experimental findings revealed that using both inserts together nearly doubled the heat transfer rate compared to using either the wire coil or twisted tape alone. Additionally, configurations featuring smaller twist ratios and tighter coil pitches delivered better thermal performance than those with larger pitch ratios under the same conditions. These results underscore the critical role of optimizing insert geometry to maximize heat transfer efficiency while maintaining manageable flow resistance.

A. *Enhancement of Heat Transfer Using Conical Ring Turbulators with Twisted Tape Inserts*

P. Promvonge and S. Eiamsa-ard [44] conducted an experimental study to evaluate the combined effects of conical ring turbulators and twisted tape swirl generators on heat transfer performance, friction factor, and overall thermal enhancement efficiency in a circular tube. Air was used as the working fluid, and experiments were performed across a Reynolds number range of 6,000 to 26,000. The results showed that incorporating conical ring turbulators significantly boosted heat transfer, with a maximum enhancement of up to 367% compared to a smooth tube.

Further analysis revealed that lower twist ratios contributed to more favorable heat transfer outcomes throughout the studied Reynolds range. In particular, the combined configuration of conical ring turbulators with twisted tapes at twist ratios of 3.75 and 7.5 resulted in average heat transfer improvements of 367% and 350%, respectively, over the plain tube baseline. These findings underscore the synergistic role of geometric modifications in intensifying turbulence and disturbing the thermal boundary layer—key mechanisms for improving overall thermal system performance.

B. Effect of Corrugated Tubes and Modified Twisted Tapes on Heat Transfer Performance

Vamsi Mokkapati and Chuen-Sen Lin [45] carried out an in-depth analysis of gas-to-liquid heat transfer in a concentric tube heat exchanger, utilizing a corrugated inner tube combined with twisted tape inserts. Their research targeted the potential for recovering waste heat from the exhaust of a heavy-duty diesel generator, with a focus on improving engine performance and overall operational efficiency. Using computational simulations, they quantified the thermal enhancements offered by this hybrid configuration. The results showed a remarkable improvement—heat transfer was enhanced by approximately 235.3% compared to a plain tube and by 67.26% over a corrugated tube without twisted tapes. These findings emphasize the effectiveness of coupling surface corrugation with swirl-inducing inserts to boost energy recovery in industrial settings.

In a separate experimental study, Pranab Kumar Pal and Sujoy Kumar Saha [46] investigated the heat transfer and friction factor behavior in a circular tube fitted with twisted tapes featuring oblique teeth. They developed empirical correlations for both the Nusselt number and the friction factor. The inclusion of oblique teeth was found to significantly increase heat transfer compared to conventional plain tube setups. This improvement was primarily attributed to the enhanced turbulence and intensified thermal boundary layer disruption caused by the modified tape geometry.

C. Investigations on while also increasing flow resistance. Corrugated Tubes and Advanced Twisted Tape Insert Configurations

Ventsislav Zimparov [47] conducted experimental investigations on single-start spirally corrugated tubes integrated with twisted tape inserts of varying twist pitches. The study demonstrated that significant heat transfer enhancement could be achieved by optimizing the corrugation height-to-diameter ratio and minimizing the pitch of the twisted tapes. The results indicated that an optimal combination of spiral corrugations and twisted tapes not only improved thermal performance but also allowed for a reduction in the required heat transfer surface area, contributing to more compact and efficient heat exchanger designs.

In a related effort, Pongjet Promvonge et al. [48] analyzed the thermal performance of helically ribbed tubes fitted with double twisted tape inserts. The findings revealed that aligning the helical direction of the ribbing with the swirl flow generated by the twisted tapes led to synergistic turbulence effects, which enhanced heat transfer rates more effectively than ribbed or smooth tubes used in isolation under similar flow conditions.

Sujoy Kumar Saha et al. [49] investigated turbulent heat transfer and friction characteristics in square and rectangular ducts with axial corrugations, incorporating twisted tape inserts modified with oblique teeth. This dual modification—axial surface structuring combined with geometric tape alterations—resulted in a substantial increase in thermal performance, achieving up to a 55% improvement in heat duty under constant pumping power conditions compared to configurations without oblique-toothed inserts.

Further expanding on this theme, Ventsislav D. Zimparov [50] examined deep corrugated tubes with twisted tape inserts under single-phase turbulent flow conditions. The study systematically varied key geometric parameters, such as corrugation height-to-diameter ratio and twist pitch, and found that lower twist ratios yielded superior thermo-hydraulic performance. The enhanced surface area of the corrugated tube coupled with induced swirl from the tape inserts played a critical role in boosting heat transfer efficiency.

In another experimental study, S. Eiamsa-ard and P. Promvonge [51] assessed the heat transfer and friction factor behavior in a wavy circular tube containing helical screw tape inserts under uniform wall heat flux conditions. With air as the working fluid, the results demonstrated that both heat transfer and friction factor increased with Reynolds number. Notably, maximum improvements were observed at 2.67 times the heat transfer rate and 22.3 times the friction factor relative to a smooth tube, underscoring the potential of combining surface waviness with swirl-generating inserts for enhanced thermal system performance.

Xin et al. [52] conducted experimental investigations to evaluate the thermal and hydraulic performance of different working fluids—namely water, ethylene glycol, and ISO VG46 turbine oil—flowing through tubes equipped with three-dimensional internal expanded surfaces and copper twisted tape inserts, configured as either continuous or segmental. The study particularly focused on laminar flow conditions for turbine oil, where the integration of continuous twisted tapes with the enhanced internal surface significantly boosted thermal performance. Specifically, the Stanton number increased by as much as 5.8 times compared to smooth tubes.

However, this improvement in heat transfer came at the cost of a substantial rise in flow resistance, with the friction factor observed to be up to 6.5 times higher than in tubes without inserts. These results highlight the trade-off between heat transfer enhancement and pressure drop, emphasizing the importance of optimizing insert geometry and fluid properties for efficient thermal system design.

D. Influence of Twisted Tape Geometry and Spacing on Thermal Performance

Xin et al. [52] conducted a comprehensive experimental study to assess the convective heat transfer and frictional behavior of various working fluids—namely water, ethylene glycol, and ISO VG46 turbine oil—flowing through tubes equipped with three-dimensional internally expanded surfaces and copper twisted tape inserts, both continuous and segmental in form. The study found that using continuous twisted tape inserts substantially enhanced thermal performance, with the Stanton number rising by up to 5.8 times compared to smooth tubes. However, this improvement came at the cost of increased friction, with the friction coefficient escalating by nearly 6.5 times relative to configurations without inserts.

In a separate numerical investigation, Date et al. [53] applied two-dimensional elliptical partial differential equations to model fully developed laminar and turbulent flows. Their work offered valuable insights into how key parameters—such as Reynolds number, twist ratio, and Prandtl number—influence heat transport and friction behavior, particularly in laminar flow regimes.

P. Sivashanmugam et al. [54] performed an experimental evaluation on round tubes fitted with straight full-twist inserts, focusing on the effect of varying spacer distances (up to four inches) between inserts under turbulent conditions. Their findings revealed that reducing the spacing between inserts had minimal impact on heat transfer enhancement. Interestingly, the heat transfer coefficient improved at lower Reynolds numbers, suggesting that the inserts were more effective in low-flow conditions.

Anil Singh Yadav [55] examined the performance of a U-bend heat exchanger outfitted with half-length twisted tape inserts. The study observed a 40% enhancement in heat transfer compared to a plain tube, primarily due to the generation of swirl or vortex flows that disrupted the thermal boundary layer and increased turbulence.

Shyy Woei Chang et al. [56] explored the thermal behavior of tubes fitted with fractured twisted tape inserts of varying twist ratios. Results indicated that lower twist ratios led to increases in both local Nusselt numbers and Fanning friction factors. Compared to conventional smooth twisted tape, the fractured configuration delivered notable improvements: heat transfer coefficient, mean Fanning friction factor, and thermal performance factor were enhanced by factors ranging from 1.28 to 2.4, 2 to 4.7, and 0.99 to 1.8, respectively.

In a follow-up study, Chang et al. [57] introduced serrated twisted tape inserts featuring square-sectioned ribs symmetrically placed on both sides of the tape. Investigating twist ratios of 1.56, 1.88, and 2.81 across a Reynolds number range of 5000 to 25,000, they found that lower twist ratios led to significantly higher local Nusselt numbers and friction factors. The serrated tape design proved especially effective in enhancing heat transfer by increasing both fluid turbulence and the available convective surface area.

E. Effect of Spacing, Geometry, and Clearance in Twisted Tape Heat Exchanger Designs

A number of experimental and numerical studies have highlighted how geometric spacing, tape shape, and clearance within tubes can significantly influence the heat transfer efficiency of twisted tape-enhanced heat exchangers.

Pongjet Promvonge et al. [58] experimentally evaluated a double-pipe heat exchanger fitted with twisted tape inserts under two configurations: full-length tapes with different twist ratios, and regularly spaced tapes with varying free space ratios. Their findings showed that increasing the twist ratio led to improved heat transfer. However, it was the reduction in free space (i.e., tighter spacing between tape sections) that caused noticeable increases in both the heat transfer coefficient and the friction factor. This emphasized the role of geometric spacing in boosting fluid mixing and thermal exchange.

Complementing these experimental insights, A. W. Date and S. K. Saha [59] used a detailed numerical model to analyze laminar flow through tubes equipped with twisted tape inserts. By solving three-dimensional forms of the Navier–Stokes and energy equations, they demonstrated that heat exchanger performance could be optimized by using smaller connecting rods and increasing the number of tape turns. Their predictions closely aligned with real-world data, reinforcing the effectiveness of such design strategies.

Further advancing the design framework, Date and U. N. Gaitonde [60] integrated the axial momentum equation into their flow model for tubes with regularly spaced inserts. Their research produced empirical formulas to estimate the Nusselt number and friction factor, particularly for systems with a Prandtl number around 5. These predictive tools offer practical guidance for engineers in designing more efficient heat exchangers.

In terms of clearance, or the gap between the tape and the inner wall of the tube, Sami Al-Fahed and Walid Chakroun [61] conducted experimental tests to understand its impact in turbulent flow conditions. Their study found that wider tapes (resulting in tighter fits) led to greater heat transfer enhancements. The best performance was seen with low twist ratios and minimal clearance, making such configurations ideal for maximizing thermal output in high-flow systems.

Lastly, L. M. Chamra et al. [62] compared plain tubes, micro-fin tubes, and those equipped with twisted tapes under laminar oil flow. The results reaffirmed the importance of both twist ratio and tape width. Lower twist ratios generally improved heat transfer but came with higher pressure drops. The study concluded that loose-fit twisted tapes may be better suited for applications tolerating higher pressure loss, while tight-fit inserts should be used in designs that require efficient flow control with reliable heat performance.

F. Evaluating the performance of Twisted Tape Variants in Heat Exchangers

To further address the influence of twisted tape geometry and fitting conditions, L. M. Chamra et al. [62] concluded that loose-fit twisted tapes were preferable in applications characterized by low twist ratios and high-pressure drops, while tight-fit configurations were more effective in other operational scenarios, particularly where pressure drop control was critical.

In a numerical investigation, S. Ray and A. W. Date [63] examined the heat transfer and friction factor characteristics in a square duct fitted with twisted tape inserts under both laminar and turbulent flow conditions. Their analysis yielded empirical correlations for the Nusselt number and friction factor that closely aligned with experimental results. This strong agreement validated the reliability of their model and affirmed its potential for practical engineering applications in heat exchanger design.

Building on the performance evaluation of twisted tape geometries, Pongjet Promvonge [64] carried out an experimental study to assess the influence of varying twist ratios in a double-pipe heat exchanger. The findings confirmed that swirl flows generated by the twisted tapes significantly enhanced convective heat transfer. A maximum improvement of 188% in heat transfer was recorded when compared to a plain tube. However, as the twist ratio decreased—resulting in more intense swirl flow—the pressure drop also rose considerably. While lower twist ratios led to higher Nusselt numbers and thermal efficiency, the increased friction factor highlighted the classic trade-off between heat transfer enhancement and hydraulic resistance.

Further advancing this line of research, M. M. K. Bhuiya et al. [65] investigated the use of double counter twisted tapes in heat exchanger tubes. Their experimental results revealed a dramatic increase in thermal performance, with heat transfer rates rising by 60% to 240%, depending on the configuration. However, these gains came at a cost, with friction factors increasing by 91% to 286% compared to those in a plain tube. The dual swirling flows generated by the counter-twisted tapes were highly effective in breaking the thermal boundary layer and promoting turbulence, though they also led to a significant pressure penalty, as illustrated in Figure 1.

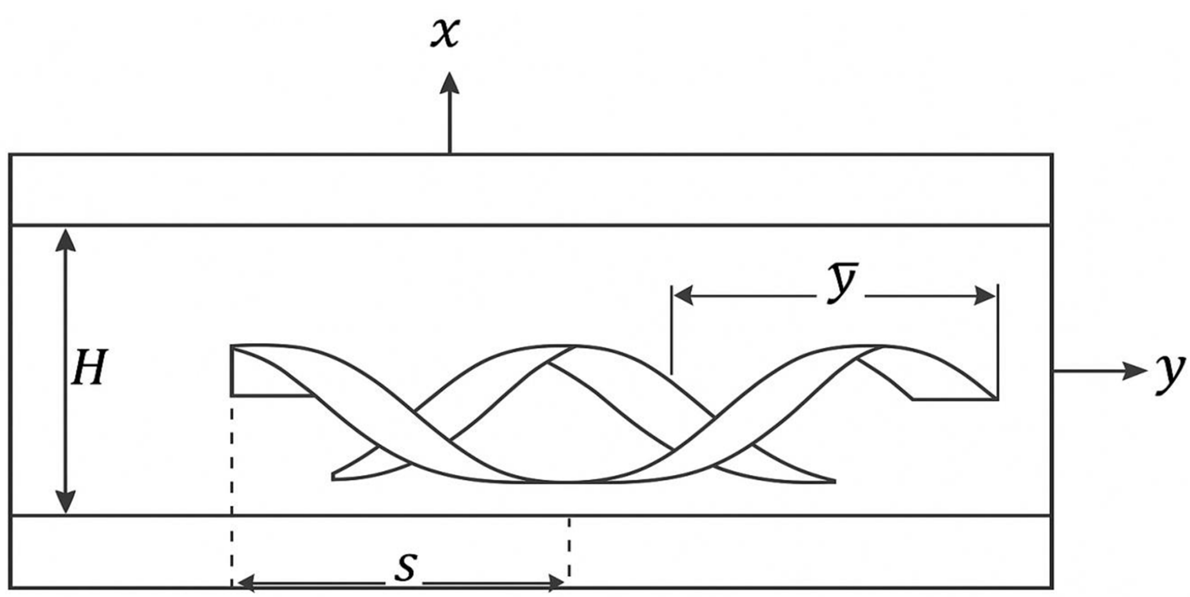

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Fig 1

G. Geometry of test section fitted with double counter twisted tape insert; (b) Geometric parameters of the double counter twisted tape insert. [65]

The experimental investigation by M. M. K. Bhuiya et al. [66] highlights the effectiveness of perforated twisted tape (PTT) inserts for enhancing convective heat transfer in circular tubes under turbulent air flow. By introducing four different porosity levels of PTTs under a uniform wall heat flux, the study found remarkable improvements in thermal performance. Specifically, the Nusselt number increased by 110% to 340% compared to that of a plain tube, signifying a substantial boost in heat transfer efficiency. This enhancement was primarily due to intensified swirl flow and boundary layer disruption caused by the perforations and twist.

However, the improved heat transfer came with a significant penalty in terms of pressure drop. The friction factor rose by 110% to 360%, a consequence of increased turbulence and flow obstruction. Despite this, the overall thermal performance factor still saw an increase of 28% to 59%, indicating that the gains in heat transfer effectiveness outweighed the losses due to increased flow resistance.

These findings suggest that perforated twisted tapes are highly beneficial in scenarios where maximizing heat transfer is critical, such as in high-efficiency heat exchangers. Yet, designers must carefully balance thermal benefits against pumping power requirements to ensure optimal system performance in Fig 2

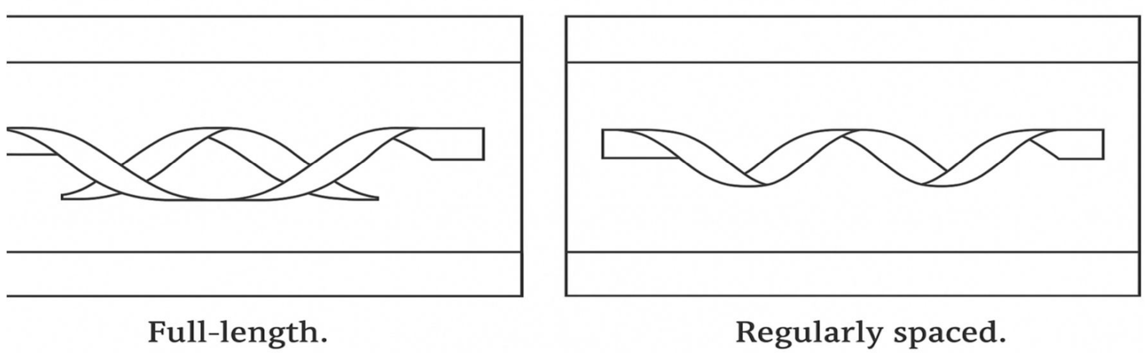

Fig 2 Full-length and regularly spaced twisted tape inserts

This literature review has provided a comprehensive overview of various heat transfer enhancement techniques, with a particular emphasis on the use of twisted tape inserts in diverse configurations. The work of researchers such as Vamsi Mokkapati, Chuen-Sen Lin, Pongjet Promvonge, and others spans a wide array of systems—including concentric tube heat exchangers, double-pipe setups, square ducts, and U-bend configurations—demonstrating the versatility of twisted tape technology across multiple engineering domains.

Consistently, these inserts have been shown to significantly boost heat transfer rates and overall thermal performance. While improvements in friction factor are often observed due to increased turbulence, the net gains in thermal efficiency often justify the additional pressure drops. Key design variables—such as twist ratio, pitch ratio, serration, perforation, and spacing—have been systematically explored, offering meaningful insights into their impact on flow behavior and heat exchange efficiency.

In particular, the numerical models and empirical correlations developed by researchers like A. W. Date and S. K. Saha have deepened the understanding of thermofluid dynamics in both laminar and turbulent flow regimes. These contributions not only validate experimental findings but also offer predictive tools for optimizing future designs.

Collectively, the reviewed literature underscores the effectiveness, adaptability, and engineering relevance of twisted tape inserts as a passive enhancement strategy. The insights gained from these studies lay a robust foundation for the next chapters of this thesis, where specific experimental investigations and detailed analyses will be conducted to address the research questions outlined in the introductory section.

V. ENTROPY GENERATION

Nagaraju et al. [67] conducted both experimental and numerical investigations into convective heat transfer and entropy generation in an Alternate Elliptical Annular Oscillating Tube (AEAOT) heat exchanger using graphene/water nanofluid. The study highlights the synergistic benefits of nanofluids and optimized heat exchanger geometry in enhancing thermal performance. The innovative elliptical tube design promotes intense swirl flow and enhances secondary flow regions, effectively thinning the thermal boundary layer. As a result, the Nusselt number increased by an average of 10.3%, 29.2%, and 39.1% for graphene nanofluid concentrations of 0.05%, 0.1%, and 0.2%, respectively, at an inlet temperature of 80 °C. Both the heat transfer coefficient and Nusselt number demonstrated significant improvement with increasing inlet temperature. Additionally, the study analysed entropy generation, reporting a reduction in the Bejan number with higher nanoparticle concentrations, indicating improved thermodynamic performance. The findings emphasize the critical role of AEAOT geometry—particularly the transition length and aspect ratio—in maximizing heat transfer while mitigating pressure losses.

Goh et al. [68] investigated entropy generation in turbulent convection within a heat exchanger equipped with self-rotating turbulator inserts. While such turbulators are effective in boosting heat transfer, they often lead to increased pressure drops due to intensified secondary swirling flows. This study examined how varying the inter-turbulator distance affects both heat transfer enhancement and entropy generation under turbulent forced convection conditions. Non-rotating and self-rotating turbulator inserts achieved maximum Nusselt number enhancements of 240% and 360%, respectively, although both configurations also exhibited elevated friction factors. As the spacing between turbulators decreased, both heat transfer and pressure drop increased. Notably, the rotating turbulator configuration proved thermodynamically favourable by reducing entropy generation by up to 202% compared to its non-rotating counterpart.

Wang et al. [69] presented a detailed entropy generation analysis of transient heat exchanger behaviour, offering valuable insights into design and operational efficiency. A dynamic model of a conventional recuperative heat exchanger was developed based on fundamental conservation equations of mass, momentum, and energy. The study employed the second law of thermodynamics to evaluate real-time entropy generation rates during transient operating conditions. The findings contribute to a deeper understanding of the temporal evolution of thermal irreversibility, offering design implications for improving the dynamic performance and sustainability of heat exchanger systems.

Wang et al. [69] also investigated entropy generation in the context of transient heat conduction and transfer in metals by introducing disturbances in the cold fluid flow rate. The analysis demonstrated that transient conditions lead to elevated entropy generation compared to steady-state scenarios. The study examined various influencing factors, concluding that higher thermal diffusivity of the metal reduces total additional entropy generation during transients. In contrast, increased metal thickness and higher specific heat capacity of the hot fluid contribute to greater entropy generation, highlighting the importance of material selection and fluid properties in transient heat exchanger design.

Kumar and Bhattacharyya [70] explored thermal performance enhancement in a Pillow-Plate Heat Exchanger (PPHE) incorporating Staggered Circular Welding Spot Configurations (SCWSCs). The study evaluated 25 design variations over a Reynolds number range of 1000 to 16,000, using dimensional and non-dimensional thermodynamic parameters such as the Nusselt number, friction factor, Bejan number, and entropy generation number. Results indicated that longer streamwise lengths in conjunction with SCWSCs induced the formation of elliptical recirculation vortices, which significantly enhanced thermal performance. The study reported maximum improvements of 41.58% in exergy efficiency and 1.54 in thermal performance factor at Re = 1000, under specific SCWSC configurations.

Ogulata and Doba [71] examined the performance of a cross-flow plate-type heat exchanger intended for waste heat recovery applications. Their experimental study assessed temperature distributions, air velocity, and pressure losses under controlled laboratory conditions. The analysis incorporated entropy generation minimization principles grounded in the second law of thermodynamics. Findings showed that the entropy generation number is closely tied to parameters such as optimal flow path length, dimensionless mass velocity, and heat transfer area. The study provided detailed graphical representations and commentary on these relationships, offering valuable insights into the design optimization of cross-flow heat exchangers.

Shahsavar et al. [72] conducted an in-depth entropy generation analysis in an oval twisted double-pipe heat exchanger utilizing a non-Newtonian nanofluid. The working fluid comprised a two-phase mixture of water and 0.5 wt.% Carboxymethyl Cellulose (CMC), with varying concentrations of CuO nanoparticles. Water was used as the heating fluid in the outer tube. Numerical simulations demonstrated that increasing the Reynolds number from 500 to 2000 led to higher thermal and frictional entropy generation. This behaviour underscores the trade-off between enhanced heat transfer and increased irreversibility when using nanofluids at elevated flow rates.

Raising the nanoparticle concentration (φ) from 0% to 3% significantly reduces both thermal and frictional entropy in the oval twisted double-pipe heat exchanger, as observed by Shahsavar et al. [72], with a more substantial effect on frictional entropy. At Re = 2000, increasing φ from 0% to 3% results in reductions of 9.2%, 15.3%, and 11.8% in thermal, frictional, and total entropy generation, respectively. The study also examines the influence of twisting pitch (2–6 mm), revealing that larger pitches lead to higher entropy generation—primarily due to increased thermal irreversibility (up to 24.2%). Moreover, the Bejan number decreases with increasing Reynolds number for all nanoparticle concentrations, while at constant Re, it tends to rise with increasing φ.

Hasan and Bhuiyan [73] investigated thermal and entropy characteristics in a helical heat exchanger equipped with various rib profiles using Al_2O_3-water nanofluid. Their steady-state computational fluid dynamics analysis, validated by experimental data, evaluated nine design configurations combining three rib profiles (2, 3, and 4 ribs) with three coil revolution counts (10, 20, and 30). Parameters such as Nusselt number, friction factor, thermal enhancement factor, and entropy generation were used to assess performance. Results show that increasing coil revolutions enhances both heat transfer and friction factor, with entropy generation rising accordingly. The configuration with 3 ribs and 10 revolutions offered the best overall performance, achieving a thermal enhancement factor of 1.34. Entropy generation increased by up to 19.5% with more coil revolutions for a constant rib profile.

Abdalla et al. [74] performed a numerical analysis of two-phase entropy generation and thermohydraulic behaviour in a heat exchanger using a hybrid nanofluid (CuO-diamond/Terminal) with various fin and turbulator configurations. The study investigated Reynolds numbers ranging from 14,000 to 26,000 and nanoparticle volume fractions up to 4%, employing a two-phase Eulerian-mixture approach with the k-ω turbulence model and SIMPLEC algorithm. Results showed that micro-fin tubes provided better pressure drop characteristics, while high-fin tubes offered the highest average Nusselt numbers. The greatest enhancement—32.67% in average Nusselt number—occurred at Re = 22,000 and ϕ = 4%. Despite higher pressure drops, the use of micro fins with hybrid nanofluids was favoured for reducing overall entropy generation.

In a study published in *Diamond and Related Materials* [75], researchers examined the heat transfer coefficient and entropy generation in a plate heat exchanger using water-based nanodiamond nanofluids. Experiments were conducted for φ ranging from 0% to 1%, Reynolds numbers from 140 to 610, and Peclet numbers between 895.78 and 3882.72. Findings showed substantial increases in heat transfer coefficient, Nusselt number, pressure drop, and pumping power with increased nanoparticle loading. At Re = 526.37 and φ = 1%, enhancements were observed in thermal performance, effectiveness, and exergy efficiency. While thermal entropy generation decreased with higher φ, frictional entropy increased, highlighting the thermodynamic trade-offs involved. The study also proposed new correlations for the Nusselt number and friction factor based on experimental results.

The research featured in the *International Journal of Thermal Sciences* [76] explored thermohydraulic performance, flow resistance, and entropy generation in a heated tube fitted with louvered winglet tape (LWT) under turbulent flow (Re = 4760–29,260). The study found that the Nusselt number and friction factor increased significantly as pitch ratio (PR) and winglet angle (θ) decreased. Entropy generation showed an inverse relationship with Re, PR, and θ, reaching minimum values under specific configurations, indicating optimized thermal performance with reduced irreversibility.

The collective body of research on entropy generation in heat exchangers underscores the pivotal role of advanced geometrical modifications, nanofluid integration, and thermodynamic optimization in improving heat transfer efficiency. Across these studies, innovations such as twisted tapes, elliptical tubes, helical coils, and turbulators consistently resulted in increased Nusselt numbers and better thermal performance. Simultaneously, entropy generation analyses illuminated the trade-offs between improved heat transfer and system irreversibility, guiding the design of more thermodynamically efficient systems.

Key thermodynamic indicators such as the Bejan number, entropy generation number, and exergy efficiency have proven instrumental in evaluating the impact of design and operating conditions on performance. Notably, nanofluids—including graphene, nanodiamond, and hybrid composites—demonstrated significant potential in enhancing heat transfer while mitigating entropy generation under specific flow and concentration conditions.

Furthermore, studies investigating transient processes revealed the dynamic nature of entropy generation and the importance of thermal diffusivity, fluid properties, and structural characteristics in real-time performance. Overall, these findings contribute to the development of next-generation thermal systems with higher efficiency and sustainability—critical for applications in waste heat recovery, industrial processing, and energy systems.

Based on the comprehensive review of experimental and numerical studies on twisted tape inserts for heat transfer enhancement, the following key conclusions have been drawn:

1) Increasing the length of twisted tape inserts results in higher Nusselt numbers, friction factors, and thermal performance criteria across a wide range of Reynolds numbers.

2) An increase in the number of twisted tapes—while keeping other parameters constant—leads to enhanced heat transfer and flow resistance, reflected by higher Nusselt numbers and friction factors.
3) Short-length twisted tapes positioned at the tube inlet are effective in improving the convective heat transfer coefficient and significantly increasing pressure drop.
4) Twisted tapes show greater effectiveness in laminar flow regimes than in turbulent conditions due to the dominance of viscous effects.
5) The twist ratio of the tape exhibits an inverse relationship with both the Nusselt number and friction factor; lower twist ratios yield higher heat transfer and flow resistance.
6) Special geometries such as U-cut and V-cut twisted tapes further improve the thermal performance compared to standard twisted tapes.
7) For the same twist ratio, using multiple short twisted tapes results in less pressure drop reduction than using a single full-length twisted tape.
8) When frictional losses are negligible, twisted tape inserts are equally effective in both laminar and turbulent flows.
9) The geometry or shape of the insert plays a critical role in determining the heat transfer enhancement and must be considered in design selection.
10) Helical screw tapes offer a greater enhancement in heat transfer compared to conventional twisted tapes due to more intense swirling flow generation.
11) For twisted tapes with surface cuts, Nusselt number and friction factor increase with the depth ratio and decrease with the width ratio.
12) The width of the twisted tape is inversely proportional to both the Nusselt number and the friction factor—narrower tapes yield higher enhancement and pressure drop.
13) The performance evaluation criteria (PEC) for all types of twisted tapes generally show an inverse relationship with Reynolds number, indicating that thermal enhancement tends to be more significant at lower flow rates.
14) Novel or modified twisted tape designs—such as those with serrations, perforations, or compound geometries—induce stronger swirl flow, resulting in superior heat transfer performance when compared to conventional twisted strips.
15) A higher magnitude of the performance evaluation criteria is a crucial factor for identifying and selecting the most efficient twisted tape configurations in heat exchanger applications.

VI. CONCLUSION

The research on entropy generation in heat exchangers highlights the effectiveness of geometrical modifications—such as twisted tapes, helical coils, and turbulators—and nanofluid integration in enhancing heat transfer. These enhancements lead to significant increases in Nusselt number and overall thermal performance, though often accompanied by higher frictional losses. Thermodynamic indicators like the Bejan number and exergy efficiency have been instrumental in evaluating these trade-offs and guiding the design of more efficient systems. Nanofluids, especially those based on graphene and hybrid nanoparticles, have shown strong potential in improving thermal conductivity while reducing entropy generation under optimized conditions.

Research on twisted tape inserts consistently highlights that key parameters—such as twist ratio, tape width, geometry (including V-cut, U-cut, and perforated designs), and tape length—play a critical role in influencing both heat transfer and flow resistance. In general, lower twist ratios and narrower tapes tend to improve thermal performance by promoting stronger swirl flows, although this typically results in higher pressure drops. More advanced configurations, such as helical screw tapes or compound geometries, have shown even greater effectiveness by further enhancing turbulence and mixing. When these optimized insert designs are used in conjunction with nanofluids, the combined effect can significantly boost heat transfer efficiency while minimizing entropy generation. This synergy offers promising potential for the design of high-performance heat exchangers, particularly in applications focused on energy recovery and industrial thermal management.

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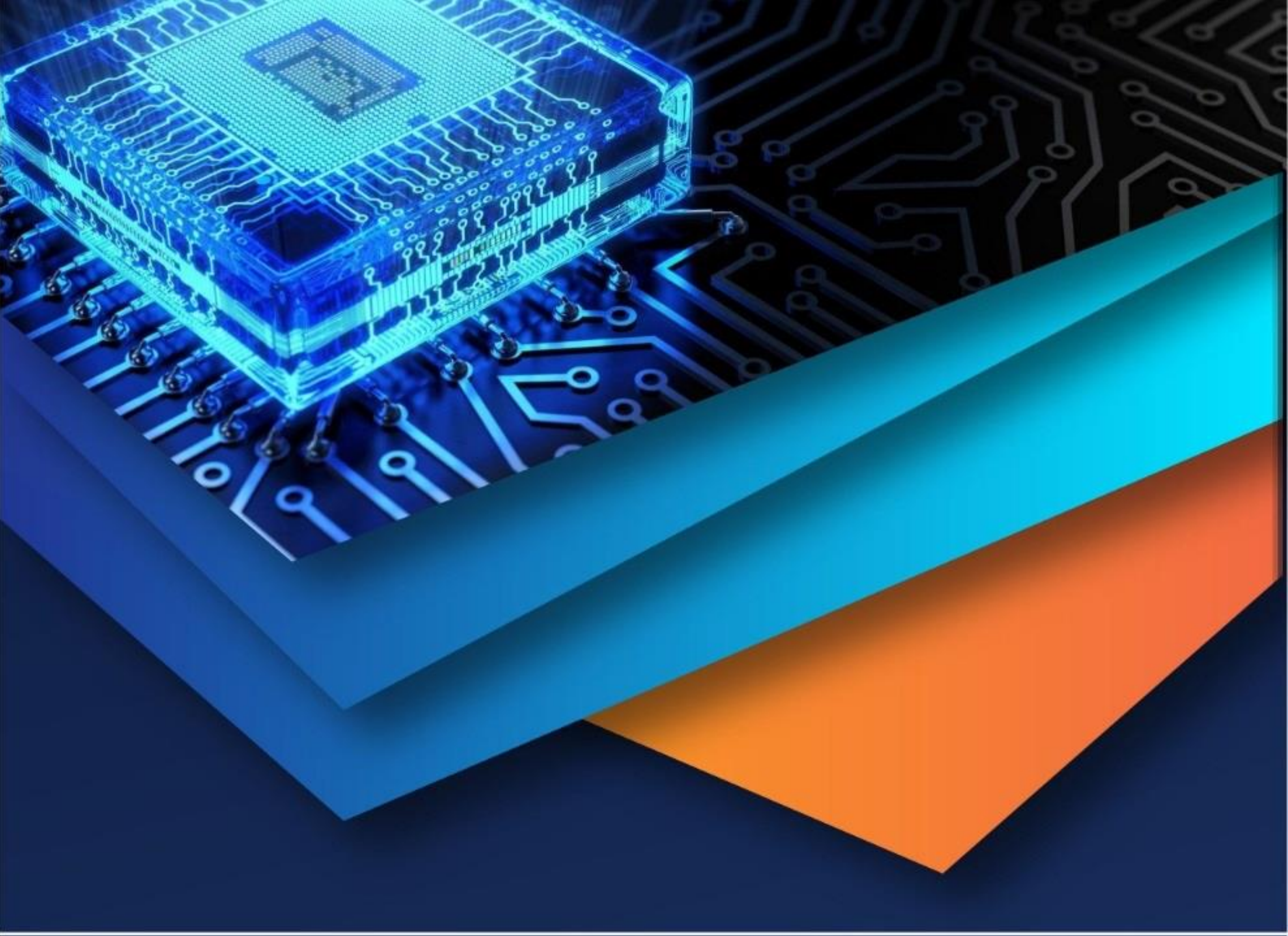

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