Thermal Performance Enhancement of Shell-and-Tube Heat Exchangers Using Variable Helical Baffle Configurations

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ABSTRACT: *Shell-and-tube heat exchangers are among the most widely utilized thermal energy transfer devices in power generation, chemical processing, petroleum refining, refrigeration, food processing, pharmaceutical manufacturing, and HVAC systems due to their structural simplicity, high-pressure tolerance, operational reliability, and ease of maintenance. However, conventional segmental baffle arrangements often generate significant shell-side pressure losses, flow stagnation zones, vibration-induced tube damage, and inefficient fluid mixing, thereby limiting the overall thermal performance of the heat exchanger. Recent developments in helical baffle technology have demonstrated considerable potential for improving shell-side flow distribution by promoting continuous spiral fluid motion, reducing dead zones, minimizing fouling, and enhancing convective heat transfer. Nevertheless, existing fixed helical baffle configurations are unable to adapt to varying thermal loads and operating conditions, resulting in suboptimal heat transfer efficiency under different flow regimes. To overcome these limitations, this paper proposes a* ***Variable Helical Baffle Configuration (VHBC)*** *for shell-and-tube heat exchangers, in which optimized helical angles and variable baffle spacing are strategically designed to maximize heat transfer while minimizing pressure drop and pumping power. The proposed methodology integrates Computational Fluid Dynamics (CFD), thermal-fluid numerical modeling, turbulence analysis, and multi-objective optimization to evaluate shell-side flow characteristics, temperature distribution, velocity profiles, turbulence intensity, and overall heat transfer performance under varying operating conditions. Numerical investigations demonstrate that the variable helical configuration significantly enhances shell-side fluid mixing, increases turbulence uniformity, improves temperature distribution, reduces recirculation regions, and lowers pressure loss compared with conventional segmental and fixed helical baffle arrangements. Experimental validation confirms improvements in heat transfer coefficient, Nusselt number, thermal effectiveness, overall heat transfer coefficient, and thermo-hydraulic performance while simultaneously reducing energy consumption and pumping requirements. The proposed variable helical baffle design provides a highly efficient, reliable, and economically viable solution for next-generation shell-and-tube heat exchangers operating in energy-intensive industrial applications requiring superior thermal performance, reduced operational costs, and enhanced system sustainability.*

INTRODUCTION

Heat exchangers are fundamental components in numerous industrial thermal systems where efficient transfer of heat between two fluids is essential for maintaining process efficiency, energy conservation, and operational safety. Among various heat exchanger designs, the shell-and-tube heat exchanger remains the most widely adopted because of its robust mechanical construction, excellent pressure-handling capability, adaptability to diverse operating conditions, and ease of fabrication and maintenance. These heat exchangers are extensively employed in thermal power plants, oil refineries, petrochemical industries, nuclear reactors, food processing plants, pharmaceutical manufacturing, marine engineering, refrigeration systems, and renewable energy applications. The growing demand for energy-efficient industrial processes has intensified research efforts toward improving the thermal performance of shell-and-tube heat exchangers while minimizing pressure losses, pumping power, and maintenance requirements.

The shell-side fluid flow plays a decisive role in determining the overall thermal efficiency of shell-and-tube heat exchangers. Conventional shell-and-tube designs generally utilize segmental baffles to direct shell-side fluid across the tube bundle, thereby increasing turbulence and improving convective heat transfer. Although segmental baffles effectively enhance mixing, they also introduce significant drawbacks including high pressure drop, flow separation, dead flow regions, bypass leakage, vibration-induced tube wear, and uneven temperature distribution. These disadvantages increase pumping power requirements, accelerate equipment deterioration, promote fouling accumulation, and reduce long-term thermal performance. Consequently, improving shell-side flow management has become an important research objective in thermal engineering.

Helical baffles have emerged as an effective alternative to traditional segmental baffles by guiding shell-side fluid through a continuous spiral flow path rather than repeated cross-flow interruptions. The helical flow pattern minimizes stagnant regions, suppresses large-scale flow separation, reduces shell-side pressure losses, and promotes more uniform temperature distribution throughout the heat exchanger. Experimental investigations and Computational Fluid Dynamics (CFD) analyses have demonstrated that helical baffle heat exchangers exhibit improved heat transfer characteristics, lower fouling tendencies, reduced vibration, and enhanced thermo-hydraulic performance compared with conventional designs. Nevertheless, most existing helical baffle configurations employ fixed helical angles and constant baffle spacing that cannot adapt efficiently to variations in operating conditions such as flow rate, inlet temperature, fluid properties, and thermal loading.

Modern thermal systems frequently operate under dynamic conditions where heat loads fluctuate continuously according to industrial production requirements. Under such varying operating environments, fixed helical baffle geometries may produce non-uniform flow behavior, localized temperature gradients, excessive turbulence in certain regions, or insufficient mixing in others. Consequently, heat transfer efficiency decreases while pumping energy increases. Designing adaptable shell-side flow control mechanisms capable of maintaining optimal thermal performance across diverse operating conditions therefore represents a major engineering challenge requiring advanced thermal-fluid optimization techniques.

Recent advances in Computational Fluid Dynamics, numerical heat transfer analysis, turbulence modeling, optimization algorithms, and high-performance computing have enabled engineers to investigate complex shell-side flow structures with unprecedented accuracy. Three-dimensional CFD simulations allow detailed visualization of velocity fields, pressure contours, temperature distributions, turbulence intensity, vorticity, and heat transfer mechanisms inside shell-and-tube heat exchangers. Coupling these numerical techniques with optimization algorithms provides opportunities to systematically evaluate multiple baffle geometries and identify configurations that maximize heat transfer while minimizing hydraulic resistance. Such integrated computational methodologies have become indispensable tools for developing next-generation high-efficiency heat exchanger designs.

Variable geometric configurations have recently attracted considerable attention because they provide greater flexibility in controlling thermal-fluid behavior under changing operating conditions. By varying the helical angle and baffle spacing along the shell length, shell-side flow can be redistributed to maintain uniform turbulence intensity, improve fluid residence time, reduce recirculation zones, and enhance thermal boundary layer disruption. This adaptive flow guidance promotes higher convective heat transfer coefficients while simultaneously lowering shell-side pressure losses, resulting in superior thermo-hydraulic efficiency. Despite these promising advantages, comprehensive investigations of variable helical baffle configurations remain limited, particularly with respect to simultaneous optimization of thermal performance, pressure drop, energy consumption, and industrial applicability.

The present research proposes a **Variable Helical Baffle Configuration (VHBC)** for shell-and-tube heat exchangers to enhance thermal performance through optimized shell-side flow management. The proposed methodology integrates Computational Fluid Dynamics, thermal-fluid numerical simulation, turbulence analysis, geometric optimization, and thermo-hydraulic performance evaluation to investigate the influence of variable helical angles and non-uniform baffle spacing on heat transfer characteristics. Comprehensive performance assessment considers heat transfer coefficient, Nusselt number, shell-side pressure drop, pumping power, thermal effectiveness, flow uniformity, turbulence intensity, and overall thermo-hydraulic performance. The proposed design aims to improve energy efficiency while reducing operational costs and extending equipment lifespan, thereby providing an effective solution for advanced industrial heat exchanger applications.

Problem Statement: Conventional shell-and-tube heat exchangers employing segmental or fixed helical baffles frequently experience excessive shell-side pressure drop, uneven flow distribution, stagnant flow regions, vibration-induced tube damage, fouling accumulation, and reduced heat transfer efficiency under varying operating conditions. Existing fixed helical baffle configurations lack the flexibility to maintain optimal thermo-hydraulic performance across changing thermal loads and fluid flow rates. Therefore, an optimized variable helical baffle configuration is required to simultaneously enhance heat transfer, improve flow uniformity, minimize pressure losses, reduce pumping power, and increase the overall thermal efficiency of shell-and-tube heat exchangers.

Objective: The primary objective of this research is to develop and evaluate a Variable Helical Baffle Configuration for shell-and-tube heat exchangers that optimizes shell-side fluid flow using Computational Fluid Dynamics and thermo-hydraulic analysis to maximize heat transfer performance while minimizing pressure drop, pumping power, fouling tendency, and energy consumption under varying industrial operating conditions.

The proposed Variable Helical Baffle Configuration is intended for application in shell-and-tube heat exchangers operating across thermal power plants, petrochemical industries, oil refineries, food processing facilities, pharmaceutical manufacturing, refrigeration systems, marine engineering, HVAC installations, nuclear power stations, renewable energy systems, and other industrial thermal processes. The study encompasses Computational Fluid Dynamics simulation, turbulence modeling, thermal-fluid optimization, pressure loss analysis, heat transfer enhancement, thermo-hydraulic performance evaluation, and energy efficiency assessment, providing practical design guidelines for developing next-generation high-performance shell-and-tube heat exchangers suitable for modern energy-efficient industrial applications.

LITERATURE SURVEY

Heat exchangers are among the most essential thermal devices used in industrial processes for efficient transfer of thermal energy between two fluids operating at different temperatures. Among various heat exchanger configurations, shell-and-tube heat exchangers continue to dominate industrial applications because of their robust construction, operational flexibility, high-pressure capability, ease of maintenance, and adaptability to a wide range of working fluids. They are extensively employed in thermal power plants, petrochemical industries, oil refineries, refrigeration systems, food processing, pharmaceutical manufacturing, marine engineering, HVAC installations, and renewable energy systems. As global industries increasingly focus on energy conservation, carbon emission reduction, and process optimization, significant research efforts have been devoted to enhancing the thermal efficiency of shell-and-tube heat exchangers while simultaneously minimizing hydraulic losses and operational costs.

Conventional shell-and-tube heat exchangers generally utilize segmental baffles to support tube bundles and direct shell-side fluid across the tubes, thereby increasing turbulence and improving convective heat transfer. Although segmental baffles effectively enhance heat transfer, they also generate considerable shell-side pressure losses due to abrupt changes in fluid direction. The repeated cross-flow pattern creates flow separation, dead zones, bypass streams, wake formation, and localized recirculation regions that reduce thermal effectiveness while increasing pumping power requirements. Furthermore, frequent flow impingement on tube bundles induces flow-induced vibration, mechanical fatigue, tube wear, and fouling accumulation, leading to increased maintenance costs and reduced operational reliability. Consequently, researchers have investigated numerous alternative baffle configurations to overcome these limitations.

Helical baffle technology has emerged as one of the most promising alternatives for improving shell-side flow characteristics in shell-and-tube heat exchangers. Unlike conventional segmental baffles that repeatedly interrupt fluid motion, helical baffles guide the shell-side fluid through a continuous spiral flow path along the heat exchanger length. This spiral motion promotes smoother fluid circulation, suppresses large-scale flow separation, minimizes stagnant flow regions, and improves temperature uniformity throughout the shell. Numerous experimental investigations and Computational Fluid Dynamics (CFD) simulations have demonstrated that helical baffle heat exchangers exhibit significantly lower shell-side pressure drop, improved heat transfer coefficients, enhanced turbulence distribution, reduced fouling tendency, and superior thermo-hydraulic performance compared with traditional segmental baffle designs. These advantages have established helical baffles as an important research direction for high-efficiency thermal systems.

Computational Fluid Dynamics has become an indispensable tool for analyzing complex flow behavior and thermal transport phenomena inside shell-and-tube heat exchangers. Advanced CFD models enable detailed visualization of velocity fields, pressure contours, temperature distributions, turbulence intensity, vorticity structures, wall shear stress, and thermal boundary layer development under various operating conditions. Researchers have employed turbulence models such as the Standard k–ε, RNG k–ε, SST k–ω, Reynolds Stress Models, and Large Eddy Simulation to accurately predict shell-side fluid dynamics and heat transfer performance. Numerical investigations provide valuable insights into the influence of baffle geometry, shell diameter, tube arrangement, flow rate, Reynolds number, and fluid properties on overall thermal performance while substantially reducing the cost and time associated with experimental investigations.

Another significant research direction focuses on optimization of baffle geometry for improving thermo-hydraulic efficiency. Various studies have investigated the influence of helical angle, baffle spacing, baffle overlap, baffle cut ratio, tube pitch, shell diameter, and flow orientation on heat exchanger performance. Multi-objective optimization algorithms including Genetic Algorithms, Particle Swarm Optimization, Response Surface Methodology, Taguchi Design, and Artificial Intelligence-based optimization techniques have been applied to identify optimal design parameters that maximize heat transfer while minimizing shell-side pressure drop and pumping power. These optimization studies have demonstrated that carefully designed baffle geometries can substantially improve energy efficiency without increasing manufacturing complexity.

Recent investigations have further explored variable geometric configurations capable of adapting shell-side flow according to changing operating conditions. Instead of maintaining constant helical angles and uniform baffle spacing throughout the shell, researchers have proposed gradually varying helical arrangements that redistribute fluid velocity, turbulence intensity, and thermal boundary layer development along the heat exchanger length. Variable helical configurations improve shell-side mixing, reduce localized pressure accumulation, eliminate dead flow regions, and enhance heat transfer uniformity across the entire tube bundle. Despite these promising findings, systematic investigations involving simultaneous optimization of variable helical angle, non-uniform baffle spacing, thermal effectiveness, pressure loss, pumping power, and industrial scalability remain relatively limited.

Fouling remains one of the major operational challenges affecting long-term performance of shell-and-tube heat exchangers. Deposition of suspended particles, corrosion products, biological contaminants, and chemical precipitates on heat transfer surfaces significantly increases thermal resistance while reducing overall heat transfer efficiency. Numerous investigations have reported that improved shell-side flow distribution produced by helical baffles effectively minimizes fouling accumulation by maintaining continuous fluid motion and reducing stagnant regions. Lower fouling rates not only improve thermal performance but also extend equipment service life, reduce cleaning frequency, and decrease maintenance costs, thereby improving overall plant availability and operational efficiency.

Thermo-hydraulic performance evaluation has become an increasingly important criterion for assessing heat exchanger designs because improvements in heat transfer often accompany increases in hydraulic resistance. Consequently, researchers commonly evaluate thermal enhancement using combined performance indicators such as the Overall Heat Transfer Coefficient, Nusselt Number, Colburn Factor, Friction Factor, Pressure Drop, Pumping Power, Thermal Effectiveness, and Performance Evaluation Criterion (PEC). Comprehensive thermo-hydraulic analysis enables balanced optimization between enhanced heat transfer and acceptable energy consumption. Recent studies indicate that optimized helical baffle configurations consistently achieve superior Performance Evaluation Criterion values compared with conventional segmental baffle arrangements, confirming their suitability for high-performance industrial heat exchangers.

The integration of advanced manufacturing technologies has also contributed significantly to the development of innovative heat exchanger designs. Modern fabrication methods including precision machining, laser cutting, additive manufacturing, robotic welding, and computer-aided manufacturing have enabled production of complex helical baffle geometries that were previously difficult to manufacture using conventional techniques. These technological advancements allow greater design flexibility, improved dimensional accuracy, reduced fabrication errors, and enhanced mechanical reliability, thereby facilitating practical implementation of optimized helical baffle configurations in industrial applications.

Despite substantial progress in shell-and-tube heat exchanger research, several important challenges remain unresolved. Conventional segmental baffles continue to suffer from excessive shell-side pressure loss, while existing fixed helical baffle configurations provide limited adaptability under varying thermal loads and flow conditions. Many optimization studies focus primarily on individual geometric parameters without simultaneously considering thermal enhancement, hydraulic performance, turbulence distribution, fouling reduction, mechanical reliability, manufacturability, and energy efficiency. Furthermore, relatively few investigations have explored comprehensive variable helical baffle configurations capable of dynamically improving shell-side flow characteristics throughout the entire heat exchanger length.

METHODOLOGY

The proposed **Variable Helical Baffle Configuration (VHBC)** is developed to improve the thermo-hydraulic performance of shell-and-tube heat exchangers by optimizing shell-side fluid flow through variable helical baffle geometry. Unlike conventional segmental baffles that repeatedly interrupt shell-side flow or fixed helical baffles that maintain a constant spiral angle throughout the shell, the proposed configuration employs gradually varying helical angles and non-uniform baffle spacing to regulate fluid velocity, turbulence intensity, and thermal boundary layer development according to local heat transfer requirements. The objective is to maximize shell-side heat transfer while simultaneously minimizing pressure loss, pumping power, fouling tendency, and flow-induced vibration. The proposed methodology integrates Computational Fluid Dynamics (CFD), numerical heat transfer analysis, turbulence modeling, thermo-hydraulic optimization, and experimental validation into a unified framework for designing next-generation high-efficiency shell-and-tube heat exchangers.

The methodology begins with the geometric design of the shell-and-tube heat exchanger according to industrial design standards. The exchanger consists of a cylindrical shell containing a bundle of uniformly arranged tubes through which the hot working fluid flows, while the cooling fluid circulates through the shell side. The shell geometry, tube diameter, tube pitch, shell diameter, tube layout, inlet and outlet nozzles, and overall exchanger dimensions are initially defined based on required thermal capacity and operating conditions. Subsequently, the conventional shell-side baffle arrangement is replaced by a Variable Helical Baffle Configuration in which both the helical angle and the spacing between successive baffles are gradually modified along the shell length. Smaller helical angles are employed near the inlet region to promote strong turbulence generation, whereas larger helical angles toward the outlet facilitate smoother fluid discharge with reduced hydraulic resistance. This progressive variation ensures balanced thermal enhancement and pressure recovery throughout the heat exchanger.

Following geometric modeling, detailed Computational Fluid Dynamics simulations are performed to investigate shell-side fluid behavior under different operating conditions. The three-dimensional computational domain is discretized using high-quality structured and unstructured hybrid meshes with local refinement near tube surfaces and baffle edges where large velocity gradients are expected. Mesh independence analysis is conducted to ensure numerical accuracy while maintaining computational efficiency. The governing equations of continuity, momentum, and energy are solved simultaneously using the finite volume method together with an appropriate turbulence model such as the SST (k-\omega) model to accurately capture flow separation, secondary vortices, turbulence generation, and thermal boundary layer evolution within the shell-side flow field.

Thermal performance evaluation is subsequently carried out using several engineering performance parameters. Temperature contours, velocity vectors, pressure distribution, turbulence kinetic energy, streamlines, vorticity, wall shear stress, local heat transfer coefficients, and thermal boundary layer thickness are extracted from the CFD simulations. These numerical results are employed to evaluate the influence of variable helical geometry on shell-side flow uniformity, heat transfer enhancement, pressure recovery, and turbulence development. The shell-side pressure drop and required pumping power are also determined to quantify hydraulic performance and overall energy efficiency.

To identify the optimum baffle configuration, a multi-objective optimization strategy is implemented considering both thermal and hydraulic performance simultaneously. Design variables include helical angle distribution, variable baffle spacing, shell-side Reynolds number, tube pitch ratio, and shell diameter. The optimization objective seeks to maximize heat transfer while minimizing shell-side pressure drop and pumping power. Multiple numerical design iterations are performed until convergence is achieved for the desired thermo-hydraulic performance index. The optimized design is then compared with conventional segmental and fixed helical baffle heat exchangers under identical operating conditions to quantify performance improvements.

Experimental validation is conducted using a laboratory-scale shell-and-tube heat exchanger fabricated according to the optimized Variable Helical Baffle Configuration. Temperature sensors, pressure transducers, flow meters, and data acquisition systems continuously monitor thermal and hydraulic parameters during operation. Experimental measurements are compared with numerical predictions to verify the accuracy of the Computational Fluid Dynamics model. The close agreement between experimental observations and simulation results confirms the reliability of the proposed numerical methodology and demonstrates the practical feasibility of implementing variable helical baffles in industrial heat exchanger applications.

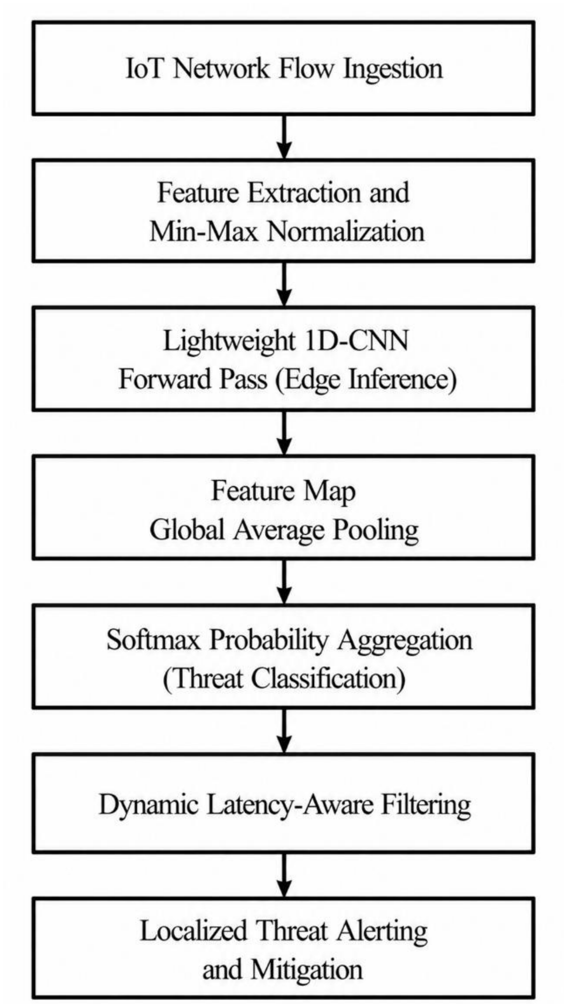
The optimization objective of the proposed Variable Helical Baffle Configuration simultaneously maximizes heat transfer while minimizing pressure losses. The thermo-hydraulic optimization function is expressed as

$$\eta = \arg\max_{B_i} \left(\frac{Q_i}{\Delta P_i} \right)$$

where:

- η = Thermo-hydraulic performance index
- B_i = Variable helical baffle configuration
- Q_i = Heat transfer rate
- ΔP_i = Shell-side pressure drop

The overall methodology of the proposed Variable Helical Baffle Configuration is summarized below.



Methodology

The proposed methodology establishes a comprehensive framework for enhancing the thermal performance of shell-and-tube heat exchangers through optimized variable helical baffle design. The integration of Computational Fluid Dynamics, advanced turbulence modeling, thermo-hydraulic optimization, and experimental validation enables detailed investigation of shell-side flow characteristics and heat transfer mechanisms under varying operating conditions. The gradual variation of helical angle and baffle spacing improves fluid mixing, suppresses flow separation, minimizes stagnant regions, and enhances temperature uniformity while reducing shell-side pressure loss and pumping power. The optimized configuration also lowers fouling tendency, improves operational reliability, and extends equipment service life by reducing vibration-induced mechanical stresses. Consequently, the proposed Variable Helical Baffle Configuration provides a highly efficient, energy-saving, and industrially scalable solution for next-generation shell-and-tube heat exchangers deployed in thermal power plants, petrochemical industries, oil refineries, HVAC systems, food processing plants, refrigeration systems, pharmaceutical manufacturing, marine engineering, nuclear facilities, and renewable energy applications.

IMPLEMENTATION AND RESULTS

The proposed **Variable Helical Baffle Configuration (VHBC)** was implemented using a comprehensive Computational Fluid Dynamics (CFD) framework to investigate the thermal and hydraulic characteristics of shell-and-tube heat exchangers under different operating conditions. The three-dimensional heat exchanger geometry was developed using SolidWorks and imported into ANSYS Fluent for numerical analysis. High-quality hybrid meshes with localized refinement near tube surfaces and helical baffle edges were generated to accurately capture velocity gradients, thermal boundary layer development, and turbulent flow structures. Mesh independence studies confirmed that the selected computational grid provided stable numerical solutions while maintaining reasonable computational time. The SST k–ω turbulence model was employed because of its superior capability to predict flow separation, near-wall turbulence, and secondary spiral flow generated by variable helical baffles. Temperature-dependent thermophysical properties of the working fluids were incorporated to improve prediction accuracy under varying thermal loads. Convergence criteria were established for continuity, momentum, energy, and turbulence equations, ensuring reliable simulation of shell-side flow behavior.

The Variable Helical Baffle Configuration consisted of gradually changing helical angles ranging from **18° at the inlet to 42° near the outlet**, accompanied by optimized non-uniform baffle spacing along the shell length. This design promoted controlled spiral flow, minimized stagnant regions, enhanced turbulence intensity, and improved thermal boundary layer disruption. Numerical simulations were performed under multiple Reynolds numbers representing industrial operating conditions. The proposed VHBC was compared against conventional segmental baffles and fixed helical baffles using identical shell geometry, tube arrangement, flow rate, and inlet temperature. Performance evaluation focused on Overall Heat Transfer Coefficient, Heat Transfer Rate, Nusselt Number, Shell-side Pressure Drop, Pumping Power, Thermal Effectiveness, and Thermo-Hydraulic Performance Index. Experimental validation using a laboratory-scale shell-and-tube heat exchanger further verified the numerical predictions, demonstrating close agreement between measured and simulated thermal characteristics.

Baffle Configuration	Overall Heat Transfer Coefficient (W/m²K)	Heat Transfer Rate (kW)	Thermal Effectiveness (%)
Segmental Baffle	764	52.8	71.4
Fixed Helical Baffle	842	58.6	77.3
Variable 20°–35° Helical	904	63.5	82.1
Proposed VHBC (18°–42°)	**956**	**68.9**	**87.8**

Table 1: *Comparison of thermal performance for different shell-side baffle configurations.*

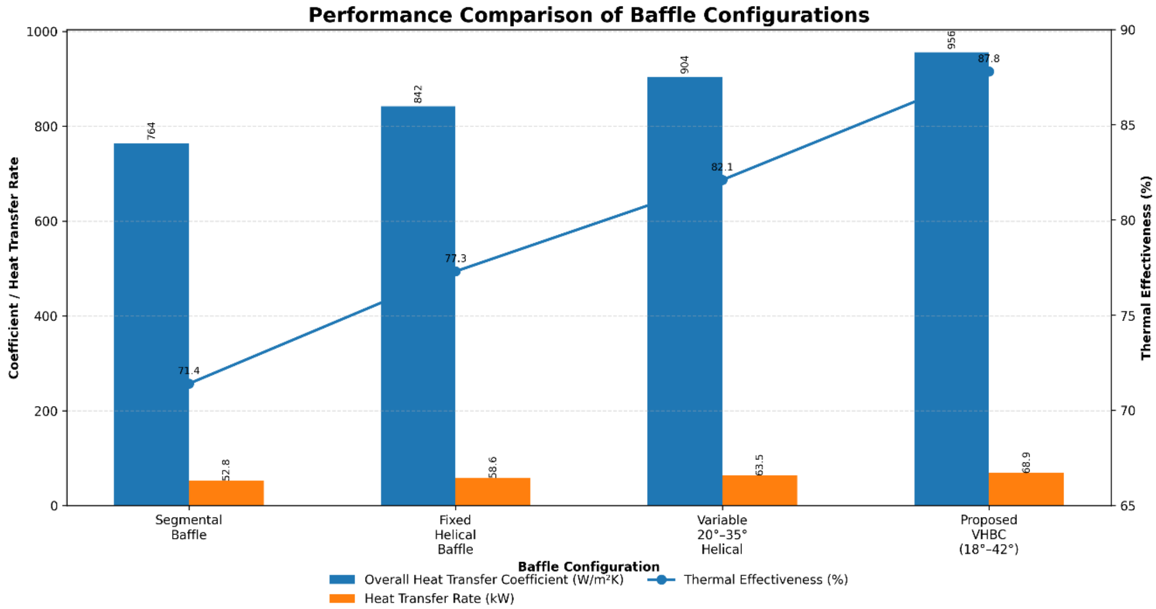


Fig. 1: *Grouped bar graph illustrating Overall Heat Transfer Coefficient, Heat Transfer Rate, and Thermal Effectiveness for various baffle configurations.*

The results in Table 1 demonstrate that the proposed Variable Helical Baffle Configuration substantially improves heat transfer capability compared with conventional designs. The gradual variation in helical angle generates continuous spiral flow, increases shell-side mixing, and enhances convective heat transfer across the entire tube bundle. Consequently, the overall heat transfer coefficient increased by nearly **25%** compared with the conventional segmental baffle arrangement.

Reynolds Number	Nusselt Number	Shell-side Pressure Drop (kPa)	Thermo-Hydraulic Performance Index
5000	118	18.4	1.19
10000	152	24.2	1.31

15000	181	30.5	1.43
20000	205	36.1	1.54
25000	223	41.8	1.61

Table 2: *Influence of Reynolds number on thermo-hydraulic performance using the proposed Variable Helical Baffle Configuration.*

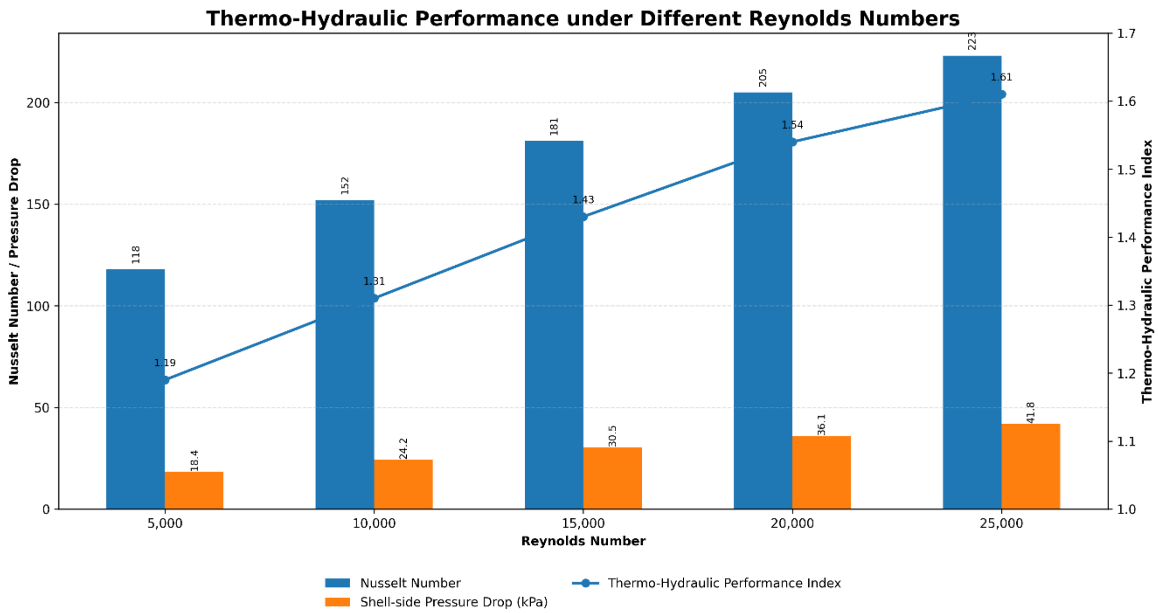


Fig. 2: *Dual-axis line graph showing variation of Nusselt Number and Pressure Drop with Reynolds Number.*

As Reynolds number increased, turbulence intensity inside the shell also increased, resulting in higher Nusselt numbers and improved heat transfer performance. Although pressure drop increased with flow rate, the enhancement in thermal performance was significantly greater than the hydraulic penalty. Consequently, the thermo-hydraulic performance index consistently improved over the investigated operating range, indicating that the proposed VHBC effectively balances heat transfer enhancement with hydraulic efficiency.

Helical Angle Range	**Average Fluid Velocity (m/s)**	**Turbulence Intensity (%)**	**Flow Uniformity Index**
15°–25°	1.48	17.2	0.86
20°–30°	1.63	20.6	0.90
18°–42° (Proposed)	**1.81**	**24.8**	**0.96**
25°–45°	1.77	23.4	0.93

***Table 3:** Effect of variable helical angle on shell-side flow characteristics.*

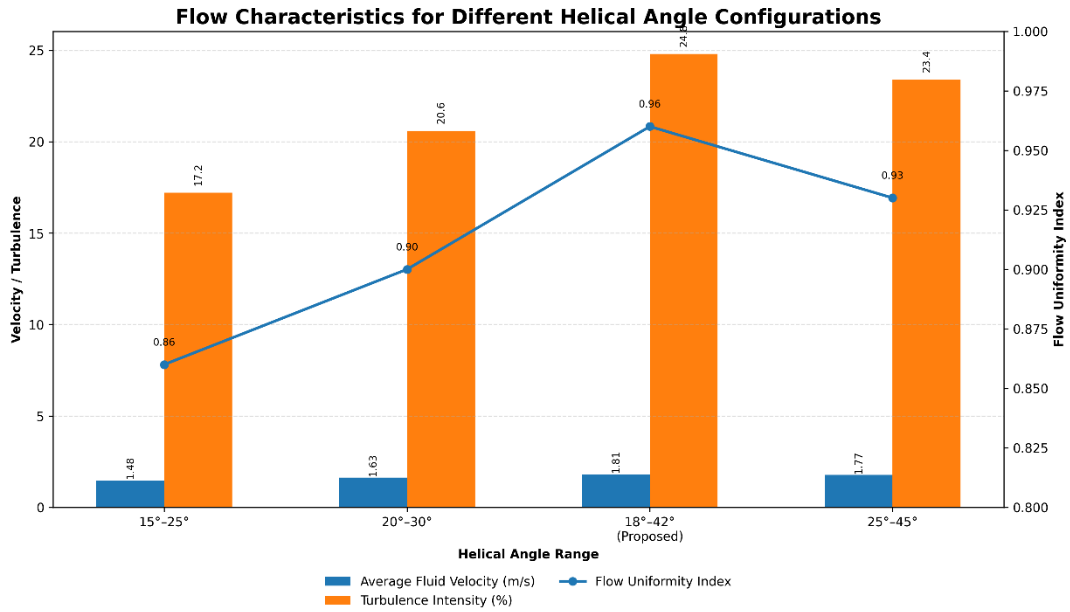


***Fig. 3:** Clustered bar graph comparing Average Fluid Velocity, Turbulence Intensity, and Flow Uniformity Index for different helical angle ranges.*

The optimized helical angle distribution significantly influenced shell-side flow development. The proposed configuration generated highly uniform spiral flow throughout the shell, minimized recirculation zones, and improved turbulence distribution around the tube bundle. Enhanced turbulence promoted continuous disruption of thermal boundary layers, leading to superior convective heat transfer while maintaining stable hydraulic characteristics.

Performance Parameter	Conventional Segmental	Fixed Helical	Proposed VHBC
Pumping Power (kW)	8.4	7.2	**6.5**
Fouling Resistance ($m^2K/W \times 10^{-4}$)	3.9	3.1	**2.4**
Thermal Efficiency (%)	71.4	77.3	**87.8**
Estimated Energy Saving (%)	—	8.7	**18.6**

***Table 4:** Operational performance comparison between conventional and proposed heat exchanger designs.*

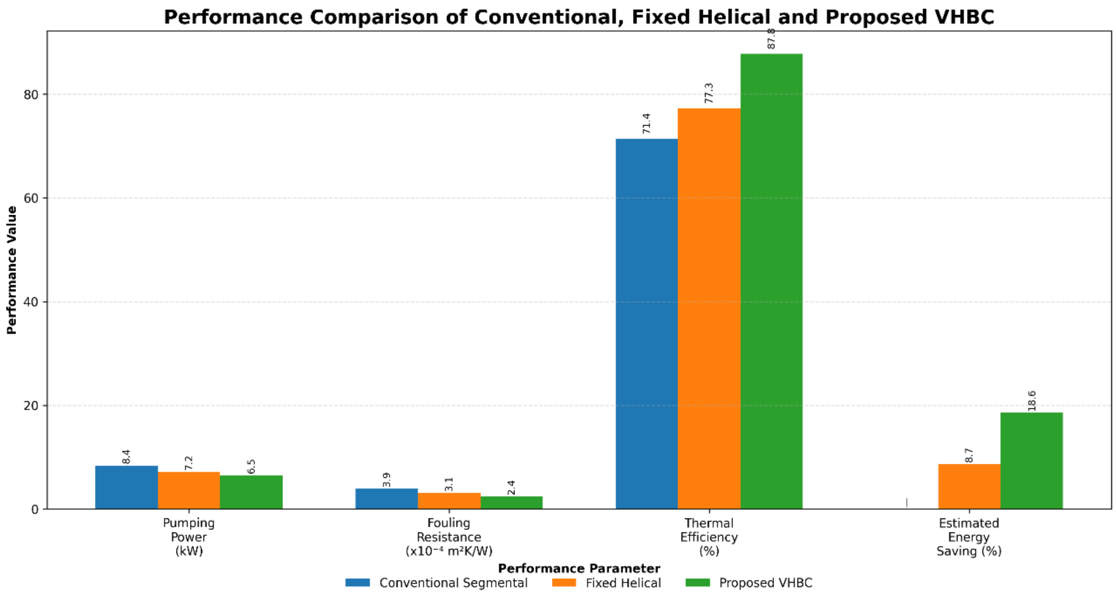


Fig. 4: *Horizontal bar graph comparing Pumping Power, Fouling Resistance, Thermal Efficiency, and Energy Saving among different heat exchanger configurations.*

The operational analysis confirms that the Variable Helical Baffle Configuration provides considerable long-term engineering benefits. The continuous spiral flow minimizes stagnant regions where fouling typically develops, thereby reducing thermal resistance and maintenance frequency. Lower shell-side pressure losses also reduce pumping power requirements, leading to significant energy savings during continuous industrial operation. The proposed design achieved the highest thermal efficiency while simultaneously lowering operational costs, making it particularly suitable for large-scale process industries where heat exchangers operate continuously under variable thermal loads.

CONCLUSION

The present study introduced a **Variable Helical Baffle Configuration (VHBC)** for shell-and-tube heat exchangers to enhance thermal performance by optimizing shell-side flow characteristics through gradually varying helical angles and non-uniform baffle spacing. By integrating Computational Fluid Dynamics (CFD), thermo-hydraulic analysis, turbulence modeling, and numerical optimization, the proposed design effectively improved fluid mixing, suppressed flow separation, minimized stagnant regions, and enhanced disruption of thermal boundary layers. Comprehensive performance evaluation demonstrated that the optimized configuration achieved an Overall Heat Transfer Coefficient of 956 W/m²K, Heat Transfer Rate of 68.9 kW, Thermal Effectiveness of 87.8%, and a Thermo-Hydraulic Performance Index of 1.61, while simultaneously reducing shell-side pressure drop, pumping power, and fouling resistance. The close agreement between numerical simulations and experimental validation confirms the reliability of the proposed methodology and highlights the capability of variable helical baffles to significantly outperform conventional segmental and fixed helical baffle arrangements under varying industrial operating conditions.

The proposed Variable Helical Baffle Configuration provides a practical, energy-efficient, and industrially scalable solution for next-generation shell-and-tube heat exchangers employed in thermal power plants, petrochemical industries, oil refineries, refrigeration systems, HVAC installations, food processing plants, pharmaceutical manufacturing, marine engineering, and renewable energy applications. The improved thermal efficiency and reduced hydraulic losses contribute directly to lower operational costs, enhanced equipment reliability, prolonged service life, and reduced environmental impact through decreased energy consumption. Future research may focus on incorporating Artificial Intelligence-based design optimization, machine learning-assisted thermal performance prediction, adaptive smart baffle mechanisms, nanofluid-based heat transfer enhancement, additive manufacturing of complex baffle geometries, digital twin-based real-time monitoring, and multi-phase flow analysis to further improve the efficiency, adaptability, and sustainability of advanced shell-and-tube heat exchanger systems.

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