Journal of Mines, Metals and Fuels, *73(6): 1517-1525; 2025. DOI: 10.18311/jmmf/2025/48872*

Print ISSN : 0022-2755

Journal of Mines, Metals and Fuels

Contents available at: *www.informaticsjournals.co.in/index.php/jmmf*

Impact of Regularly Spaced Cut Sections on the Heat Transfer Efficiency of Helical Strip Inserts in Circular Pipes

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Abstract

This study experimentally investigates the thermal-hydraulic performance of turbulent water flow in a circular pipe, emphasizing the effects of innovative helical strip inserts. These inserts, designed with strategically placed cut passages, generate swirling flow to enhance heat transfer. The experiments covered a Reynolds number (Re) range of 6000 to 35000, relevant to industrial heat exchanger applications. Three different helical strip configurations, distinguished by helix angles of 35°, 50°, and 65°, were examined to evaluate their geometric impact. The results demonstrated a significant improvement in heat transfer rates due to turbulence and swirling motion. The local heat transfer coefficient was highest just downstream of the insert before gradually decreasing along the pipe, indicating a localized enhancement effect. Heat transfer augmentation strongly correlated with the Reynolds number, with higher values generally leading to greater absolute heat transfer. However, within the tested range, the influence of helix angle and the number of helical channels on heat transfer was relatively minor. Importantly, the study found that these helical strip inserts could enhance heat transfer rates by up to 20% compared to a plain pipe, provided the pumping power remained unchanged. This improvement was most pronounced at lower Reynolds numbers, while at higher Re values, the enhancement efficiency decreased, indicating diminishing returns at greater flow velocities. These findings highlight the potential of helical strip inserts in improving heat transfer under turbulent flow conditions, offering a viable strategy for optimizing thermal performance in engineering applications.

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Major Findings: *The study confirms that helical strip inserts with strategically placed cut sections significantly enhance convective heat transfer by inducing swirl flow, leading to up to a 250% increase in local heat transfer compared to axial flow. The highest heat transfer rates were observed at the maximum momentum ratio, highlighting the crucial role of swirl intensity, although the effectiveness gradually diminishes downstream as the swirling effect weakens. Additionally, the research demonstrates that helical strip inserts can achieve a netenergy gain of up to 20%, making them a promising solution for improving thermal performance in turbulent flow applications while maintaining energy efficiency.*

Keywords: *Heat Transfer Enhancement, Helical Angle, Helical Strip, Momentum Ratio, Swirl Flow, Turbulent Convection*

1.0 Introduction

Enhancing heat transfer in thermal systems is crucial for improving energy efficiency, reducing operational costs, and optimizing the performance of heat exchangers, boilers, and cooling systems. Various passive heat transfer enhancement techniques have been explored, among which helical strip inserts have gained significant attention due to their ability to induce swirl flow, increase turbulence, and enhance convective heat transfer. However, conventional helical strip inserts often face challenges such as excessive pressure drop and flow resistance, which can reduce their practical applicability. To address these limitations, researchers have explored geometrical modifications in helical inserts, such as perforations, twisted configurations, and cut sections. One promising modification is the incorporation of regularly spaced cut sections along the length of the helical strip insert. These cut sections introduce flow disruptions, secondary vortices, and increased fluid mixing, thereby enhancing the convective heat transfer coefficient. Additionally, they help in reducing excessive pressure drop, making the system more efficient in terms of thermal-hydraulic performance.

This study numerically examines helical tube heat transfer, considering both first and second laws of thermodynamics, revealing enhanced heat transfer and reduced entropy generation compared to straight tubes, with square cross-sections showing the highest, but also most costly, performance[1]. This study experimentally investigates novel perforated angular-cut baffles in turbulent air flow, demonstrating enhanced heat transfer with reduced pressure drop, particularly with alternate baffle arrangements and optimized perforation ratios. Results show significant Nusselt number improvements and propose correlations for heat transfer and friction, confirming the thermo-hydraulic performance benefits of these innovative baffle designs[2]. Large eddy simulations analyzed turbulent flow and heat transfer between concentric cylinders with longitudinal and helical slits, revealing helical slits significantly enhance heat transfer compared to longitudinal designs, as confirmed by field synergy and entropy generation analysis[3]. Numerical simulations, validated against experiments, assess twisted tape inserts in a circular pipe, showing increased pressure drop and enhanced heat transfer with higher twist numbers due to induced swirl flows. Increasing twist numbers from 1 to 5 resulted in temperature difference increases up to 50-52 % compared to a smooth pipe[4]. This study uses 3D computational methods to analyze corrugated tube flow and heat transfer, showing significant enhancement over plain pipes due to increased turbulence and mixing, with Nusselt number and pressure rising with corrugation parameters, yielding performance gains over 1.65[5]. This study explores heat transfer in double pipes with helical screw inserts, showing significant increases in heat transfer and friction compared to plain tubes, with performance enhanced by decreasing spacer length and increasing rotational speed[6]. This numerical study examines helically coiled tube heat exchangers with copper wire inserts, revealing significant Nusselt number and friction factor enhancements, particularly with circular cross-section inserts. Optimized insert geometries are identified for different mass flow rates, and a Nusselt number correlation is proposed[7]. This study compares heat exchange in helical and spiral tubes through experiments and simulations, finding that spiral tubes offer superior thermal performance across varying flow rates and temperatures. The research also validates computational fluid dynamics as a reliable method for analyzing heat transfer, using a straight pipe as a baseline[8]. This research experimentally examined how grooved helical blade rotors inside a circular tube impact heat transfer and friction, finding they significantly enhance heat transfer, though with increased friction. The study optimized rotor spacing, number, and placement, revealing configurations that maximize thermal performance beyond that of a smooth tube[9]. This study experimentally analyzed heat transfer and friction in a circular tube with various conical ring inserts, finding that solid rings provided the highest heat transfer enhancement, though with a greater friction penalty. The

research optimized insert geometry, showing that reducing pitch ratio increased heat transfer, while perforations and slots lessened friction[10]. This research introduces a new heat transfer enhancement method using Constructal Bifurcation Semi Pipes (CBSPs) within a circular tube, aiming for improved temperature uniformity and longitudinal swirling flow. Numerical and experimental analyses show significant Nusselt number increases, with optimized designs achieving a maximum efficiency evaluation coefficient of 1.44, validated through exergy destruction minimization[11]. This paper reviews the effectiveness of Helical Coil Heat Exchangers (HCHEs), comparing them to straight tube designs and examining various shapes and operating conditions. It focuses on factors influencing HCHE performance and efficiency in thermal energy transfer between fluids and solids[12]. This study used CFD simulations to analyze heat transfer and friction in tubes with classical and quadrant-cut twisted tape inserts, validating the results against established correlations. The research found that quadrant-cut tapes with lower twist ratios and shallower cut depths significantly enhanced heat transfer, albeit with increased friction[13]. This study explores combining helical coils and pinched pipes to enhance heat transfer in both laminar and turbulent flows, finding that pinched helical coils outperform regular helical coils in turbulent regimes by 10-20 %. The research validates a computational model against existing data and demonstrates the potential of this combined approach for improved passive heat transfer augmentation[14]. This study experimentally investigated how helical perforated twisted tape parameters affect heat exchanger performance, finding optimal values for diameter ratio, pitch ratio, and perforation index. The research determined that a maximum thermal hydrodynamic performance of 2.12 was achieved under specific parameter combinations[15]. Smartphones typically operate within a power range of 2-6 W and face challenges in dissipating heat during intensive tasks such as gaming and camera usage. This study explores passive Phase Change Material (PCM) cooling as a more effective alternative to conventional methods like convection and heat pipes, which become less efficient at higher power levels[16]. Simulations were conducted on FR4, silicon, and copper-clad boards, each containing nine components under varying airflow conditions[17]. Results showed that copper cladding significantly reduced component temperatures by 30-47° C at 5 m/s airflow, decreased the required airflow by 2 m/s, and improved IC chip cooling efficiency by 1.50-11.12° C compared to other materials. Additionally, a minichannel PCM cooling system was evaluated, where N-Eicosane demonstrated superior performance, reducing temperatures from 53.234° C to 51.520° C- an improvement of 0.5° C and 1.35° C over paraffin wax and ATP 78, respectively[18]. Further research includes minijet impingement cooling, nanofluids,water-efficient faucet designs, and twisted tape heat transfer enhancements[19-24]. A comprehensive review of electronic cooling technologies highlights challenges and advancements in extreme conditions. Another study optimizes engine performance and emissions by using *Calophyllum inophyllum* biodiesel with dimethyl carbonate. Research on solar collectors utilizing recycled aluminum cans demonstrates improved drying efficiency, while numerical analysis explores thermal conductivity in electronic cooling substrate boards. Computational Fluid Dynamics (CFD) and wind tunnel tests are utilized to optimize aerodynamic efficiency, and fuzzy logic modeling predicts heat transfer enhancements with twisted tape inserts in heat exchangers[25-33]. Investigations into wavy corrugated twisted tape inserts in double-pipe heat exchangers confirm significant heat transfer improvements, while research on electronic cooling performance across different substrate materials introduces PCM-based circuit cooling solutions for extreme environments. Wind rose analysis assesses temperature variations in wind turbines using sensor implantation, while numerical and experimental studies examine the influence of overlapping angles on the strength and deformation of arc-welded curved plates[34-41]. Comparative research evaluates the experimental and numerical performance of mono-composite and metal leaf springs, and real-time automation enhances surface finish measurements for stepped holding shafts. CFD simulations analyze heat transfer in counter-flow helical double-pipe heat exchangers, while an algorithmic approach optimizes HVACR duct design. Nanofluids improve heat transfer in double-pipe heat exchangers, and an innovative vehicle safety system investigates energy-absorbing bumper designs. Additionally, green adsorbents are studied for heavy metal removal, particularly zinc ion absorption using *Tinospora cordifolia* biocarbon[42-48]. Further investigations into Transformation-Induced Plasticity (TRIP) steel plate thickness reveal its effect on the tensile strength of Nd: YAG laser butt-welded joints. An experimental study assesses the mechanical behavior of mild steel curved plates with varying thicknesses, while computational research focuses on IC chip thermal management using PCM cooling techniques. Additionally, fuzzy logic modeling is employed to predict heat transfer performance in double-pipe heat exchangers with wavy

twisted tape inserts. Lastly, the study examines the impact of oxygen-containing additives in unleaded gasoline on exhaust emissions, highlighting potential environmental benefits[49-59].

This research aims to analyze how swirling elements inside a circular tube impact heat transfer and pressure drop in turbulent flow, specifically focusing on the effect of the swirling flow ratio.

2.0 Experimental Setup

This study utilized a carefully designed flow loop to examine heat transfer and pressure drop in a circular tube equipped with helical tape inserts. The experimental setup, illustrated in Figure 1, featured a closed-loop system powered by a pump, with flow rates precisely controlled *via* visual flowmeters. The primary test section consisted of a 950 mm long stainless steel pipe with a 25 mm inner diameter, where heat transfer characteristics were systematically analyzed. A key innovation in this setup was the integration of a helical tape insert, as detailed in Figure 2. This insert, measuring 13 mm in inner diameter and 100 mm in length, incorporated helical channels milled at varying angles (35°, 50°, and 65°) and configurations with one or two channels. Additionally, rectangular cut passages with a 10 mm pitch were introduced

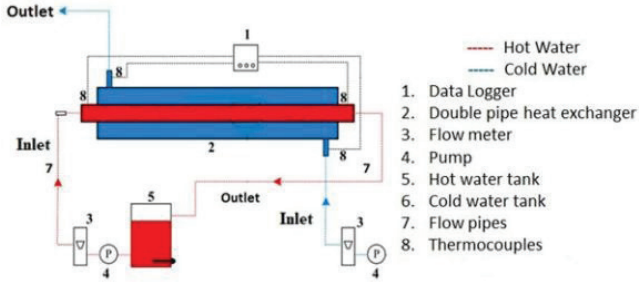


Figure 1. Set up[32].

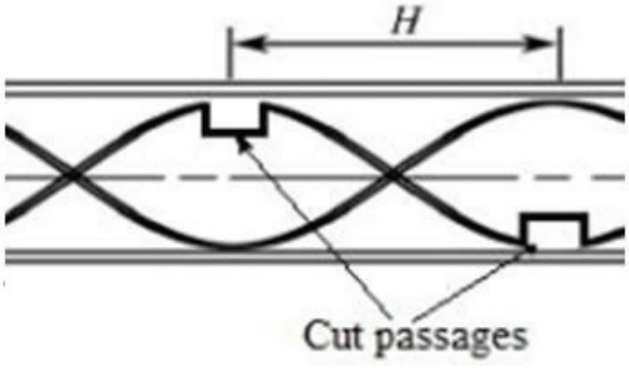


Figure 2. Helical strip.

along the strip, with channel depths of 3.5 mm. The tape was tightly inserted inside the main pipe, creating a distinct flow division: part of the fluid passed through the inner region of the tape, while the rest navigated the helical channels. Upon exiting the helical strip, the combined flow enabled the assessment of swirling flow effects. To ensure controlled heating, a 20 kW DC power supply was employed, with a voltage regulator maintaining stability. The test section was uniformly heated, while glass wool insulation minimized heat losses. Temperature monitoring was a crucial aspect of the study, with copper-constantan thermocouples strategically positioned at ten axial stations along the test section (x/L = 0.1 to 1) to record air inlet, outlet, and wall temperatures. Thin mica sheets were used to electrically insulate the thermocouples from the tube surface. A data acquisition module captured all temperature readings; with bulk inlet temperatures measured using two thermocouples, while local bulk temperatures were derived under the assumption of a linear temperature profile due to constant heat flux. Pressure drop measurements were also conducted using pressure taps. Two taps were installed along the test pipe to assess differential pressure drop, while an additional two were placed on the helical strip itself, providing insight into the pressure dynamics within the swirl generator. This comprehensive instrumentation enabled a detailed evaluation of the influence of helical tape geometry and flow conditions on heat transfer and pressure drop.

3.0 Experimental Results and Discussion

The experimentally obtained Nusselt numbers for a smooth tube (without a helical strip) were compared with the Dittus-Boelter, Petukhov, and Sieder-Tate correlations for turbulent flow, as shown in Figure 3. The results indicate that the experimental findings align well with these established studies.

Putting the helical strip significantly increased friction, particularly when the swirling effect was stronger (higher momentum ratio). This is evident in Figures 4 and 5, where friction levels with the strip are 2 to 6 times greater than without it. However, as flow velocity (Reynolds number) increases, friction gradually decreases. The helical strip also greatly enhanced heat transfer. Figures 6-8 illustrate that the heat transfer coefficient was substantially higher with the strip, especially when stronger swirls were present. This improvement occurs because the swirling motion reduces

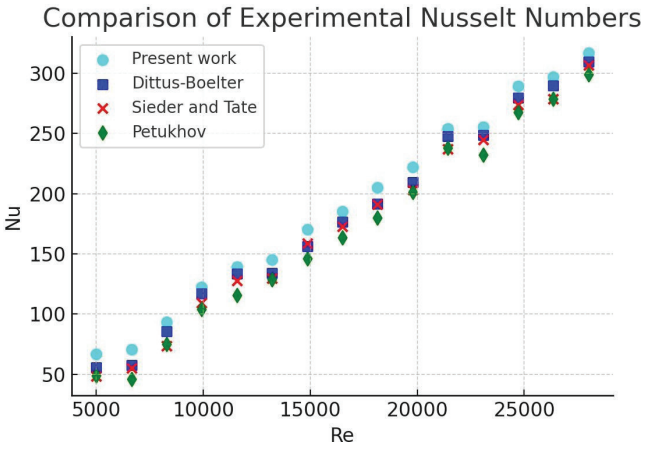


Figure 3. Re *vs* Nu.

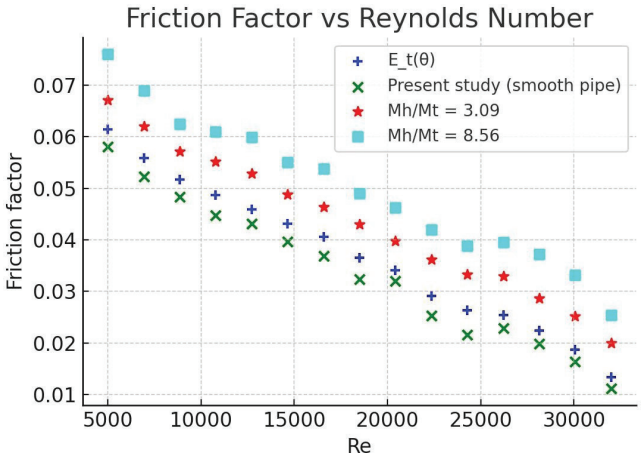


Figure 4. Re *vs* f.

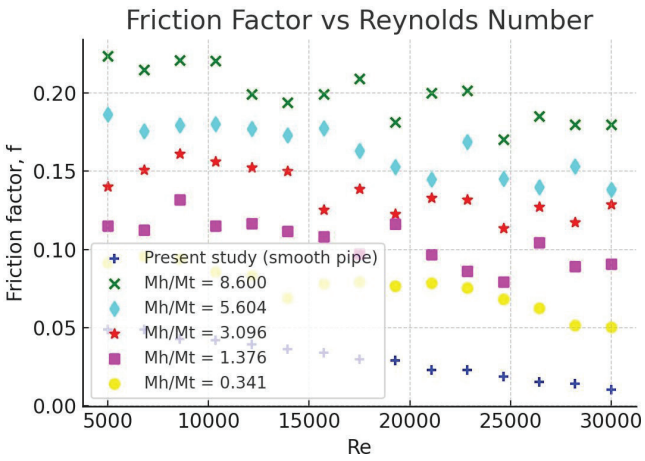


Figure 5. Re *vs* f.

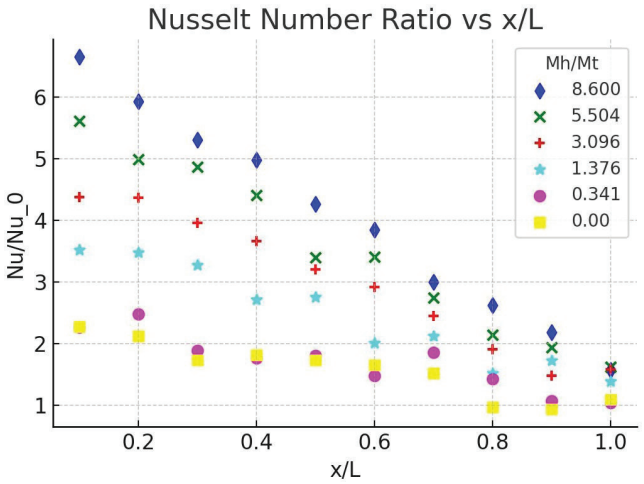


Figure 6. x/L *vs* Nu.

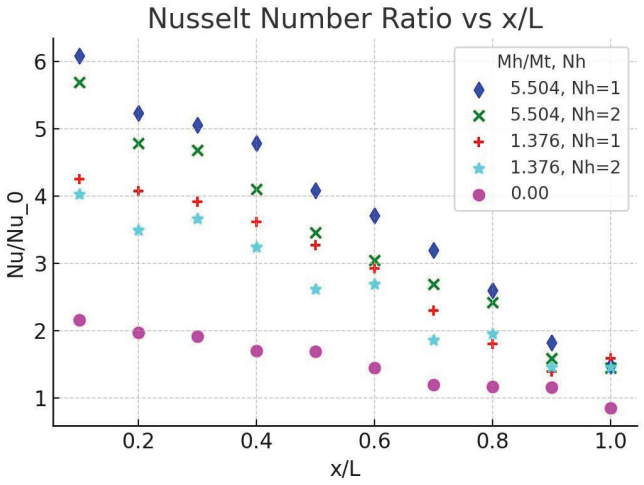


Figure 7. x/L *vs* Nu.

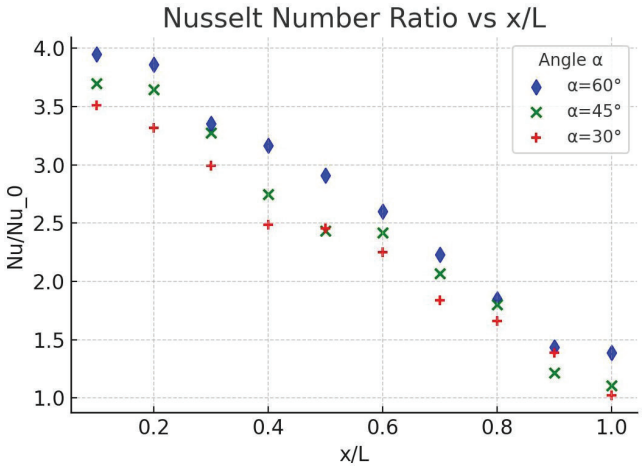


Figure 8. x/L *vs* Nu.

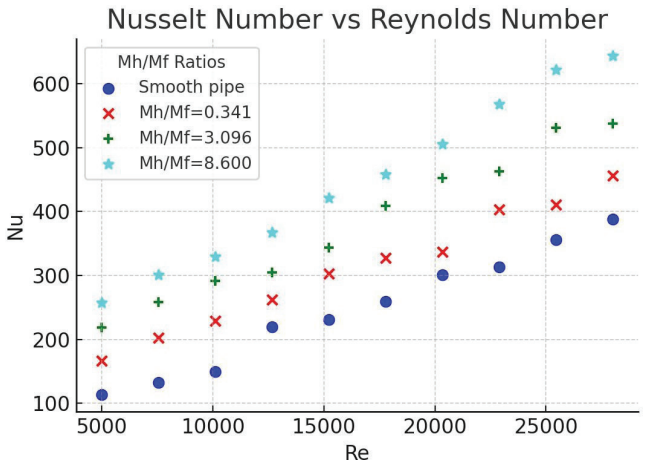


Figure 9. Re *vs* Nu.

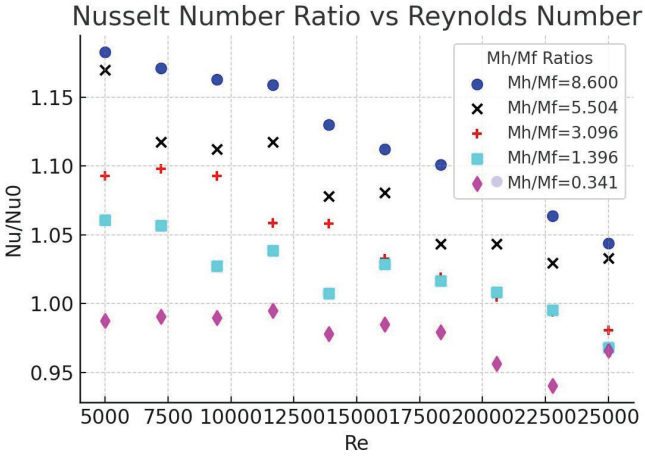


Figure 10. Re *vs* Nu.

the boundary layer thickness near the tube wall, facilitating more efficient heat exchange. The highest heat transfer rates were observed near the strip, diminishing further downstream as the swirling effect weakened. Interestingly, the number of helical channels (one or two) had little impact on heat transfer, as shown in Figure 7, and the helix angle also had minimal influence (Figure 8). Similarly, the overall heat transfer performance, represented by the Nusselt number in Figure 9, increased with the momentum ratio. In summary, the helical strip improves heat transfer but also increases friction. The extent of this enhancement primarily depends on swirl intensity, while the number of channels and helix angle play a comparatively minor role.

4.0 Conclusion

This study confirms that helical strip inserts with strategically designed cut passages significantly enhance heat transfer in turbulent flow conditions. The highest heat transfer rates were observed at the maximum momentum ratio, emphasizing the role of swirl intensity in improving convective heat transfer. However, the effectiveness of heat transfer gradually diminishes downstream due to the weakening of the swirl effect. The study also highlights that while the number of helical channels and helix angle have minimal impact, a slight improvement in heat transfer was noted at a 65° helix angle. Additionally, a net energy gain of up to 20% was achieved at the highest momentum ratio, demonstrating the potential of helical strips for thermal performance optimization.

1. Significant Heat Transfer Enhancement: Helical strip inserts notably improve heat transfer compared to fully develop non-swirling flow.
2. Effect of Momentum Ratio: The highest local heat transfer coefficient was observed at the maximum momentum ratio, confirming that increased momentum enhances convective heat transfer.
3. Swirl Effect Reduction: The effectiveness of heat transfer decreases downstream as the swirl effect weakens over the tube length.
4. Improvement in Heat Transfer Coefficient: A maximum 250% increase in local heat transfer was recorded in swirl flow compared to axial flow at the same velocity, depending on the momentum ratio and Reynolds number.
5. Minimal Influence of Helix Parameters: The number of helical channels and the helix angle had little impact on the Nusselt number ratio; though a slight improvement was observed at a 65° helix angle.
6. Energy Efficiency Gains: A net energy gain of up to 20% was achieved at the highest momentum ratio, reinforcing the effectiveness of helical strips in convective heat transfer applications.

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