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Experimental Investigation of Heat Transfer Improvement Using Perforated Helical Twisted Tapes in a Tube-In-Tube Heat Exchanger

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Abstract

This study presents a comprehensive experimental analysis of thermal performance enhancement in a tube-in-tube heat exchanger by integrating Perforated helical Twisted Tape (PTT) inserts. The investigation focuses on the effects of varying perforation diameter ratios (d/W = 0.2, 0.4, 0.6) and pitch ratios (y/W = 2.5, 3.5, 4.5) on heat transfer characteristics, friction factor, and pressure drop. Results reveal that PTT inserts significantly improve convective heat transfer by inducing enhanced swirl flow and turbulence, which disrupts the thermal boundary layer and intensifies fluid mixing. The highest thermal enhancement—an increase of 226% in Nusselt number was achieved with a PTT configuration of d/W = 0.4 and y/W = 4.5, yielding a thermal performance factor of 1.93. Furthermore, the study demonstrates that larger perforations and wider pitch ratios reduce flow resistance and pressure drop, improving energy efficiency without excessive pumping power requirements. Comparative evaluations with plain tubes and non-perforated twisted tapes confirm the superior performance of optimised PTT designs.

Major Findings: *The experimental findings are well-supported by quantitative analysis, including Nusselt number variation, friction factor behaviour, and performance evaluation criteria. These results not only validate the effectiveness of perforated inserts but also provide valuable design insights for developing compact, high-efficiency heat exchangers. The proposed technique holds strong potential for implementation in automotive, chemical, and thermal power systems, where enhanced heat transfer with minimal energy penalties is critical.*

Keywords: *Heat Transfer Enhancement, Perforated Twisted Tapes, Pressure Drop, Thermal Performance, Tube-in-Tube Heat Exchanger*

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1.0 Introduction

Effective energy utilisation is a critical need in today's world, which necessitates the efficient development of equipment. Heat exchangers play a vital role in facilitating the exchange of heat between two media and are widely used in various applications, such as automotive systems, air conditioning, oil refineries, and large-scale chemical processes. Improving the performance of heat exchangers requires cost-effective designs that consider material selection, energy efficiency, and operational savings.

Optimising energy utilisation has become a fundamental necessity in modern industries, driving the need for highly efficient equipment. Heat exchangers, which facilitate thermal energy exchange between two fluids, are essential components in a wide range of applications, including automotive systems, air conditioning, oil refineries, and large-scale chemical processing. Enhancing their performance requires innovative and cost-effective designs that prioritise material efficiency, energy conservation, and operational sustainability.

The efficiency of a heat exchanger is largely influenced by its design parameters and operating conditions. Research indicates that fluid flow behaviour within a heat exchanger is strongly dependent on its geometry. By optimising structural configurations, it is possible to maximise the heat transfer coefficient while adhering to design constraints. The ultimate objective is to achieve high thermal efficiency within a compact surface area, thereby increasing heat flux and improving overall system effectiveness.

Heat transfer augmentation techniques are crucial for improving thermal performance, leading to significant energy savings, material cost reduction, and enhanced system reliability. These methods, commonly referred to as heat transfer enhancement strategies, focus on reducing thermal resistance and increasing convective heat transfer. Effective implementation of these techniques can significantly enhance the heat exchange process, making systems more efficient and sustainable.

Several augmentation approaches have been developed to improve heat transfer efficiency. These include surface roughening, extended surfaces, fluid or structural vibrations, electrostatic field applications, vortex generators, and the integration of inserts such as twisted tapes and wire matrix coils. While these techniques can substantially improve thermal performance, their implementation must be carefully evaluated.

In specialised applications, such as space vehicle heat exchangers, where size and weight limitations are critical, heat transfer enhancement methods become indispensable. However, these strategies often introduce trade-offs, including increased costs, additional weight, and higher pumping power requirements. As a result, engineers and designers must carefully assess the advantages and limitations of each technique to achieve an optimal balance between efficiency, feasibility, and cost-effectiveness.

2.0 Heat Transfer Augmentation Techniques

Enhancing the heat transfer rate in a heat exchanger is known as heat transfer augmentation, a crucial approach for improving thermal performance and achieving cost-effective system design. Various augmentation techniques are employed to maximise efficiency while minimising energy consumption and operational costs. These methods are generally classified into three categories: Passive, Active, and Compound techniques.

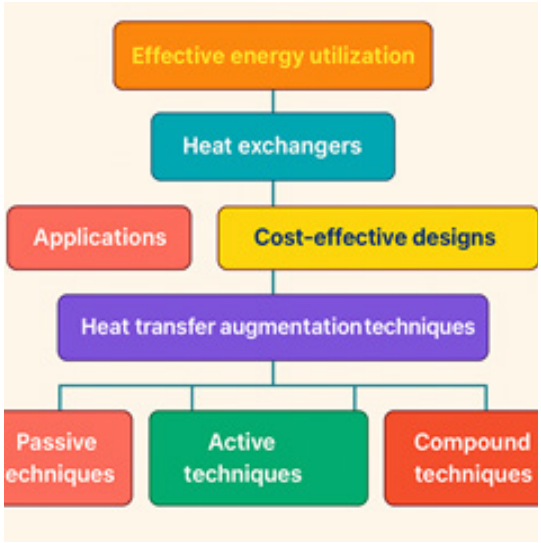


Figure 1. Classification of heat transfer augmentation techniques for efficient energy utilisation in heat exchangers.

2.1 Active Techniques

These methods require an external power source to improve heat transfer. They may involve mechanical, electrical, or magnetic influences to modify fluid flow characteristics or thermal properties. Examples include surface vibrations, electrostatic fields, and the use of induced pulsations to enhance convective heat transfer.

2.2 Passive Techniques

Unlike active methods, passive techniques do not require additional power input. Instead, they rely on structural modifications to the heat exchanger, such as changes in surface geometry, the incorporation of extended surfaces, or the use of turbulence-inducing inserts like twisted tapes and wire coils. These alterations enhance fluid mixing and disrupt thermal boundary layers, leading to improved heat transfer.

2.3 Compound Techniques

This approach combines two or more augmentation methods to achieve superior thermal performance. By integrating both active and passive strategies, compound techniques offer enhanced heat transfer rates and improved thermo-hydraulic efficiency, making them highly effective for advanced engineering applications.

3.0 Literature Review

Heat exchangers are essential components in mechanical and process industries, playing a critical role in the efficient utilisation, conversion, and recovery of thermal energy. They are widely employed in applications such as steam generation and condensation in power plants, as well as in heating and cooling processes across various industrial sectors. Enhancing the performance of heat exchangers remains a key area of research, with a primary focus on maximising heat transfer efficiency while maintaining pressure drops within acceptable limits.

Heat transfer enhancement is crucial for improving the efficiency of heat exchangers in various industrial applications. Extensive research has been conducted to develop innovative methods that maximise heat transfer rates while maintaining optimal pressure drop conditions. Eiamsa-ard *et al.*,[1] found that full-length twisted tapes improve thermal performance more effectively than regularly spaced ones. Kumar *et al.*,[2] highlighted that twisted tapes enhance turbulence and heat transfer but also increase friction factors. Azmi *et al.*,[3] examined SiO_2/water and TiO_2/water nanofluids in twisted tape-enhanced tubes, finding a 27.9% and 11.4% increase in heat transfer coefficients, respectively. Zohir[4] demonstrated that a downstream propeller swirl generator improves heat transfer in a sudden expansion pipe. Eiamsa-ard *et al.*,[5] showed that combining twisted and helical screw tapes enhances heat transfer by 10% over single-tape methods. Kuzma-Kichta *et al.*,[6] investigated double-thread screw knurling in tubes, identifying optimal heat transfer conditions between Reynolds numbers 7000 and 30000. Agrawal *et al.*,[7] analysed twisted tape inserts in heating and cooling applications, revealing that the Nusselt number increased up to 5.35 times under constant pumping power conditions.

Al-Fahed *et al.*,[8] studied the effect of tube-tape clearance on heat transfer, concluding that smaller twist ratios and tighter fits achieved higher thermal performance. Al-Fahed and Chamra[9] compared twisted tape inserts, microfin tubes, and plain tubes in laminar flow, finding that twisted tapes performed best at smaller twist ratios. Liao *et al.*,[10] explored three-dimensional internal extended surfaces (3DIEST), which significantly enhanced heat transfer for highly viscous fluids. Thianpong *et al.*,[11] found that perforated twisted tapes improved heat transfer by up to 208%, with the highest thermal performance factor of 1.33 at a Reynolds number of 5500. Tamna *et al.*,[12] examined V-ribbed twisted tapes, achieving a maximum enhancement factor of 1.4. Nanan[13] investigated perforated helical twisted tapes (P-HTTs), which reduced friction losses while maintaining high heat transfer rates, with optimal performance at a Reynolds number of 6000. This review highlights that twisted tapes, perforations, extended surfaces, and hybrid strategies effectively enhance heat exchanger performance, leading to improved thermal efficiency, energy savings, and sustainability. The best performance was observed at a Reynolds number of 6000, with a maximum thermal performance factor of 1.28 achieved using a perforation diameter ratio of 0.2 and a pitch ratio of 2.0. This comprehensive review highlights the advancements in heat transfer augmentation techniques. The studies demonstrate that modifications

Table 1. Summary of heat transfer enhancement techniques in the literature

Sr. No.	Reference	Study Focus	Key Findings
1	Eiamsa-ard *et al.*[1]	Comparison of regularly spaced and full-length twisted tapes	Full-length twisted tapes provided higher heat transfer rates and friction factors compared to regularly spaced tapes.
2	Rahul Kumar *et al.*[2]	Swirl flow behaviour and twisted tape inserts in laminar flow	Twisted tapes increased turbulence, resulting in higher heat transfer coefficients and friction factors. Long-term performance and economic analysis were emphasised.
3	Azmi *et al.*[3]	Nanofluids (SiO_2/water and TiO_2/water) with twisted tapes	Heat transfer enhancement decreased with increasing twist ratio. SiO_2/water (3%) improved heat transfer by 27.9%, while TiO_2/water improved by 11.4% compared to water.
4	Zohir[4]	Propeller swirl generator in turbulent flow	Downstream placement of the propeller led to better heat transfer performance than upstream placement.
5	Eiamsa-ard *et al.*[5]	Combination of twisted and helical screw tapes	Combined swirl flow improved thermal performance by 10% over single-tape methods.
6	Kuzma-Kichta *et al.*[6]	Heat transfer enhancement using double-thread screw knurling	Optimal parameters for heat transfer improvement were within Reynolds numbers 7000–30000. Screw threads influenced both heat transfer and pressure drop.
7	Agrawal *et al.*[7]	Twisted tape inserts in the heating and cooling of Servotherm oil	Isothermal friction factor increased by 3.13–9.71 times compared to plain tubes. The Nusselt number increased by up to 5.35 times.
8	Al-Fahed *et al.*[8]	Effect of tube-tape clearance on heat transfer	Smaller tube-tape clearance improved heat transfer. Tight-fitting twisted tapes with smaller twist ratios performed best.
9	Al-Fahed and Chamra[9]	Comparison of twisted tapes and microfin tubes in laminar flow	Twisted tapes were the most effective for heat transfer enhancement. Microfin tubes showed minimal improvement in heat transfer and pressure drop.
10	Liao *et al.*[10]	3D internal extended surface tubes	The 3DIEST technique significantly improved heat transfer for viscous fluids in laminar flow, with moderate improvement in turbulent flow. The friction factor increased considerably.
11	Thianpong *et al.*[11]	Perforated twisted tapes in turbulent flow	Perforated twisted tapes achieved heat transfer enhancement up to 208%. The highest thermal performance factor of 1.33 was at Reynolds number 5500.
12	Tamna *et al.*[12]	V-ribbed twisted tapes in round tubes	Higher Reynolds numbers and blockage ratios improved heat transfer. The maximum enhancement factor for V-ribbed twisted tapes was 1.4.
13	Nanan[13]	Perforated helical twisted tapes (P-HTT)	P-HTTs reduced friction losses while maintaining high heat transfer rates. Best performance was at Re = 6000 with a thermal performance factor 1.28.

such as twisted tapes, perforations, extended surfaces, and hybrid enhancement strategies effectively improve heat exchanger performance. By optimising these techniques, industries can achieve better thermal efficiency, energy savings, and overall operational sustainability.

The table summarises various heat transfer enhancement techniques, their study focus, and key findings from existing research.

Salimpour[14] explored the heat transfer characteristics of temperature-dependent engine oil in shell-and-coiled tube heat exchangers, concluding that smaller coil pitches result in higher heat transfer coefficients, particularly at elevated temperatures. Kurhade *et al.*,[15-20], Waware *et al.*,[21-23] and Khot *et al.*,[24-28] have investigated various heat transfer enhancement techniques, including material selection, twisted tape inserts, and Computational Fluid Dynamics (CFD) analysis. Kurhade *et al.*,[29-31] examined solar collector performance and the impact of biodiesel and dimethyl carbonate blends on engine efficiency, while Waware *et al.*,[32] reviewed studies on nanofluids in heat exchangers. Further research by Kurhade *et al.*,[33-38] explored Minimum Quantity Lubrication (MQL) grinding and heat transfer in electronic components, emphasising substrate thermal conductivity and phase change material placement.

Further studies have explored heat transfer in Integrated Circuit (IC) chips mounted on Switch Mode Power Supply (SMPS) boards, offering a thorough review of electronic cooling technologies designed for harsh environments. Optimisation of aerofoil designs using CFD simulations, coupled with fuzzy logic techniques to predict heat transfer improvements from twisted tape inserts, has provided valuable insights into enhancing heat exchanger efficiency. Additional research has examined the mechanical behaviour of curved plates[39,40], the thermal performance of electronic components[41], and methods to improve heat transfer with twisted tape inserts[42,43]. Other investigations have focused on advanced cooling solutions for electronics in extreme conditions[44] and CFD-based optimisation of heat exchangers[45-48].

4.0 Experimentation

The experimental setup investigates heat transfer enhancement in a tube-in-tube heat exchanger using PTT. It comprises a 1.5m long copper inner tube (26mm inner diameter, 1mm wall thickness) fitted with PTT inserts, and an outer tube facilitating counter-flow of hot and cold water circulated by centrifugal pumps. Temperature monitoring is achieved with thermocouples at inlets, outlets, and along the tube length, while a U-tube manometer measures pressure drops. Flow rates are precisely controlled using rotameters, and the test section is insulated with 8mm thick polyurethane foam to minimise heat loss. Experiments are conducted across various Reynolds numbers and configurations, including plain tubes, non-perforated twisted tapes, and PTT with

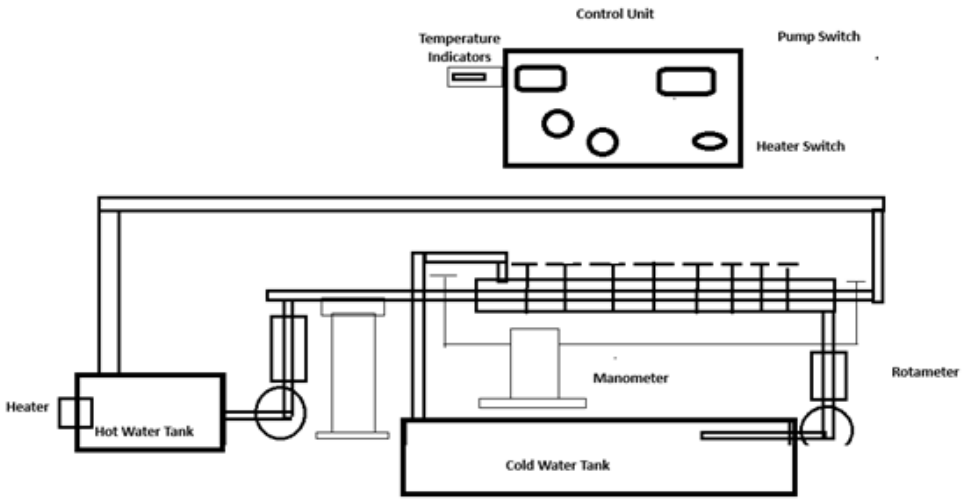


Figure 2. Schematic diagram of experimental setup.

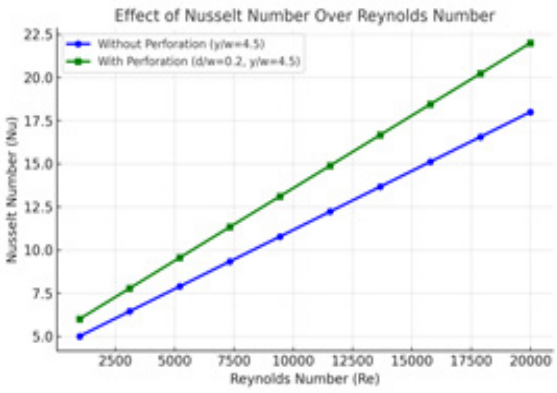
different hole diameter ratios (d/W = 0.2, 0.4, 0.6) and pitch ratios (y/W = 2.5, 3.5, 4.5). Results indicate that PTT, especially with d/W = 0.4 and y/W = 4.5, significantly enhance heat transfer, up to 226% compared to plain tubes, by inducing swirl flow and turbulence, albeit with an increased pressure drop.

5.0 Results and Discussion

The previous chapter provided a comprehensive explanation of the experimental procedure and sample calculations. This chapter presents the results obtained from the study and their interpretation. It focuses on analysing the influence of Reynolds (Re) number on the Nusselt (Nu) number, pressure drop, and the performance evaluation criterion (R1). These parameters are examined for different configurations, including plain tubes, tubes with inserts, and tubes with both perforated and non-perforated inserts at varying d/w and y/w ratios. A comparative assessment of the findings is conducted and summarised to highlight the effectiveness of each configuration.

5.1 Nusselt Number

Graph 1 shows that the Nu increases with the Re and is higher for tubes with Perforated Twisted Tape (PTT) inserts than for plain tubes. The enhancement ranges from 158.4% to 183.46% due to the swirling flow, which intensifies turbulence and improves heat transfer. The disruption of the thermal boundary layer by the inserts further contributes to this improvement.



Graph 1. Effect of Nu over Re.

The Nu increases as the d/w ratio decreases due to stronger turbulence and extended flow paths enhancing heat transfer. A pitch ratio of 4.5 results in a 138.4% higher Nu than a pitch ratio of 2.5 at the same Re. The twist ratio (y/w) improves heat transfer up to a threshold, beyond which excessive turbulence reduces effectiveness.

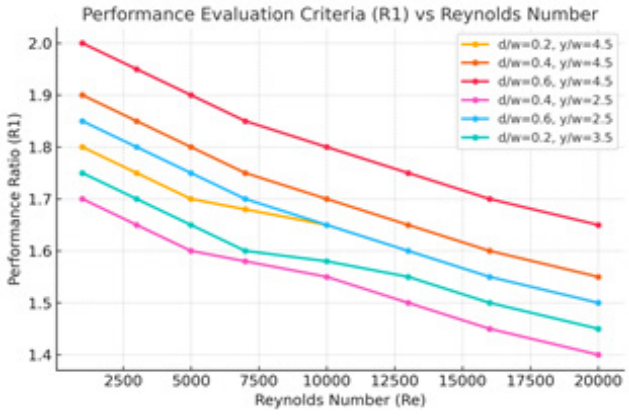
The graph demonstrates the relationship between Nusselt number and Reynolds number for two different configurations: one using twisted tapes without perforation (y/W = 4.5) and the other with perforated twisted tapes (d/W = 0.2, y/W = 4.5). It is evident that the configuration with perforation consistently achieves higher Nusselt numbers across the entire Reynolds number range, indicating superior heat transfer performance. As the Reynolds number increases from 2500 to 20000, both configurations show a steady increase in Nusselt number. However, the perforated design enhances turbulence and disrupts the thermal boundary layer more effectively, resulting in improved convective heat transfer.

There are several criteria available to assess the performance evaluation criteria R1 of heat transfer enhancement devices. Bergles[15] has also proposed multiple evaluation criteria for this purpose. The effectiveness of a heat transfer enhancement device is typically analysed under conditions of a constant mass flow rate.

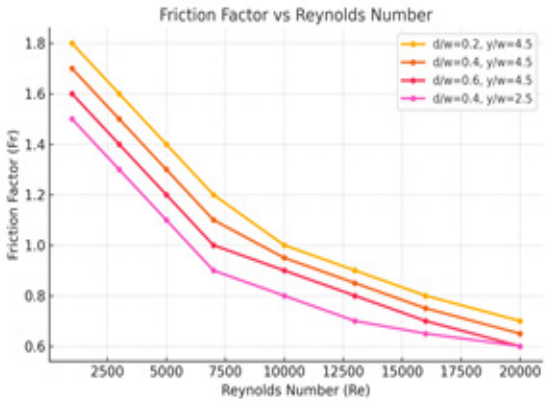
The performance can be quantified using the ratio:

R1=hPTT/hWTT

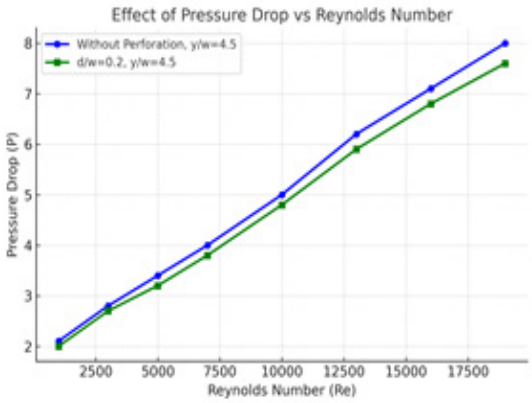
Graph 2 depicts the variation of the performance evaluation criterion (R1) with Reynolds number for different combinations of perforation diameter ratios



Graph 2. Performance Evaluation Criteria (R1) Vs Reynolds number for all cases.



Graph 2. Friction factor Vs Reynolds number for all studied arrangements.



Graph 4. Effect of pressure drop over the Reynolds number for different arrangements.

(d/W) and pitch ratios (y/W). It is observed that R1 decreases gradually with increasing Reynolds number across all configurations. Among them, the configuration with d/W = 0.4 and y/W = 4.5 consistently exhibits the highest performance ratio, indicating superior thermal efficiency. In contrast, configurations with smaller pitch ratios (y/W = 2.5) or lower perforation diameter ratios tend to yield lower R1 values, reflecting relatively less efficient heat transfer performance.

In heat exchanger design, the pressure drop directly affects the pumping power requirements, making the analysis of the friction factor essential. As illustrated in Graph 3, the friction factor tends to decline with an increase in Reynolds number across different pitch ratios (y/W = 2.5, 3.5, 4.5) and perforation diameter ratios (d/W = 0.2, 0.4, 0.6). Lower perforation diameter ratios (d/W) lead to higher friction factors due to the extended flow path and intensified tangential interactions, resulting in greater resistance. The maximum friction factor is recorded at lower Reynolds numbers. Conversely, configurations with larger perforations and higher pitch ratios effectively reduce flow resistance. Among all setups, the combination of d/W = 0.6 and y/W = 4.5 yields the lowest friction factor, indicating optimal flow with minimal energy loss.

5.2 Pressure Drop

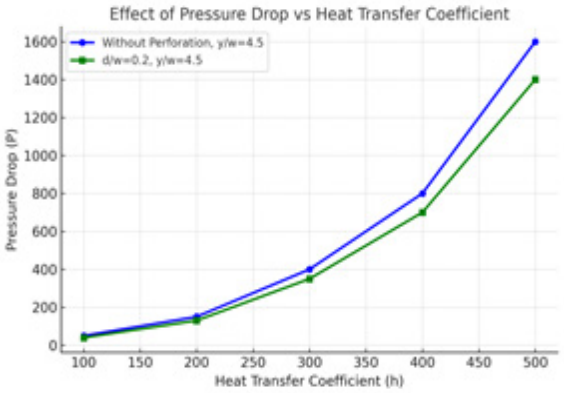
Graph 4 illustrates the impact of pressure drop across various insert configurations concerning the Reynolds number. When inserts are introduced into the tube, they create resistance to fluid motion, leading to a reduction in system pressure.

For an efficient heat exchanger, minimising pressure drop is desirable. However, in this study, the presence of inserts contributes to an unavoidable pressure reduction due to the increased resistance they impose on the fluid flow.

Graph 4 shows that the pressure drop increases with Reynolds number due to intensified turbulence, with plain tubes experiencing the lowest pressure drop. Twisted tape inserts significantly raise the pressure drop, reaching up to 300%, especially at higher Reynolds numbers. The highest resistance occurs in non-perforated twisted tapes, while the lowest pressure drop is observed for PTT with d/w=0.6 and y/w=4.5. Larger perforations and increased pitch size reduce flow resistance, allowing more fluid to pass through. As d/w and pitch size increase, pressure drop decreases, making such configurations more suitable for efficient heat exchanger design.

5.3 Heat Transfer Coefficient

Graph 5 illustrates the relationship between the heat transfer coefficient and pressure drop for various configurations. An efficient heat exchange system ideally requires a high heat transfer coefficient while maintaining a minimal pressure drop. However, in practical applications, the use of twisted tapes enhances heat transfer by inducing turbulence but also increases resistance to fluid flow, leading to a higher pressure drop.



Graph 5. Pressure Drop Vs Heat Transfer Coefficient

Among the studied configurations, twisted tapes without perforations exhibit a greater pressure drop compared to (PTT). Additionally, PTT demonstrate a higher heat transfer coefficient, making them a more effective choice for thermal performance improvement. The optimal arrangement, considering both pressure drop and heat transfer coefficient, is found to be d/w=0.6 and y/w=4.5, as it provides superior heat transfer while maintaining a lower pressure drop than other PTT configurations and non-perforated twisted tapes.

Overall, the introduction of perforations in twisted tapes enhances heat transfer performance by approximately 184%, making them a promising approach for improving thermal efficiency while mitigating excessive pressure loss.

6.0 Conclusion

The effect of twisted tape inserts with circular holes on forced convection heat transfer. The results demonstrate notable enhancements in heat transfer performance, thermal efficiency, and pressure drop characteristics. The key findings from the analysis are summarised below:

- The experimental study explored the impact of PTT inserts on the performance of a tube-in-tube heat exchanger.
- The incorporation of circular perforations enhanced heat transfer by inducing turbulence and disrupting the thermal boundary layer.
- The best thermal performance was observed with a perforation diameter ratio of d/W = 0.4 and pitch ratio of y/W = 4.5, resulting in a 226% increase in heat transfer compared to plain tubes and a thermal performance factor of 1.93 under constant pumping power.
- Smaller perforation sizes (lower d/W) created more intense turbulence, while higher pitch ratios (larger y/W) helped reduce pressure losses and improve flow distribution.
- Non-perforated twisted tapes led to significantly higher friction and pressure drop, increasing the energy requirement for fluid flow.
- PTT configurations with d/W = 0.6 and y/W = 4.5 achieved a good trade-off between high heat transfer and reduced flow resistance.
- The findings demonstrate that perforated twisted tapes are effective passive augmentation devices, providing improved heat exchanger efficiency without the need for external energy sources.
- This technique is well-suited for real-world applications where energy efficiency, compact design, and low operational cost are critical.

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