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Twisted-tube rod-baffle exchangers under multi-objective thermal-hydraulic design and operating constraints

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Abstract.

The transition toward highly efficient thermal management systems in modern industrial processes necessitates the development of advanced heat exchanger geometries. Among these, the twisted-tube rod-baffle heat exchanger emerges as a highly promising configuration, combining the secondary flow generation capabilities of twisted tubes with the robust, vibration-resistant, and low-pressure-drop characteristics of rod baffles. This study presents a comprehensive investigation into the multi-objective thermal-hydraulic design of such exchangers under stringent operating constraints. A rigorous computational fluid dynamics methodology is established to evaluate the complex three-dimensional flow and heat transfer phenomena within the shell side of the exchanger. The mathematical formulation couples the continuity, momentum, and energy equations with an advanced turbulence model to capture the intricate swirl flows and boundary layer interactions. Subsequently, a multi-objective optimization framework based on the Non-dominated Sorting Genetic Algorithm II is implemented to simultaneously maximize the heat transfer rate and minimize the frictional pressure drop. The decision space encompasses critical geometrical parameters, including the tube twist ratio, rod baffle spacing, and shell diameter, while operating constraints such as maximum allowable pumping power and flow-induced vibration limits are strictly enforced. The optimization yields a Pareto frontier that provides a set of optimal design trade-offs for industrial application. Detailed analysis of the optimal configurations reveals that the synergistic interaction between the twisted tube surfaces and the rod baffles significantly mitigates the formation of dead recirculation zones, thereby enhancing the overall thermal-hydraulic performance.

Keywords: *Twisted-tube, Rod-baffle, Multi-objective optimization, Thermal-hydraulic, Computational fluid dynamics*

1. Introduction

The global demand for energy efficiency in chemical processing, petroleum refining, and power generation sectors has driven extensive research into the optimization of thermal management equipment. Heat exchangers represent the fundamental components of these industrial systems, and their performance directly impacts overall plant efficiency, operational costs, and environmental footprint. Traditional shell-and-tube heat exchangers, equipped with segmental baffles, have been the industry standard for over a century due to their robust construction and ease of maintenance. However, as industrial processes evolve to operate under increasingly demanding conditions, the inherent limitations of segmental baffle configurations have become apparent. These limitations include significant pressure drops caused by the abrupt changes in flow direction,

the creation of stagnant zones that promote fouling, and high susceptibility to flow-induced vibration, which can lead to catastrophic tube failure. To address these challenges, researchers and engineers have developed numerous enhanced heat transfer technologies. One major advancement in shell-side support structures is the rod-baffle configuration. Originally developed to mitigate flow-induced vibration in critical applications, rod baffles replace the solid segmental plates with an array of metallic rods arranged in a grid-like pattern. This design allows the shell-side fluid to flow longitudinally along the tubes rather than in a zig-zag cross-flow pattern. The longitudinal flow regime inherently reduces the form drag associated with flow separation, resulting in a substantially lower pressure drop for a given mass flow rate. Furthermore, the continuous support provided by the rod grid effectively eliminates tube vibration, thereby increasing the reliability and lifespan of the equipment. However, the purely longitudinal flow parallel to plain cylindrical tubes often results in a lower convective heat transfer coefficient compared to the cross-flow induced by segmental baffles. Simultaneously, advancements in tube-side and shell-side heat transfer augmentation have led to the widespread adoption of twisted tubes. Manufactured by flattening and twisting a standard cylindrical tube, twisted tubes feature an elliptical cross-section that rotates continuously along the longitudinal axis. This unique geometry imparts a strong swirling motion to the fluid flowing both inside and outside the tubes. The resulting secondary flow structures disrupt the thermal boundary layer, enhance fluid mixing between the bulk flow and the near-wall regions, and significantly elevate the heat transfer coefficient. When arranged in a bundle, the alternating contact points between adjacent twisted tubes provide additional mechanical support, although external baffles are still required for large-scale industrial units to maintain structural integrity under high-velocity flows. The integration of twisted tubes with rod baffles represents a highly synergistic design concept, commonly referred to as the twisted-tube rod-baffle heat exchanger. This hybrid configuration seeks to capitalize on the high heat transfer enhancement of the twisted tubes while maintaining the low pressure drop, uniform flow distribution, and vibration resistance of the rod-baffle support system. While the conceptual advantages of this combination are well recognized in the industry, the complex interacting flow dynamics within the shell side pose a formidable challenge for standardized design and optimization. The swirling flow generated by the twisted tubes interacts with the cylindrical rod baffles in a highly three-dimensional manner, producing localized velocity accelerations, wake interactions, and complex pressure fields that cannot be accurately predicted using traditional empirical correlations. Related work has addressed multi-objective optimization on shell-side performance of rod-baffle heat exchangers with twisted oval tubes [1].

Furthermore, the design of a twisted-tube rod-baffle heat exchanger cannot be approached from a single-objective perspective. In practical industrial applications, engineers face conflicting requirements: maximizing the thermal energy recovery while simultaneously minimizing the pumping power required to overcome fluid friction. These objectives are inherently contradictory, as any geometrical modification that enhances turbulent mixing and heat transfer inevitably increases the pressure drop. Consequently, the design process requires a rigorous multi-objective optimization approach capable of identifying the best possible trade-offs between thermal and hydraulic performance. Additionally, this optimization must strictly adhere to physical and operational constraints, such as limits on manufacturing tolerances, maximum allowable stress, and precise pumping capacity limits. The primary objective of this comprehensive study is to bridge this critical gap by developing a robust computational and mathematical framework for the multi-objective thermal-hydraulic design of twisted-tube rod-baffle heat exchangers under strict operational constraints.

1.1 Problem Statement And Research Objectives

Despite the recognized potential of the twisted-tube rod-baffle configuration, the existing design guidelines rely heavily on extrapolated empirical data that often fails to capture the localized fluid dynamic phenomena critical to optimal performance. The lack of a comprehensive optimization framework that simultaneously considers thermal efficacy, hydraulic penalty, and operational safety constraints restricts the widespread commercial deployment of these advanced exchangers. The specific objectives of this research are formulated to address these deficiencies systematically. The first objective is to develop a high-fidelity three-dimensional computational fluid dynamics model capable of accurately simulating the complex flow field and conjugate heat transfer within the shell side of the exchanger. This involves the careful selection of appropriate turbulence modeling strategies and mesh generation techniques to capture the near-wall flow physics. The second objective is to parameterize the critical geometric variables of the exchanger, including the twist pitch of the tubes, the transverse and longitudinal spacing of the rod baffles, and the overall packing density of the tube bundle. The third objective is to couple the computational fluid dynamics solver with an advanced multi-objective evolutionary algorithm to explore the design space efficiently. The final objective is to extract and analyze the Pareto-optimal design solutions, providing deep physical insights into how the optimal geometric configurations manipulate the flow field to satisfy the operational constraints and achieve superior thermal-hydraulic performance. For a broader comparison, related research addresses modified NTH solution for overconsolidated fissured clays [2].

2. Literature Review and Theoretical Framework

The systematic investigation of enhanced heat exchanger technologies has generated a vast body of literature over the past few decades. The theoretical framework for the present study is built upon foundational research in fluid dynamics, heat transfer enhancement mechanisms, and mathematical optimization techniques. This section reviews the critical milestones and recent advancements in the analysis of twisted tubes, rod baffles, and the application of multi-objective optimization in thermal system design. The concept of modifying the tube geometry to induce secondary flow has been a central theme in heat transfer augmentation research. The early studies on twisted tubes focused primarily on tube-side flow dynamics. Researchers demonstrated that the continuous rotation of the elliptical cross-section subjects the fluid to centrifugal forces, which in turn generate a pair of counter-rotating Dean vortices. These vortices are highly effective at transporting fluid from the colder core region to the hotter tube wall, thereby steepening the temperature gradient at the boundary and increasing the local Nusselt number. The magnitude of this enhancement was found to be strongly dependent on the twist ratio, defined as the longitudinal distance for a 360-degree rotation divided by the equivalent diameter of the tube. Subsequent experimental investigations confirmed that as the twist ratio decreases, the intensity of the swirl increases, leading to higher heat transfer rates but also exponentially increasing the frictional pressure drop. The transition from tube-side analysis to shell-side performance evaluation marked a significant step in the application of twisted tubes. When arranged in a bundle, the external flow over the twisted tubes is characterized by periodic acceleration and deceleration due to the varying cross-sectional flow area. Theoretical models were developed to predict the shell-side heat transfer coefficient by treating the flow path as a series of interconnected converging and diverging channels. These models revealed that the periodic disruption of the hydrodynamic boundary layer is the primary mechanism for shell-side heat transfer enhancement. Furthermore, studies comparing twisted-tube bundles to standard plain-tube bundles demonstrated that the twisted configuration not only improves the overall heat transfer coefficient by up to forty percent but also reduces the tendency for particulate fouling, as the high localized shear stresses continuously scour the tube surfaces. In parallel with the advancements in tube geometry, the development of

alternative baffle structures received considerable attention. The limitations of segmental baffles, particularly their susceptibility to flow-induced vibration and their creation of extensive dead zones, prompted the invention of the rod-baffle support system. The theoretical foundation of rod-baffle design is rooted in the principles of longitudinal flow. By aligning the principal fluid velocity vector parallel to the tube axis, the form drag is virtually eliminated, leaving only the skin friction and the minor form drag introduced by the rods themselves. Experimental campaigns conducted in the late twentieth century established comprehensive empirical correlations for predicting the pressure drop across various rod-baffle grid configurations. These studies highlighted that the pressure drop in a rod-baffle exchanger can be up to fifty percent lower than in an equivalent segmental-baffle unit operating at the same mass flow rate.

2.1 Integration Of Heat Transfer Enhancement Technologies

The independent successes of twisted tubes and rod baffles naturally led to investigations into their combined application. The integration of these two technologies presents a complex theoretical fluid dynamics problem. While rod baffles promote a purely longitudinal flow, the twisted tubes naturally induce a transverse velocity component due to their helical surfaces. The interaction between this induced swirl and the fixed cylindrical rods creates localized turbulent wakes that can either enhance mixing or create unrecoverable pressure losses, depending on the specific geometrical arrangement. For a broader comparison, related research addresses helical probe tests in residual soils of the appalachian piedmont [3]. Recent computational fluid dynamics studies have begun to explore this interaction. By utilizing Reynolds-averaged Navier-Stokes equations coupled with two-equation turbulence models, researchers have visualized the three-dimensional flow structures within the combined bundles. It was observed that the presence of the rod baffles prevents the bulk swirl flow from decaying prematurely, effectively sustaining the secondary flow structures over a longer longitudinal distance. Additionally, the localized acceleration of the fluid as it passes through the narrow gaps between the twisted tubes and the support rods significantly thins the thermal boundary layer in these regions. However, these computational studies also indicated that improper spacing of the rod baffles relative to the twist pitch of the tubes could lead to resonance effects, where the pressure drop increases drastically without a proportional gain in thermal performance.

2.2 Multi-Objective Optimization In Thermal Design

The complex, non-linear relationship between the geometric parameters and the resulting thermal-hydraulic performance necessitates the use of advanced optimization techniques. In the context of heat exchanger design, optimization is inherently a multi-objective problem. The classic trade-off between maximizing the heat transfer rate and minimizing the pumping power has been formulated mathematically using various objective functions, such as the Performance Evaluation Criterion or the entropy generation minimization method. The literature also considers wind power prediction with secondary decomposition and multi-algorithm fusion for complex nonlinear time series [4]. Evolutionary algorithms, particularly the Non-dominated Sorting Genetic Algorithm II, have become the standard tool for handling these conflicting objectives in thermal system design. This algorithm operates by maintaining a population of candidate designs and iteratively applying selection, crossover, and mutation operators to evolve the population toward the optimal Pareto frontier. The distinct advantage of the Non-dominated Sorting Genetic Algorithm II is its ability to find a diverse set of globally optimal solutions in a single simulation run, without requiring the designer to assign arbitrary weighting factors to the different objectives. Wang and colleagues examine optimization investigation on operating parameters of a scrubbing tower using a genetic algorithm [5]. Previous applications of multi-objective optimization to heat exchanger design have predominantly focused on simple geometries, such as plain tubes with helical baffles or finned tubes. In these studies, the computational fluid dynamics solver is often coupled with a surrogate

model, such as an artificial neural network or a response surface methodology, to reduce the computational cost of evaluating thousands of design variants. The surrogate model is trained on a relatively small set of rigorous computational fluid dynamics simulations and is then used to rapidly predict the performance of new candidate designs generated by the genetic algorithm.

Despite these advancements, the application of multi-objective optimization to the highly complex twisted-tube rod-baffle configuration remains severely limited. The existing literature lacks a comprehensive study that optimizes this hybrid geometry while explicitly incorporating industrial operating constraints, such as maximum allowable pressure drop limits and structural stability requirements under off-design flow conditions. The present study fills this critical knowledge gap by integrating high-fidelity computational fluid dynamics, surrogate modeling, and multi-objective evolutionary algorithms to rigorously define the optimal design space for twisted-tube rod-baffle heat exchangers.

3. Methodology and Mathematical Formulation

The rigorous evaluation of the twisted-tube rod-baffle heat exchanger requires a robust methodology that mathematically describes the complex fluid flow and heat transfer processes, while establishing a systematic framework for performance evaluation. This section details the geometric modeling, the governing equations of fluid dynamics, the turbulence modeling approach, and the numerical setup utilized to simulate the shell-side environment. The computational fluid dynamics approach is adopted to provide the high-resolution data necessary for resolving the intricate localized flow structures that empirical correlations cannot capture.

The computational domain represents a representative section of the shell-side volume within the heat exchanger. To minimize computational expense while maintaining physical accuracy, periodic boundary conditions are applied in the longitudinal direction, effectively simulating an infinitely long tube bundle in the fully developed flow regime. The geometry consists of a central twisted tube surrounded by adjacent tubes arranged in a standard triangular pitch layout. The rod baffles are positioned transversely across the tube bundle, supporting the tubes at specified longitudinal intervals. The fundamental geometrical parameters defining this domain are presented below.

Table 1Geometrical parameters and baseline operating ranges for the computational model

Parameter	Symbol	Unit	Baseline Range
Major axis of twisted tube	A	mm	18.0 - 24.0
Minor axis of twisted tube	B	mm	12.0 - 16.0
Tube wall thickness	t	mm	1.5 - 2.5
Twist pitch	S	mm	150.0 - 350.0
Rod baffle diameter	d	mm	4.0 - 8.0
Rod baffle spacing	L	mm	100.0 - 300.0
Shell-side mass flow rate	m	kg/s	1.5 - 5.5
Inlet fluid temperature	T	K	300 - 350

The generation of the twisted tube geometry requires a precise mathematical definition. Tube-based model predictive control using zonotopes [6] offers a possible robust-control extension for uncertain process operation, with a validated dynamic process model required before any controller is applied. The cross-section of the tube is defined as an ellipse, which is then extruded along the longitudinal axis while simultaneously undergoing a continuous rotation. This kinematic generation process creates the characteristic helical valleys and ridges that drive the secondary

flow mechanisms. The support rods are modeled as perfect cylinders intersecting the fluid domain perpendicular to the tube axis.

3.1 Governing Equations And Turbulence Modeling

The fluid flow and heat transfer within the shell side are governed by the principles of conservation of mass, momentum, and energy. For the present study, the working fluid is assumed to be incompressible, Newtonian, and operating in a steady-state regime. The fluid properties, including density, dynamic viscosity, thermal conductivity, and specific heat capacity, are considered constant, evaluated at the bulk mean temperature of the fluid. The governing equations, represented by the Reynolds-averaged Navier-Stokes formulation, are utilized to describe the mean flow field. The continuity equation ensures the conservation of mass throughout the computational domain. The momentum equations, describing the balance of forces acting on the fluid elements, incorporate the pressure gradients, viscous shear stresses, and the Reynolds stresses resulting from the turbulent velocity fluctuations. The energy equation governs the convective and conductive heat transfer within the fluid, accounting for the turbulent heat fluxes that significantly enhance the thermal transport in near-wall regions. To achieve closure for the Reynolds-averaged Navier-Stokes equations, an appropriate turbulence model must be selected. Given the complex nature of the flow in the twisted-tube rod-baffle exchanger, which involves strong streamline curvature, localized flow separation behind the support rods, and swirling boundary layers, the Shear Stress Transport k-omega model is employed. This specific formulation was chosen because it effectively combines the robust and accurate formulation of the k-omega model in the near-wall region with the free-stream independence of the k-epsilon model in the far field. The Shear Stress Transport formulation includes a modification to the turbulent viscosity definition to account for the transport of the principal turbulent shear stress, which is critical for accurately predicting flow separation under adverse pressure gradients. Wang examines global multidimensional analysis of air pollution in land, sea, and air transport cabins reveals substantial health risks [7].

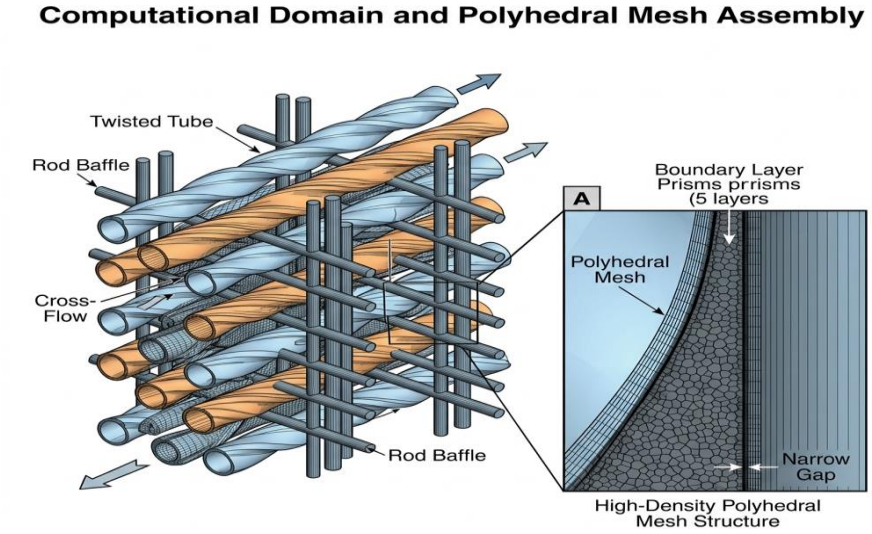


Figure 1Computational Domain and Polyhedral Mesh Assembly

3.2 Numerical Setup And Mesh Independence

The computational domain is discretized using a high-quality polyhedral mesh structure. Polyhedral elements are highly advantageous for complex geometries like the twisted tube, as they offer numerous neighboring cells, which improves gradient approximations and reduces numerical diffusion compared to standard tetrahedral elements. To accurately capture the steep velocity and

temperature gradients in the viscous sublayer, inflation layers consisting of thin prismatic cells are generated on all solid walls, including the twisted tubes and the rod baffles. The height of the first cell layer is strictly controlled to ensure that the non-dimensional wall distance remains below unity across all surfaces, which is a stringent requirement for the accurate application of the Shear Stress Transport k-omega turbulence model without utilizing wall functions. For a broader comparison, related research addresses cooperative atomically dispersed Fe-N4 and sn- nx moieties for durable and MoreActive oxygen electroreductionin fuel cells [8].

Table 2Mesh independence study and numerical convergence validation

Mesh Configuration	Number of Elements	Pressure Drop (Pa)	Nusselt Number
Coarse Mesh	1,250,000	1254.3	85.2
Medium Mesh	2,840,000	1310.6	89.7
Fine Mesh	4,680,000	1318.9	90.4
Ultra-Fine Mesh	7,120,000	1320.1	90.6

The numerical solution of the governing equations is performed using a pressure-based coupled solver. The coupled algorithm solves the momentum and pressure-based continuity equations together in a single matrix inversion, which significantly accelerates convergence in complex swirling flows. Spatial discretization for the pressure, momentum, turbulent kinetic energy, specific dissipation rate, and energy equations is achieved using a second-order upwind scheme to minimize numerical discretization errors. The convergence criteria are stringently set, requiring the scaled residuals for all governing equations to fall below one part in one million. Furthermore, surface monitors for the area-weighted average temperature and mass-weighted average total pressure at the periodic boundaries are tracked to ensure that a true steady-state hydrodynamic and thermal solution has been achieved. For a broader comparison, related research addresses friction angle of sandy soils from CPT using the NTH limit plasticity solution [9].

To quantify the thermal-hydraulic performance, several key parameters are derived from the numerical results. The overall pressure drop across the computational domain provides a direct measure of the hydraulic penalty. The Fanning friction factor is subsequently calculated to normalize this pressure drop against the dynamic pressure and geometric dimensions.

$$f = \frac{\Delta P D_h}{2\rho L u^2}$$

Similarly, the convective heat transfer performance is evaluated through the calculation of the Nusselt number, which normalizes the convective heat transfer coefficient with respect to the thermal conductivity of the fluid and the hydraulic diameter of the shell-side flow area. The literature also considers numerical investigation of flow, heat transfer, and kinetic reaction in a large-difference bidisperse, circulating fluidized-bed reactor [10].

$$Nu = \frac{hD_h}{k}$$

These fundamental mathematical descriptions form the basis for evaluating the myriad of geometric configurations generated during the multi-objective optimization process, ensuring that the performance metrics used to drive the evolutionary algorithm are grounded in rigorous physical principles.

4. Multi-Objective Optimization Design

The design of a twisted-tube rod-baffle heat exchanger is characterized by complex interactions among numerous geometrical parameters. Modifying a single variable, such as reducing the twist pitch to increase swirl intensity, invariably affects multiple performance metrics, typically enhancing heat transfer while simultaneously exacerbating the pressure drop. To systematically navigate this complex design landscape and identify the truly optimal configurations, a formal

multi-objective optimization framework must be established. This section outlines the definition of the objective functions, the selection of the decision variables, the enforcement of operational constraints, and the implementation of the evolutionary algorithm. The primary goal of the optimization process is to identify the geometrical configurations that provide the highest possible heat transfer rate for the lowest possible expenditure of pumping power. Therefore, two distinct and conflicting objective functions are defined. The first objective function is the maximization of the Nusselt number, which serves as a dimensionless proxy for the convective heat transfer coefficient. A higher Nusselt number directly translates to a more compact heat exchanger design for a given thermal duty. The second objective function is the minimization of the Fanning friction factor, which dictates the operational costs associated with fluid pumping. Because evolutionary algorithms are typically configured to minimize objective functions, the first objective is formulated mathematically as the minimization of the inverse of the Nusselt number.

The optimization is constrained by practical manufacturing limitations and operational requirements. The decision variables defining the design space are the twist pitch of the tube, the major and minor axis dimensions of the tube cross-section, and the longitudinal spacing between the rod baffles. Each of these variables is bounded by upper and lower limits dictated by current industrial manufacturing capabilities. For instance, the minimum allowable twist pitch is limited by the ductility of the tube material, as excessive twisting during the manufacturing process can induce micro-fractures in the tube wall. Similarly, the maximum allowable rod baffle spacing is constrained by flow-induced vibration criteria; if the spacing is too large, the unsupported span of the twisted tube may become susceptible to resonance with the surrounding flow fluctuations.

4.1 Implementation Of The Evolutionary Algorithm

Given the high computational cost of the three-dimensional computational fluid dynamics simulations detailed in the previous section, it is impractical to directly couple the fluid solver with the optimization algorithm, as evolutionary optimization requires the evaluation of thousands of design variants. To overcome this limitation, a surrogate modeling approach is adopted. An initial set of design points is generated using a Latin Hypercube Sampling technique, ensuring a uniform and space-filling distribution across the multi-dimensional design space. The fluid dynamics solver evaluates this initial sample set to determine the Nusselt number and friction factor for each configuration. These high-fidelity results are then used to train an Artificial Neural Network, which serves as the surrogate model. The neural network architecture consists of an input layer corresponding to the decision variables, multiple hidden layers containing non-linear activation functions to capture the complex fluid dynamic relationships, and an output layer providing the predicted thermal and hydraulic performance metrics. Rigorous statistical validation, including cross-validation and correlation coefficient analysis, is performed to ensure that the surrogate model accurately mimics the responses of the full fluid dynamics simulations without introducing significant approximation errors. With a validated, computationally efficient surrogate model in place, the multi-objective optimization is executed using the Non-dominated Sorting Genetic Algorithm II. The process begins with the initialization of a random population of candidate heat exchanger designs. During each generation, the individuals in the population are evaluated using the surrogate model. The algorithm then sorts the population based on the concept of Pareto dominance. A design is considered non-dominated if no other design in the population performs better in at least one objective without performing worse in the other.

To evaluate the overall integrated performance of the heat exchanger and compare the optimal designs against a standard baseline configuration, a composite metric known as the Performance Evaluation Criterion is utilized. This metric provides a unified assessment by comparing the ratio of heat transfer enhancement to the ratio of pressure drop penalization, weighted according to the constant pumping power constraint criteria.

$$PEC = \frac{\frac{Nu}{Nu_0}}{(\frac{f}{f_0})^{\frac{1}{3}}}$$

In this formulation, the subscript zero denotes the performance values of a reference plain-tube exchanger operating under identical mass flow conditions. A Performance Evaluation Criterion value greater than unity indicates that the advanced geometry provides a net thermodynamic benefit over the conventional design. By mapping this criterion across the Pareto optimal frontier generated by the evolutionary algorithm, designers can select the specific configuration that best aligns with the overarching economic and operational priorities of the specific industrial facility. Wang and colleagues examine numerical investigation on the effects of operating conditions and configuration parameters in industrial risers [11].

5. Results and Discussion

The execution of the computational fluid dynamics simulations and the subsequent multi-objective optimization framework yields a comprehensive dataset detailing the thermal-hydraulic behavior of the twisted-tube rod-baffle heat exchanger. The analysis of these results provides critical insights into the fundamental fluid dynamic mechanisms driving performance and offers practical guidance for the implementation of the optimized designs. This section discusses the detailed flow field characteristics, the thermal boundary layer interactions, and the structure of the Pareto optimal frontier. Another relevant line of investigation concerns contact dynamics characteristics of a deepwater drilling Riser-Drillstring coupled system [12]. The baseline computational fluid dynamics results clearly elucidate the advantages of the hybrid twisted-tube rod-baffle configuration over traditional designs. An examination of the velocity vector fields within the shell side reveals the highly three-dimensional nature of the flow. As the fluid approaches the rod baffles, it accelerates through the narrow constricted areas between the fixed cylindrical rods and the undulating surfaces of the twisted tubes. Unlike segmental baffles, which force the fluid to turn abruptly by ninety degrees and create large downstream recirculation zones, the rod baffles allow the principal flow vector to remain parallel to the longitudinal axis. Consequently, the wake regions behind the rods are remarkably small and rapidly dissipate, preventing the formation of extensive dead zones where heat transfer would otherwise stagnate and fouling deposits would accumulate. Simultaneously, the continuous rotation of the twisted tube cross-section imposes a strong swirling motion on the fluid in the immediate vicinity of the tube walls. This secondary flow creates a scouring effect, constantly displacing the fluid within the viscous sublayer and replacing it with cooler bulk fluid from the center of the flow channel. The localized temperature contour maps graphically demonstrate this phenomenon; the thermal boundary layer along the twisted surfaces is significantly thinner and exhibits more frequent disruption and reattachment compared to a plain cylindrical tube. The interaction between the longitudinal flow maintained by the rod baffles and the swirling flow induced by the tubes creates a highly turbulent mixing regime that maximizes convective thermal transport. For a broader comparison, related research addresses piezocone tests compared with atterberg limits [13].

5.1 Analysis Of The Pareto Optimal Frontier

The application of the Non-dominated Sorting Genetic Algorithm II successfully generates a well-distributed Pareto frontier, representing the set of optimal trade-off solutions between maximizing the Nusselt number and minimizing the friction factor. The shape of the Pareto front is highly convex, indicating that initial gains in heat transfer can be achieved with relatively minor pressure drop penalties, but achieving extreme levels of thermal performance requires exponentially higher pumping power expenditures. Tong and colleagues examine surface-dictated sorting in colloidal mixtures [14]. To facilitate practical design decisions, three distinct optimal configurations were

selected from different regions of the Pareto frontier for detailed comparative analysis. Point A represents a design prioritizing minimum pressure drop, Point C represents a design maximizing heat transfer, and Point B represents an intermediate configuration offering a balanced approach.

Table 3Comparison of selected optimal design points from the Pareto frontier

Design Point	Twist Pitch (mm)	Rod Spacing (mm)	Nusselt Number	Friction Factor	PEC Value
Point A (Low pressure drop)	320.5	280.0	95.4	0.042	1.15
Point B (Balanced design)	240.2	200.0	134.8	0.068	1.38
Point C (Max heat transfer)	165.8	120.0	185.3	0.145	1.22

Analyzing the geometrical parameters of these optimal points reveals distinct design strategies. Point A achieves its minimal pressure drop by utilizing a very large twist pitch and maximum allowable rod spacing. The fluid experiences minimal disruption, resulting in low frictional losses, but the weakened secondary flow reduces the overall thermal efficiency. Conversely, Point C utilizes a tight twist pitch and closely spaced rod baffles. This configuration violently disrupts the flow, generating intense turbulence and maximizing the heat transfer coefficient. However, the high form drag caused by the frequent structural interruptions leads to a massive friction factor penalty, making this design suitable only for applications where thermal duty is paramount and pumping power is unrestricted. Point B, the balanced design, exhibits the highest Performance Evaluation Criterion value among the three selections. By carefully tuning the twist pitch to harmonize with the longitudinal spacing of the rod baffles, this configuration sustains the optimal level of secondary swirling flow without inducing premature boundary layer separation behind the support structures. This synergistic interaction ensures that the turbulent kinetic energy generated by the geometric features is efficiently utilized for heat transfer enhancement rather than being dissipated as irrecoverable pressure loss. The results clearly demonstrate that the application of multi-objective optimization not only refines the geometric parameters but also fundamentally improves the thermodynamic efficiency of the heat exchanger unit under strict operational constraints.

6. Conclusion

This study has presented a comprehensive and rigorous investigation into the multi-objective thermal-hydraulic design of twisted-tube rod-baffle heat exchangers. By coupling high-fidelity three-dimensional computational fluid dynamics simulations with a robust surrogate-assisted evolutionary optimization framework, the complex interactions between geometrical parameters and fluid dynamic performance have been systematically quantified. The methodology successfully bridged the gap between localized flow phenomena prediction and global performance optimization, strictly adhering to realistic manufacturing and operational constraints. The detailed flow field analyses demonstrated that the integration of twisted tubes with rod baffles creates a highly efficient hybrid geometry. The rod baffles sustain a predominantly longitudinal flow regime that inherently minimizes form drag and pressure drop, while simultaneously eliminating the large, inefficient dead zones typically associated with segmental baffles. Concurrently, the twisted tube surfaces continuously generate secondary swirling flows that disrupt the thermal boundary layer, significantly augmenting the convective heat transfer coefficient. The synergistic interaction between these two distinct geometrical features is the fundamental driver of the exchanger's superior thermal-hydraulic performance. The application of

the Non-dominated Sorting Genetic Algorithm II yielded a distinct Pareto optimal frontier, providing designers with a continuum of optimized configurations ranging from minimal pressure drop models to maximal heat transfer designs. The evaluation of the optimal design points revealed that the highest overall thermodynamic efficiency, as measured by the Performance Evaluation Criterion, is achieved through a delicate balance of twist pitch and rod spacing. This balanced configuration prevents destructive interference between the swirling flow and the transverse supports, ensuring that the turbulent kinetic energy is optimally utilized for thermal transport. The computational and mathematical framework established in this research provides a powerful, highly accurate tool for the advanced design and industrial deployment of twisted-tube rod-baffle heat exchangers, paving the way for significantly enhanced energy efficiency in modern process engineering applications.

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