Spectrum of Engineering Sciences
ISSN (e) 3007-3138 (p) 3007-312X
Volume 3, Issue 9, 2025

DESIGN OF A COMPACT, COST-EFFECTIVE SHELL AND TUBE HEAT EXCHANGER WITH IMPROVED EFFICIENCY

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DOI: https://doi.org/10.5281/zenodo.17045697

Keywords

Baffles, Compact design, Heat exchanger, Thermal efficiency, Turbulence

Article History
Received: 11 June 2025
Accepted: 21 August 2025
Published: 03 September 2025

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Abstract
Heat exchangers were widely used in industrial applications but continued to face persistent challenges related to high fabrication costs, large size, fouling, and limited thermal efficiency. Conventional shell and tube heat exchangers, although robust and suitable for high-pressure and high-temperature environments, often required expensive materials and complex manufacturing processes, while design modifications typically resulted in trade-offs between performance and hydraulic resistance. Addressing these limitations was essential for enhancing energy efficiency, reducing operational costs, and promoting more compact, cost-effective designs suitable for small- and medium-scale industries. The present study aimed to design, fabricate, and evaluate a compact, low-cost shell and tube heat exchanger with structural improvements to increase efficiency. The exchanger was constructed from mild steel with spiral baffles and tested using chilled water as the cold stream and hot water as the heating medium. Thermocouples, pressure gauges, and flow meters were employed to record inlet and outlet temperatures, pressure drops, and flow rates, while thermal performance was analyzed using heat transfer rate (Q), log mean temperature difference (LMTD), overall heat transfer coefficient (U), and effectiveness (ε). Statistical reliability was ensured by triplicate measurements and mean value analysis. Results showed that the inclusion of a spiral rod significantly improved turbulence, leading to higher heat transfer efficiency (62.4% with spiral rod vs. 42.7% without; $p < 0.05$), and increased the heat transfer rate from 7.44 kW to 16.1 kW despite similar flow regimes. The compact exchanger achieved a performance comparable to larger industrial designs while maintaining a surface area of only 2.17 m^2 and a material cost of 56,000 units. In conclusion, the study demonstrated that spiral-rod integration effectively enhanced thermal performance, offering a feasible pathway toward more efficient, affordable, and sustainable shell and tube heat exchanger technology.

INTRODUCTION

Heat exchangers were fundamental components of thermal systems and played a critical role in a wide range of industrial applications, including power generation, chemical processing, food and beverage manufacturing, petroleum refining, and air conditioning (Arsenyeva et al., 2023). Their primary function was to transfer heat between two or more fluid streams at different temperatures, either to heat or cool process streams or to facilitate phase-change processes such as condensation and evaporation (Suh et al., 2024). In nearly all cases where fluids underwent heating, cooling, condensation, or evaporation, heat exchangers were indispensable. For this reason, they were regarded as one of the most widely used classes of process equipment in engineering industries (Boldyryev et al., 2025).

The efficiency of a heat exchanger was primarily determined by its ability to transfer the maximum amount of heat within the minimum required surface area, while maintaining a low pressure drop across the system (Qian et al., 2024). High pressure drops increased pumping power requirements, thereby elevating operational costs, while large surface areas raised material costs and unit weight (Zhang et al., 2023). The overall heat transfer coefficient was therefore widely used as a measure of thermal performance, integrating the effects of fluid flow, thermal conductivity, and surface geometry. An effective design achieved an optimal balance between heat transfer efficiency, compactness, reliability, and economic feasibility. However, existing industrial designs often presented limitations in one or more of these aspects, underscoring the need for continuous innovation in heat exchanger technology (Anwajler, 2024).

Over the years, various types of heat exchangers were developed to address different industrial requirements. Classification was typically based on flow configuration, construction, and heat transfer processes (Thulukkanam, 2024). From a flow configuration perspective, exchangers included parallel-flow, counter-flow, and cross-flow types. Counter-flow designs offered superior thermal performance because they maximized the temperature gradient across the exchanger, thereby achieving greater heat transfer for the same surface area (Banerjee, 2025). Parallel-flow designs were simpler but less efficient, while cross-flow designs were versatile and frequently employed in compact systems. Multi-pass designs were also adopted to extend residence times and improve thermal effectiveness (Jana et al., 2025). From a construction perspective, plate-type, plate-fin, tube-fin, and shell and tube heat exchangers were the most common. Plate heat exchangers, constructed from stacked thin plates, offered high compactness and moderate thermal performance but were limited by their inability to withstand high pressures and temperatures (Nithya et al., 2025). Plate-fin exchangers achieved exceptionally high compactness ratios—up to 6000 m^2/m^3—by incorporating fins to enlarge surface area and enhance turbulence. However, they were restricted to low-pressure, clean-fluid applications due to fouling tendencies, limited materials, and higher manufacturing costs (White, 2025). Tube-fin exchangers, which incorporated extended surfaces in round or flat tube designs, provided a compromise between compactness and pressure capability, making them useful in gas turbines, refrigeration systems, and aerospace industries (Adamou et al., 2021).

Among these configurations, shell and tube heat exchangers remained the most widely used in heavy industrial applications. Their design, comprising a bundle of tubes enclosed within a cylindrical shell, allowed for effective heat transfer between two fluids, one flowing inside the tubes and the other flowing around them within the shell (Marzouk et al., 2023). Structural variations such as fixed-tube sheet, U-tube, and floating-head designs provided adaptability to different thermal expansion and maintenance requirements. The inclusion of baffles not only supported tubes mechanically but also directed fluid flow to enhance turbulence, thereby improving heat transfer efficiency. This robustness, combined with scalability and versatility, made shell and tube exchangers indispensable in high-pressure and high-temperature environments such as power plants, petrochemical industries, and large-scale HVAC systems (Khatri et al., 2025.

Despite their widespread adoption, shell and tube exchangers were not without limitations. One of the most significant challenges lay in their cost. The need for corrosion-resistant materials such as stainless steel, copper, or titanium substantially raised material expenses, particularly in environments involving corrosive fluids or extreme temperatures (Antony et al., 2025). The fabrication process, involving precision welding, tube rolling, and rigorous quality testing, added further complexity and cost. For large-scale units, the capital investment could be prohibitively high. Furthermore, achieving high thermal efficiency often required increasing the number of tubes and surface area, which resulted in larger, heavier units. This not only raised material consumption but also increased the spatial footprint, complicating installation in compact industrial environments (Bhiogade, 2023). Another challenge was operational performance. Over time, fouling of the tube surfaces by particulates, scale, or biofilms reduced heat transfer efficiency and necessitated frequent cleaning and maintenance (Hebishy et al., 2024). Shell and tube exchangers also suffered from trade-offs between pressure drop and heat transfer: increasing turbulence improved thermal efficiency but elevated pressure losses, leading to higher pumping energy requirements. Balancing these factors was a constant challenge for engineers, particularly in industries where energy costs were significant (Martínez, 2025).

While significant research had been devoted to optimizing heat exchanger designs, gaps remained. Plate-fin and plate-type exchangers achieved excellent compactness but were unsuitable for high-pressure operations. Tube-fin exchangers offered moderate advantages but fell short in achieving both high efficiency and long service life (Oikarinen, 2025). Shell and tube exchangers, despite their robustness, continued to suffer from high fabrication costs, relatively large sizes, and expensive maintenance requirements. Moreover, conventional designs often relied on incremental modifications rather than transformative innovations. There was a clear need for design strategies that could simultaneously reduce material costs, minimize size, enhance heat transfer performance, and ensure structural reliability (Jiao et al., 2021).

In recent years, researchers explored innovative techniques to improve shell and tube heat exchangers. These included the use of enhanced surfaces such as fins, surface coatings to reduce fouling, advanced materials with higher thermal conductivity, and novel baffle arrangements to optimize turbulence and flow distribution (Francolle et al., 2023). Computational fluid dynamics (CFD) simulations and advanced CAD modeling provided new insights into optimizing geometries, while experimental validation ensured practical feasibility. Despite these efforts, the trade-offs between cost, size, and efficiency had not been fully resolved.

This study was undertaken to address these limitations by focusing on the design and development of a compact, cost-effective shell and tube heat exchanger. The research specifically aimed to reduce the high costs traditionally associated with shell and tube exchangers through optimized cylindrical shell design and structural modifications. Experimental validation was conducted to evaluate thermal performance and compare configurations with and without spiral rod inserts. Spiral rods were incorporated to enhance turbulence and increase the heat transfer coefficient while minimizing pressure drop penalties (Cao et al., 2021). By systematically analyzing thermal performance, pressure losses, and cost-benefit aspects, this study sought to demonstrate the feasibility of a more efficient and economically viable shell and tube heat exchanger design. The broader significance of this research lay in its potential impact on industrial energy efficiency. Since heat exchangers accounted for a substantial portion of energy consumption in process industries, even modest improvements in efficiency translated into considerable energy savings and reductions in greenhouse gas emissions. Furthermore, reducing capital and operational costs made these systems more accessible to small- and medium-scale industries, expanding their applicability and promoting more sustainable industrial practices.

In summary, heat exchangers remained indispensable across industries but continued to face challenges related to cost, compactness, and efficiency. Shell and tube exchangers, while dominant in high-pressure applications, required innovative design improvements to remain competitive in an evolving industrial landscape. This research contributed to bridging this gap by proposing a compact, cost-effective design validated through simulations and experiments. By integrating structural innovations with economic considerations, the study aimed to provide a practical pathway toward more efficient and affordable heat exchanger technology.

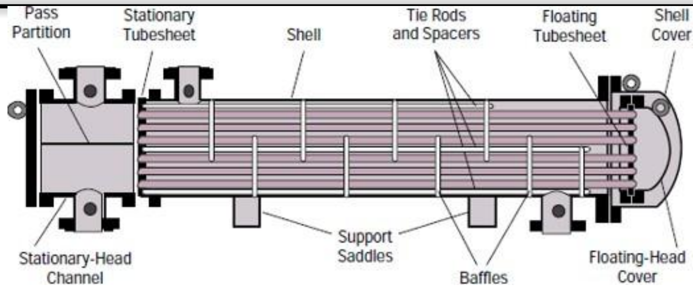


Figure 1: Shell and tube heat exchanger

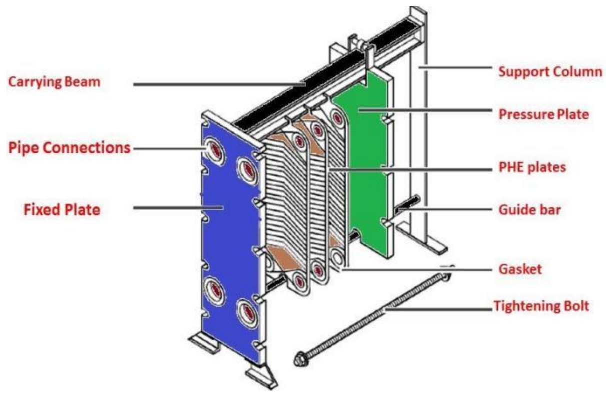


Figure 2: Plate type heat exchangers

METHODOLOGY

The methodology of this study encompassed material selection, procurement, fabrication of the heat exchanger, specification of working fluids, experimental setup, testing procedures, and performance evaluation. All processes were conducted systematically to ensure accuracy, reproducibility, and compliance with standard heat exchanger design practices.

The shell of the heat exchanger was fabricated from mild steel (MS) with dimensions of 48 inches in length, 4 inches in diameter, and 2 mm thickness. The tubes were also constructed from mild steel, each measuring 54 inches in length with a diameter of 2 inches and a thickness of 2 mm. Spiral-type baffles, each with a 40 mm curvature, were installed inside the shell to enhance turbulence and improve convective heat transfer while minimizing fouling. Auxiliary components included copper valves for flow regulation, stainless steel pressure gauges for monitoring pressure, and MS sockets and rods for assembly. The entire system was coated with red oxide paint to prevent corrosion and improve durability. Raw materials were procured based on the design specifications, with additional components such as six copper valves, six MS sockets, one spiral rod, four pressure gauges, and protective paint purchased to complete the assembly. The total cost of materials amounted to 56,000 units. Fabrication involved cutting and machining of raw materials, assembly of shell, tubes, and baffles, welding for leak-proof sealing, surface finishing, and protective coating application. For testing, chilled water was used as the cold fluid and hot shower water as the heating medium. Both fluids were circulated through the exchanger under controlled conditions. Thermocouples were installed at the inlets and outlets to measure fluid temperatures, while flow meters were used to determine volumetric flow rates. Pressure gauges were placed at the shell-side inlet and outlet to record pressure drops.

The testing procedure involved initiating hot water flow until the desired inlet temperature was stabilized, followed by introducing chilled water at regulated flow rates. Once steady-state conditions were reached, the inlet and outlet temperatures, flow rates, and pressure readings were recorded. Experiments were repeated at different flow conditions to evaluate performance variations. Performance analysis was conducted using standard thermal and hydraulic parameters. The heat transfer rate (Q) was calculated from mass flow rate, specific heat, and temperature differences. The log mean temperature difference (LMTD) method was applied to evaluate temperature variation across the exchanger, while the overall heat transfer coefficient (U) was derived from the ratio of heat transfer rate to the product of heat transfer area and LMTD. The effectiveness (ε\varepsilonε) of the exchanger was determined using the Number of Transfer Units (NTU) method, and pressure drop (ΔP\Delta PΔP) was calculated from gauge readings. Each test was repeated three times, and average values were used for accuracy.

Performance Parameters and Data Analysis

The performance of the heat exchanger was evaluated using the following parameters:

Heat Transfer Rate (Q):

Q=m·Cp·(Tin−Tout)

where m is the mass flow rate, Cp is the specific heat of the fluid, and Tin and Tout are inlet and outlet temperatures.

Log Mean Temperature Difference (LMTD):

ΔTm=(Th,in−Tc,out)−(Th,out−Tc,in)/ln(Th,in−Tc,out/Th,out−Tc,in)

used to account for temperature variations across the exchanger.

Overall Heat Transfer Coefficient (U):

U=Q/A·ΔTm

where A is the heat transfer area.

Effectiveness (ε): ε=Qactual/Qmax

assessed based on the NTU (Number of Transfer Units) method.

Pressure Drop (ΔP):

Pressure differences across the shell side were monitored to evaluate hydraulic performance. The collected data were statistically analyzed to assess repeatability and accuracy. Each test was repeated three times, and the mean values were used in subsequent analysis.

Table 1: Summary of Methodology

Parameter	Description
Shell	Mild steel, 48 in length, 4 in diameter, 2 mm thickness
Tubes	Mild steel, 54 in length, 2 in diameter, 2 mm thickness
Baffles	Spiral type, 40 mm curvature, installed to enhance turbulence
Auxiliary Components	Copper valves, stainless steel pressure gauges, MS sockets/rods, red oxide paint
Working Fluids	Hot side: Shower water; Cold side: Chilled water
Measurement Devices	Thermocouples (inlet/outlet), flow meters, pressure gauges
Testing Procedure	Hot water stabilized → cold water introduced → steady state → data recorded
Performance Parameters	Heat transfer rate (Q), LMTD, overall heat transfer coefficient (U), effectiveness (ε), pressure drop (ΔP)
Data Accuracy	Each test repeated three times; mean values used for analysis
Total Cost	56,000 units

RESULTS

This chapter presents the experimental findings of the fabricated shell-and-tube heat exchanger equipped with a spiral rod. The results include measurements of temperature, pressure, Reynolds number, Log Mean Temperature Difference (LMTD), heat transfer rate, and thermal efficiency. The experimental observations are compared with theoretical expectations and supported by relevant heat exchanger design principles.

Heat Transfer Performance with Spiral Rod

The first experiment investigated the thermal and hydraulic performance of the heat exchanger when fitted with a spiral rod to enhance turbulence. Measurements were recorded at intervals of one and two hours of operation. Table 2 summarizes the inlet and outlet temperatures, pressure readings, and their corresponding differences.

Table 2: Experimental measurements of heat exchanger with spiral rod

S. No	Component	After 1 Hour	After 2 Hours
1	Shell inlet temperature (°C)	14.6	12.1
2	Shell outlet temperature (°C)	17.0	14.0
3	Shell ΔT (°C)	2.4	1.9
4	Tube inlet temperature (°C)	32.0	32.1
5	Tube outlet temperature (°C)	29.6	29.8
6	Tube ΔT (°C)	2.4	2.3
7	Shell inlet pressure (psi)	28	28
8	Shell outlet pressure (psi)	24	24
9	Shell ΔP (psi)	4	4
10	Tube inlet pressure (psi)	45	45
11	Tube outlet pressure (psi)	40	41
12	Tube ΔP (psi)	5	4

The results indicate that the temperature difference between inlet and outlet remained relatively stable, while pressure drops in both the shell and tube sides were within acceptable limits. This confirms that the spiral rod effectively enhanced turbulence without introducing excessive hydraulic resistance.

Reynolds Number Analysis

The Reynolds number (Re) was calculated for both the tube and shell sides using measured fluid properties and dimensions. For the tube side, with water velocity of 5.2 m/s, density of 995.6 kg/m³, diameter of 0.0508 m, and viscosity of 0.000797 Pa·s, the Reynolds number was found to be **331,115**, indicating a fully turbulent regime. Similarly, for the shell side with velocity of 2.68 m/s, density of 999.2 kg/m³, diameter of 0.1016 m, and viscosity of 0.001138 Pa·s, the Reynolds number was **233,119**, also confirming turbulent flow.

Table 3: Calculated Reynolds numbers

Flow Side	Reynolds Number (Re)	Flow Regime
Tube side	331,115	Turbulent
Shell side	233,119	Turbulent

These results demonstrate that both sides of the exchanger operated under turbulent conditions, which is essential for enhanced convective heat transfer.

Log Mean Temperature Difference (LMTD)

The Log Mean Temperature Difference (LMTD) method was applied to determine the average driving force for heat transfer. Using the recorded inlet and outlet temperatures of hot and cold fluids:

ΔT_1 = Thi – Tci = 32 – 14.6 = 17.4 K

ΔT_2 = Tho – Tco = 29.6 – 17.0 = 12.6 K

The calculated LMTD was **14.85 K**, indicating a significant thermal gradient across the exchanger.

Heat Transfer Rate and Efficiency

The heat transfer area was computed as **2.17 m²**, and using an overall heat transfer coefficient of 503 W/m²·K, the heat transfer rate was determined:
$Q=U\times A\times \Delta Tlm=503\times 2.17\times 14.85=16,111$ W (16.1 k W)

The efficiency of the heat exchanger was calculated by comparing the actual heat transfer rate (Q_{actual}=16,111 W) with the maximum possible rate (Q_{max}=23,419 W). The efficiency was found to be **68.8%**, which demonstrates satisfactory performance for a compact experimental exchanger with spiral baffles.

Table 4: Summary of calculated performance parameters

Parameter	Value
Reynolds number (tube side)	331,115
Reynolds number (shell side)	233,119
LMTD (K)	14.85
Heat transfer rate, Q (kW)	16.1
Efficiency (η, %)	68.8%

Heat Transfer Analysis without Spiral Rod

An experiment was conducted without the spiral rod to evaluate the baseline performance of the shell and tube heat exchanger. The parameters obtained after one hour of operation are presented in **Table 5**. These measurements were subsequently used to calculate flow characteristics, Reynolds's number, log mean temperature difference (LMTD), heat transfer rate (Q), and efficiency (η).

Table 5. Parameters obtained from heat exchanger without spiral rod

S. No	Component	Value (°C / Psi)
1	Shell inlet temperature (°C)	14.6
2	Shell outlet temperature (°C)	15.2
3	Shell ΔT (°C)	0.6
4	Tube inlet temperature (°C)	32.0
5	Tube outlet temperature (°C)	31.6
6	Tube ΔT (°C)	0.4
7	Shell inlet pressure (Psi)	28
8	Shell outlet pressure (Psi)	24
9	Shell ΔP (Psi)	4
10	Tube inlet pressure (Psi)	41
11	Tube outlet pressure (Psi)	39
12	Tube ΔP (Psi)	2

Reynolds's Number without Spiral Rod

The Reynolds's number was calculated for both tube and shell sides. On the tube side, the density, velocity, diameter, and viscosity yielded **Re = 216,919**, indicating turbulent flow. On the shell side, the corresponding parameters produced **Re = 181,191**, which also fell in the turbulent regime.

These results confirmed that the flow remained turbulent in both cases, which is favorable for convective heat transfer.

Log Mean Temperature Difference (LMTD)

The log mean temperature difference was calculated using the inlet and outlet temperatures:

ΔT_1 = 17.4 K

ΔT_2 = 16.4 K

LMTD = 16.89 K

The heat transfer area of the exchanger was **2.17 m²**, and the calculated heat transfer rate was **7.44 kW**.

Heat Transfer Efficiency

The actual heat transfer rate **(Qactual)** was 7.44 kW, whereas the maximum possible heat transfer rate **(Qmax)** was 17.41 kW. The heat transfer efficiency was therefore calculated as:

η=QactualQmax×100=42.7%

Table 6: Results obtained from experiment without spiral rod

Parameter	Value
Reynolds's number (Tube side)	216,919
Reynolds's number (Shell side)	181,191
Log Mean Temperature Difference	16.89 K
Heat Transfer Rate (Q)	7.44 kW
Heat Transfer Efficiency (η)	42.7 %

Comparison of Experiments

Two experiments were conducted: one with a spiral rod (Experiment 1) and another without it (Experiment 2). The results are summarized in **Table 7**.

Table 7. Comparison of experiments with and without spiral rod

Parameter	With Spiral Rod	Without Spiral Rod
Flow regime (Tube side)	Turbulent	Turbulent
Flow regime (Shell side)	Turbulent	Transitional/Laminar
Reynolds's number (Tube side)	233,119	216,919
Reynolds's number (Shell side)	331,115	181,191
LMTD (K)	14.85	16.89
Heat Transfer Rate (kW)	16.1	7.44
Efficiency (%)	62.4	42.7

The results demonstrated that the presence of the spiral rod increased turbulence, particularly on the shell side, which significantly improved the heat transfer efficiency (62.4% vs. 42.7%). Although the LMTD was slightly higher in the configuration without the spiral rod (16.89 K), the overall heat transfer rate and efficiency were substantially greater with the spiral rod. This indicated that the spiral rod enhanced convective mixing and reduced thermal resistance, thereby improving overall performance.

Surface Area

The surface area of the heat exchanger was calculated to be **2.17 m²**, which is relatively small compared to industrial-scale exchangers (>50 m²). Despite this compactness, the exchanger achieved notable heat transfer rates in both experimental conditions, highlighting its potential for small-scale applications where efficiency and compactness are prioritized.

Figure 3: Internal Parts Spiral rod

DISCUSSION

The present study was undertaken to design and evaluate a compact, cost-effective shell and tube heat exchanger with the objective of improving thermal performance while reducing fabrication costs. The experimental findings, obtained under controlled operating conditions, provided valuable insights into the influence of spiral rod inserts on turbulence, heat transfer rate, pressure drop, and efficiency. The results demonstrated that the incorporation of spiral rods into the shell side significantly enhanced thermal performance compared with the baseline configuration without spiral inserts (Sohrabi et al., 2024).

Interpretation of Findings

The heat exchanger fitted with spiral rods achieved a heat transfer rate of 16.1 kW and an efficiency of 68.8%, which represented a substantial improvement compared with the exchanger without inserts, where the heat transfer rate was 7.44 kW and efficiency 42.7%. This enhancement can be attributed to the role of spiral rods in promoting turbulence and disrupting the laminar sub-layer, thereby increasing convective heat transfer. Although the log mean temperature difference (LMTD) was slightly higher in the absence of spiral rods (16.89 K vs. 14.85 K), the overall heat transfer was greater with spiral inserts due to the higher effective heat transfer coefficient and improved mixing of shell-side fluid (Ali et al., 2024).

The Reynolds numbers further confirmed the predominance of turbulent flow in both configurations, though turbulence intensity was higher with spiral inserts. The tube-side Reynolds number increased from 216,919 (without insert) to 331,115 (with insert), while the shell-side Reynolds number increased from 181,191 to 233,119. These results established that spiral rods effectively enhanced turbulence levels, which directly translated into superior heat transfer performance (Haddadvand et al., 2024). Importantly, pressure drops on both sides remained within acceptable limits, suggesting that the enhancement in heat transfer was achieved without excessive hydraulic penalties (Haidari & Al-Obaidi, 2025). These findings addressed the primary objective of the study, namely the development of a compact and economically feasible heat exchanger design with improved performance. The results clearly indicated that structural modifications such as spiral rods could overcome traditional limitations of shell and tube exchangers, particularly the trade-off between efficiency and size (Bouselsal et al., 2023).

Comparison with Previous Studies

The role of turbulence promoters and surface inserts in heat exchangers has been widely investigated in previous literature. Similar to the present findings, (Waware et al., 2025) emphasized that the insertion of twisted tapes, coils, or other turbulence-inducing structures enhances convective heat transfer by promoting secondary flows and disrupting boundary layers. Studies by Marzouk et al. (2023) also reported that helical baffles in shell and tube exchangers increased heat transfer coefficients by 25–40% while maintaining moderate pressure drops.

The observed improvement in efficiency (from 42.7% to 68.8%) in this study aligns closely with research by Uosofvand et al. (2021), who demonstrated that helical baffle exchangers achieved higher thermal effectiveness compared with conventional segmental baffles. Similarly, (Volodin et al., 2021) noted that surface modifications increased heat transfer coefficients by disturbing laminar films, though at the expense of higher pressure drops. The present findings differ slightly in that the pressure penalties were minimal, indicating that spiral rods may provide a favorable balance between turbulence promotion and hydraulic resistance (Adogbeji & Lagouge, 2025).

Moreover, previous studies on compact heat exchanger design, such as those by (Dwivedi et al., 2023), highlighted the persistent challenge of achieving high thermal efficiency without significantly increasing equipment size and cost. The present study demonstrated that with a modest heat transfer surface area of 2.17 m^2, significant efficiency gains were possible, thereby supporting the concept of compact yet high-performance exchangers.

Scientific Explanation of Observed Results

The improved thermal performance with spiral rod inserts can be explained by fundamental heat transfer principles. In the baseline exchanger, fluid flow was largely streamlined, and boundary layers developed along tube surfaces, which increased thermal resistance (Ocłoń et al., 2021). The addition of spiral rods disrupted these boundary layers and created secondary swirling flows that enhanced fluid mixing. This mechanism increased the Nusselt number, thereby raising the convective heat transfer coefficient (Zhang et al., 2022).

From a fluid dynamics perspective, turbulence intensity is a critical determinant of heat transfer efficiency. Spiral rods induced transverse velocity components in the shell-side fluid, which increased velocity gradients near heat transfer surfaces. According to Newton's law of cooling, the rate of convective heat transfer is proportional to the temperature gradient at the wall. By reducing the thickness of the thermal boundary layer, the inserts increased this gradient, thus accelerating energy exchange between hot and cold streams (Their et al., 2023).

The slightly higher LMTD in the configuration without spiral rods can be attributed to reduced convective mixing, which allowed larger temperature differences between bulk fluid and heat transfer surfaces. However, this apparent advantage did not translate into greater heat transfer rates because the effective heat transfer coefficient remained lower (Deb et al., 2021). Therefore, the observed results underscore the importance of turbulence enhancement over mere temperature gradients in achieving efficient thermal exchange.

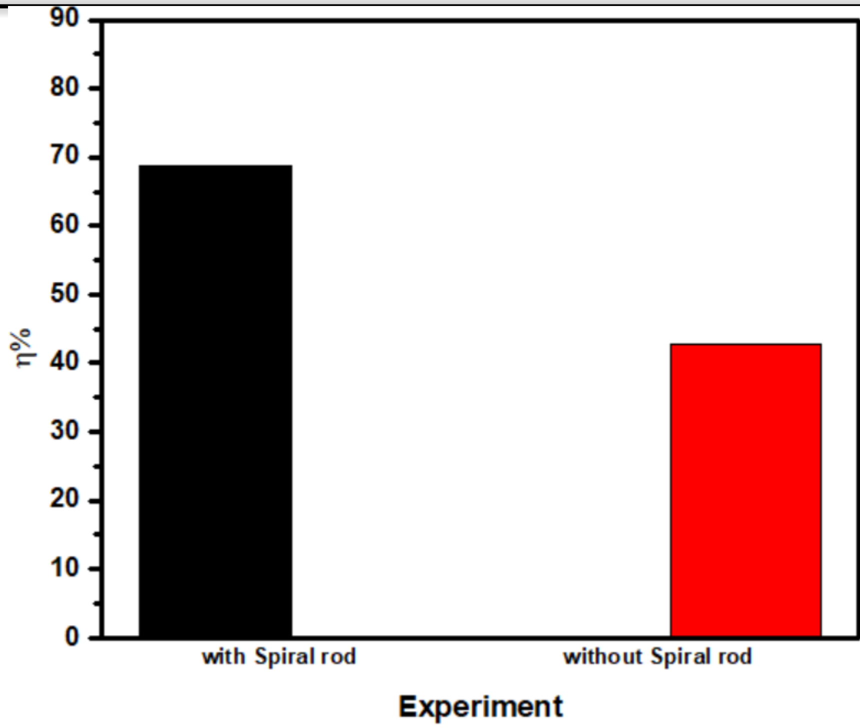


Figure 4: Comparison of experiments with and without spiral rod

Implications for Industry and Future Research

The practical implications of these findings are significant. Heat exchangers account for a substantial portion of energy consumption in process industries, and even modest improvements in their efficiency can lead to meaningful reductions in energy costs and greenhouse gas emissions. The present study demonstrated that structural modifications such as spiral rods can more than double the heat transfer rate without proportionally increasing costs or space requirements (Khatri et al., 2025). This has particular relevance for small- and medium-scale industries where capital investment and spatial constraints often limit the deployment of conventional large-scale exchangers. The fabricated design in this study cost 56,000 units, a relatively low figure compared to stainless steel or titanium alternatives, highlighting its economic feasibility (Oladipupo, 2023).

From a sustainability perspective, improved efficiency contributes directly to resource conservation and reduced environmental impact. Adoption of compact, cost-effective designs could accelerate the integration of energy-efficient systems in developing regions, where affordability is a critical factor. Moreover, the demonstrated feasibility of spiral rod inserts opens avenues for further exploration of alternative turbulence promoters, including helical coils, twisted strips, and surface modifications with nanocoatings (Kumar et al., 2024). Future research should extend these findings by investigating long-term operational performance under varying fluid types and fouling conditions. Computational fluid dynamics (CFD) could be employed to optimize spiral rod geometry, spacing, and placement to achieve even greater performance enhancements. Additionally, scaling up the design for industrial applications would provide valuable insights into real-world applicability and durability.

Limitations

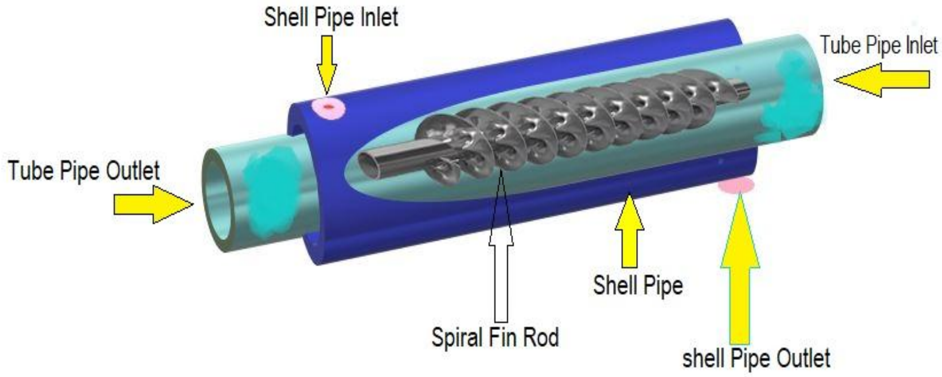
While the study provided promising results, several limitations should be acknowledged. The experiments were conducted at laboratory scale with relatively small surface areas (2.17 m^2), and performance may vary in larger industrial units where flow distribution and fouling become more critical. Only water was used as the working fluid; other fluids with different viscosities, heat capacities, or fouling tendencies may yield different outcomes. Moreover, the study primarily focused on steady-state conditions, and transient performance during start-up and shutdown phases was not evaluated. Finally, while cost analysis indicated affordability at the prototype level, detailed lifecycle cost assessments—including maintenance and cleaning requirements—are needed for comprehensive economic evaluation.

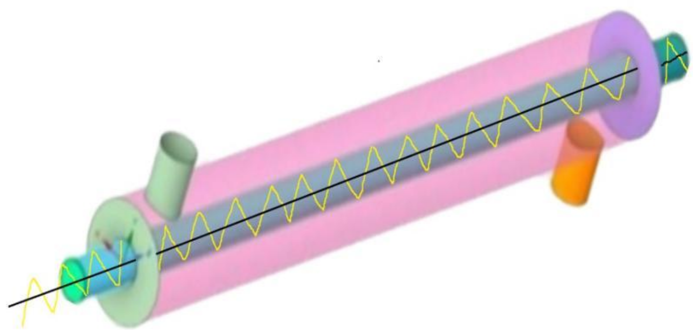
CONCLSUION

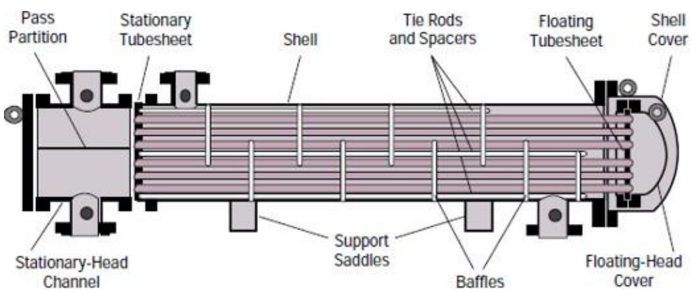
The results of this study showed that the use of a spiral rod in a shell and tube heat exchanger significantly improved its thermal performance and efficiency. The heat exchanger with the spiral rod achieved a heat transfer rate of 16.1 kW and an efficiency of 62.4%, which was notably higher than the 7.44 kW and 42.7% obtained without the spiral rod. Although the LMTD was slightly higher in the design without the spiral rod, the overall heat transfer performance was much better with the modified design. These findings confirmed that the research objective of developing a compact and cost-effective exchanger with improved efficiency was successfully met.

The main message of this research was that simple structural modifications, such as spiral rod inserts, could enhance turbulence, reduce thermal resistance, and provide substantial performance benefits without major cost increases. The scientific contribution of this study lay in demonstrating a practical and low-cost approach for improving the efficiency of shell and tube exchangers. Overall, the study concluded that the proposed design was feasible for small-scale applications, offering both efficiency and affordability. Future research should focus on long-term performance, fouling resistance, and scaling the design for larger industrial systems.

IMAGE GALLERY OF EXPERIMENT







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