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Advancements in Heat Transfer Enhancement using Perforated Twisted Tapes: A Comprehensive Review

Shital Yashwant Waware[1,6]*, Pallavi Pankaj Ahire[2], Kiran Napate[3], Ramdas Biradar[2], Suhas Prakashrao Patil[4], Sandeep Sadashiv Kore[5] and Anant Sidhappa Kurhade[1,6]

[1]*Department of Mechanical Engineering, Dr. D. Y. Patil Institute of Technology Pimpri, Pune – 411018, Maharashtra, India; sywdit@gmail.com*

[2]*School of Engineering and Technology, PCET's Pimpri Chinchwad University, Sate, Pune – 412106, Maharashtra, India*

[3]*Department of Electronics and Telecommunication Engineering, PCET's Pimpri Chinchwad College of Engineering and Research, Ravet – 412101, Pune, Maharashtra, India*

[4]*Department of Mechanical Engineering, Arvind Gavali College of Engineering, Satara – 415015, Maharashtra, India*

[5]*Department of Mechanical Engineering, Vishwakarma Institute of Information Technology, Pune – 411048, Maharashtra, India*

[6]*School of Technology and Research, Dr. D. Y. Patil Dnyan Prasad University, Pune – 411018, Maharashtra, India*

Abstract

Improved heat transfer is crucial for better heat exchanger performance in many industries, from power plants to spacecraft. These methods facilitate improved energy utilisation, reduced operational expenses, and more compact system configurations, underscoring their critical role in ongoing research and development efforts. Typically classified into passive, active, and compound categories, these techniques cater to different needs: passive methods, devoid of external power requirements, are favoured for their simplicity, reliability, and cost-effectiveness. In contrast, active techniques harness external energy inputs to augment performance, while compound methods integrate advantages from both passive and active approaches to achieve synergistic outcomes. This review critically examines passive heat transfer enhancement techniques, highlighting recent advancements and their practical implementations across thermal systems. Key emphasis is placed on strategies like twisted tape inserts, perforated surfaces, and vortex generators, which disrupt boundary layers, induce turbulence, and enhance swirl flows to elevate convective heat transfer coefficients and optimise thermal performance without compromising system efficiency.

Major Findings: *The study highlights that perforated twisted tape inserts play a significant role in enhancing convective heat transfer by generating swirl flows, increasing turbulence, and reducing the thermal boundary layer thickness. Various geometrical modifications, such as rectangular-winged, alternate-axis, and dual twisted tapes, have demonstrated remarkable improvements in heat transfer performance, with enhancement rates reaching up to 219%, albeit with an associated increase in pressure drop. Overall, the review confirms that passive heat transfer enhancement methods, particularly optimised twisted tape designs, offer an energy-efficient and cost-effective solution for improving the thermal performance of heat exchangers across industrial applications.*

Keywords: *Heat Transfer Enhancement, Twisted Tape, Twist Ratio, Passive Methods*

**Author for correspondence*

1.0 Introduction

Heat transfer enhancement techniques are vital for optimising the performance and efficiency of heat exchangers, which are crucial in numerous industrial and engineering applications. Heat exchangers are essential in sectors such as process industries, thermal power plants, air conditioning, refrigeration, automotive radiators, and spacecraft cooling systems. Improving heat transfer in these systems leads to better energy utilisation, reduced operational costs, and more compact designs, making it a key focus of ongoing research and development.

As the demand for more efficient thermal systems increases, significant efforts are being made to enhance heat transfer performance. These advancements allow for better thermal energy management, resulting in cost savings and optimised system operation. The primary objective of these techniques is to improve heat transfer rates while effectively managing high heat fluxes, thereby achieving higher heat transfer coefficients at lower fluid velocities, reducing pressure drops, and lowering operational expenses. Figure 1 shows parallel and counterflow arrangements in a pipe heat exchanger, with fluids moving in the same or opposite directions, respectively.

Heat transfer enhancement techniques are generally divided into three categories: passive, active, and compound methods. Passive methods, which do not require external power sources, have gained considerable attention due to their simplicity, reliability, and cost-effectiveness, making them especially suitable for applications where energy conservation and ease of implementation are crucial. Active techniques, on the other hand, require external energy inputs to boost performance, while compound methods combine the benefits of both passive and active techniques for superior results.

This paper presents a comprehensive review of passive heat transfer enhancement techniques, emphasising recent developments and their practical applications in thermal systems. It specifically explores methods such as twisted tape inserts, perforated surfaces, and vortex generators, which enhance heat transfer by disrupting the boundary layer, increasing turbulence, and inducing swirl flows. These techniques have demonstrated significant improvements in convective heat transfer coefficients, Nusselt number, and overall thermal performance while maintaining system efficiency. The subsequent sections discuss the working principles, benefits, and challenges of these approaches, providing valuable insights for their implementation in heat exchanger systems.

Twisted-tape inserts, known for their efficiency, affordability, and ease of installation, are widely used in various industries to improve convective heat transfer. With a growing emphasis on energy and material conservation, as well as economic considerations, efforts have been made to develop more efficient heat exchanger systems. By conserving thermal energy, these systems enable cost-effective thermal management, improving the economic viability of heat exchangers. As the demand for high-performance thermal systems rises, interest in methods to enhance heat transfer, particularly for managing high heat fluxes, has increased. These techniques help heat exchangers achieve higher heat transfer coefficients at lower fluid velocities, reducing pressure drops and lowering operational costs.

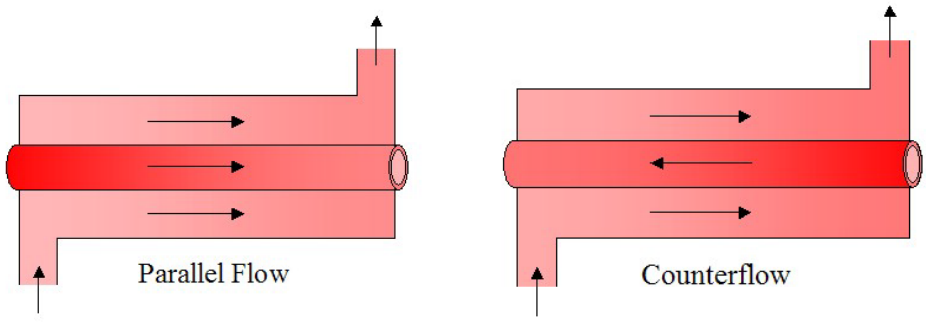


Figure 1. Parallel and counterflow pipes in the pipe heat exchanger.

2.0 Different Techniques

2.1 Active Heat Transfer Enhancement

Active heat transfer enhancement uses external power (*e.g.*, pulsations, magnetic fields, vibrations). Passive methods modify the surface or flow channel (*e.g.*, inserts, rough surfaces, extended surfaces). Compound methods combine active and passive techniques for greater enhancement.

2.2 Passive Heat Transfer Enhancement

Passive methods, as previously discussed, do not require external power sources. One of the most effective ways to improve convective heat transfer is by increasing the effective surface area and the residence time of the heat transfer fluid. This is typically achieved by techniques that induce swirl flows and disturb the boundary layer, which increases both the effective surface area and the fluid residence time, thereby improving the heat transfer coefficient in the existing system.

Heat transfer enhancement techniques are categorised into active, passive, and compound methods, each playing a crucial role in improving thermal system efficiency. Active methods require external energy input and include techniques like surface vibration, mechanical aids, fluid injection, impingement, suction, and fluid vibration, all of which enhance convection and turbulence. Passive methods rely on geometric modifications and material properties without external energy, employing strategies such as swirl flow, liquid/gas additives, extended surfaces, surface roughness, surface treatment, coiled tubes, surface tension devices, and displaced enhancement devices to improve heat transfer. Compound methods integrate both active and passive approaches, offering superior performance by maximising heat transfer while balancing energy consumption and system complexity. Selecting the appropriate technique depends on application requirements, cost considerations, and efficiency goals, making these enhancements vital for optimising heat exchangers, boilers, and industrial cooling systems. Figure 2 categorises heat transfer enhancement techniques into active, passive, and compound methods based on their mechanisms and energy input requirements.

Passive heat transfer enhancement techniques are generally more practical and cost-effective than active and compound methods because they do not require external energy input or complex control mechanisms. They rely on geometrical modifications, surface treatments, and turbulence-inducing inserts to improve heat transfer efficiency. However, their enhancement potential is often limited compared to active methods, which use external forces such as vibrations, magnetic fields, or electric fields to achieve higher heat transfer rates. Compound techniques combine both passive and active methods,



Figure 2. Heat transfer enhancement techniques: Active, passive, and compound methods.

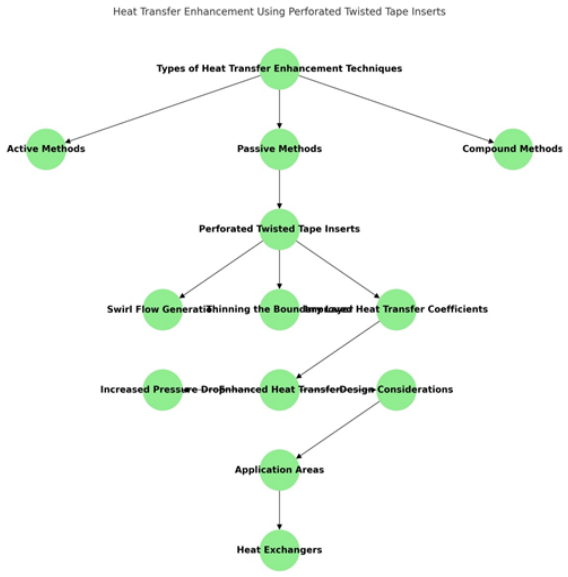


Figure 3. Heat transfer enhancement using perforated twisted tape inserts.

offering superior performance but at the cost of increased complexity and operational expenses. Ultimately, the choice depends on application requirements, feasibility, and economic considerations.

Nine common passive heat transfer enhancement methods: (i) Treated surfaces (pits/cavities), (ii) Rough surfaces (turbulent flow), (iii) Extended surfaces (fins), (iv) Displaced devices (fluid mixing), (v) Swirl flow devices (secondary circulation), (vi) Coiled tubes (vortices), (vii) Surface tension devices (liquid flow control), (viii) Liquid additives (drag/surface tension reduction), (ix) Gas additives (droplets/particles). Figure 3 illustrates how passive techniques like perforated twisted tape inserts enhance heat transfer in heat exchangers by generating swirl flow, thinning the boundary layer, and increasing heat transfer coefficients.

3.0 Review of Work Carried Out

Several studies explore heat transfer enhancement using twisted tape inserts. Eiamsa-ard *et al.*[1] found rectangular-winged Twisted Tapes (TT-RWs) doubled the Nusselt number compared to plain tubes, with a 0.3 wing-depth ratio being the most effective. Bas *et al.*[2] also showed helical tapes increased Nusselt number by 145-160%. Eiamsa-ard *et al.*[3] found alternating twisted tapes (C-CC) improved heat transfer by 219%. Silapakijwongkul *et al.*[4] showed Helically Twisted Tapes (HTTs) had lower Nusselt numbers but better thermal performance than conventional helical tapes. Eiamsa-ard *et al.*[5] found that twisted tapes with clearance enhanced heat transfer but increased pressure drop, with smaller clearance and twist ratios yielding higher Nusselt numbers. Joshi *et al.*[6] reviewed various heat transfer enhancement techniques. Thianpong *et al.*[7] showed perforated twisted tapes with parallel wings (PTT) achieved up to 208% heat transfer enhancement.

The table provides a comprehensive overview of key studies on heat transfer enhancement using various twisted tape insert techniques, including perforated, helical, and dual twisted tapes. It summarises the performance improvements in heat transfer rates and

Table 1. Heat transfer enhancement techniques

S. No.	Study	Key findings	Techniques used	Performance enhancement	Main focus
1	Eiamsa-ard *et al.*[1]	TT-RWs with a wing-depth ratio of 0.3 showed the highest Nusselt number, nearly double that of a plain tube.	Rectangular-winged Twisted Tapes (TT-RWs)	100% increase in heat transfer performance	Friction factor and heat transfer in tubes with TT-RWs
2	Bas *et al.*[2]	Twisted tapes increased heat transfer but also raised pressure drops, especially at higher Reynolds numbers.	Twisted tape swirl generators	Significant heat transfer enhancement with increased pressure drop	Flow friction and heat transfer with twisted tape swirl generators
3	Silapakijwongkul *et al.*[4]	C-CC twisted tapes and standard twisted tapes achieved 219% and 204% higher heat transfer rates, respectively.	Clockwise-Counterclockwise (C-CC) twisted tapes	204%-219% increase in heat transfer rates	Heat transfer and friction factor in a double-pipe exchanger

4	Joshi *et al.*[6]	Review of passive heat transfer methods with a focus on efficiency and minimal energy consumption.	Passive heat transfer enhancement techniques	Improved heat transfer efficiency without major system performance compromise	Passive heat transfer methods in heat exchangers
5	Thianpong *et al.*[7]	HTTs showed lower Nusselt numbers but higher thermal performance factors than conventional helical tapes.	Helically Twisted Tapes (HTTs)	Higher thermal performance factor despite lower Nusselt numbers	Comparison of HTTs and CHTs for heat transfer enhancement
6	Seemawute *et al.*[8]	Twisted tapes with alternate axes showed better fluid mixing and heat transfer performance at lower twist ratios.	Alternate axis twisted tapes (TA)	Better mixing and higher heat transfer at lower twist ratios	Flow and heat transfer with twisted tapes consisting of alternate axes
7	Giri *et al.*[10]	Twisted tape inserts enhance heat transfer by increasing turbulence, but increase friction factors.	Various twisted tape inserts	Higher heat transfer and friction factors with tape inserts	Heat transfer characteristics using tube inserts
8	Ray *et al.*[11]	Wire coil inserts enhance heat transfer by up to 200% in transitional flow regions, though pressure drop increases.	Wire coil inserts	200% increase in heat transfer in transitional flow regions	Heat transfer enhancement with wire coil inserts
9	Eiamsa-ard *et al.*[12]	Perforated twisted tapes enhanced heat transfer by 208%, compared to plain tubes, and reduced pressure loss.	Perforated twisted tapes with parallel wings (PTT)	208% increase in heat transfer, optimised pressure loss	Heat transfer and pressure drop using perforated twisted tapes
10	Eiamsa-ard [13]	Dual twisted tapes showed a 12%-29% increase in heat transfer compared to single tapes.	Dual twisted tapes	12%-29% increase in heat transfer	Effects of dual twisted tapes on heat transfer enhancement

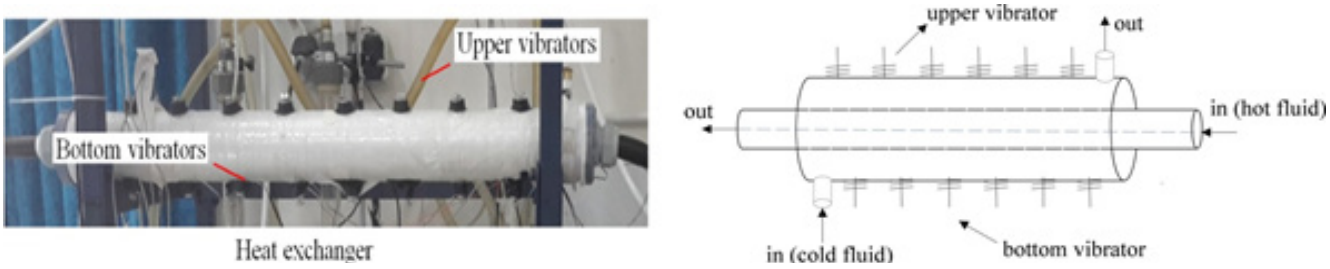


Figure 4. The double-pipe heat exchanger was used in the experiment[50].

thermal efficiency, highlighting the associated challenges such as increased pressure drops and friction factors. Table 1 summarises various heat transfer enhancement studies using twisted tape techniques, highlighting significant improvements in heat transfer rates along with associated pressure drops and flow friction considerations.

The table summarises key research findings on heat transfer enhancement using various twisted tape insert techniques, including perforated, helical, and dual twisted tapes. It highlights the performance improvements in heat transfer rates and thermal efficiency, alongside associated challenges such as increased pressure drops and friction factors.

Several studies have investigated heat transfer enhancement. Seemawute *et al.*[8] found that twisted tapes with alternate axes (TA) performed better than conventional Twisted Tapes (TT). Joshi *et al.*[9] analysed the effects of twisted tapes and annular protrusions. Giri *et al.*[10] reviewed tube inserts, highlighting that while twisted tapes enhance turbulence, they also increase pressure drop, whereas conical rings provide improved heat transfer. Ray *et al.*[11] examined wire coils and reported significant heat transfer improvements in transitional flow. Eiamsa-ard *et al.*[12] found that dual twisted tapes outperformed single tapes. Vermahmoudi[14] and Mohammed *et al.*[15] studied nanofluids, showing significant Nusselt number enhancements. Kurhade *et al.*[16-17,19-21], Kurhade and Murali[18], Waware *et al.*[22,24], Waware and Kore[23] and Khot and Kadam[25], Khot and Kadam[26], Khot *et al.*[27,29], and Khot and Rao[28] investigated various techniques, including materials, inserts, and CFD. Further research has examined electronic cooling[30-39], aerofoil optimisation, and mechanical behaviour of curved plates, electronic component thermal performance, and CFD optimisation of heat exchangers[40-49]. Figure 4 shows a double-pipe heat exchanger setup with upper and bottom vibrators used to enhance heat transfer during experimental analysis.

The study investigates the impact of twisted tape inserts with circular holes on forced convection heat transfer enhancement. Experimental results demonstrate a significant improvement in heat transfer performance compared to plain twisted tapes. The modified inserts promote better fluid mixing and turbulence, leading to increased heat transfer rates. These findings provide insights for optimising heat exchanger designs for improved thermal efficiency[50].

4.0 Conclusion

This paper offers a critical review of passive methods for improving heat transfer performance, with a particular focus on perforated twisted tape inserts.

- The review examines passive heat transfer enhancement techniques, emphasising the use of perforated twisted tape inserts.
- Perforated twisted tapes improve convective heat transfer by generating swirl flows in the fluid, which disrupt the thermal boundary layer at the tube surface.
- These inserts modify the surface geometry, promoting increased turbulence and vortex motion, resulting in a thinner boundary layer.
- The application of twisted tape inserts leads to higher heat transfer coefficients and enhanced Nusselt numbers, thereby boosting overall thermal performance.
- Various twisted tape insert geometries were investigated to evaluate their impact on heat transfer efficiency.
- While effective at improving heat transfer, twisted tape inserts contribute to increased pressure drops within the tube.

- Despite these higher pressure drops, the improvement in thermal performance typically outweighs the associated drawbacks.
- Perforated twisted tapes present a promising solution for enhancing heat transfer in heat exchangers while preserving system efficiency.
- Ongoing research focused on optimising the design of these inserts could help reduce pressure losses and enhance their practical applicability.
- The study underscores the potential of perforated twisted tapes to provide more efficient and cost-effective thermal management in industrial systems.

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