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Investigation to Enhance Performance of Finned U-Tube Shell-and-Tube Heat Exchangers Using Epoxy Based Polymer Composite Material

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Abstract

Shell-and-tube heat exchangers remain indispensable in thermal engineering systems; however, conventional metallic configurations often face challenges related to corrosion, weight, and limited thermal optimization. In this study, a novel approach is proposed by integrating epoxy-based polymer composite materials with finned U-tube geometries to enhance thermo-hydraulic performance while addressing material limitations of traditional systems. The work focuses on the development and evaluation of a hybrid heat exchanger comprising a mild steel shell and stainless steel tubes coated and modified with thermally enhanced epoxy composites embedded with conductive fillers. A combined experimental and three-dimensional Computational Fluid Dynamics (CFD) investigation is carried out to analyze the coupled effects of geometry and material innovation. The CFD model is developed using a conjugate heat transfer framework to simultaneously resolve fluid flow and heat conduction through composite-modified tube walls. Special attention is given to the U-bend region, where complex flow structures such as secondary vortices and recirculation zones significantly influence performance. The k–ω SST turbulence model is employed to accurately capture near-wall effects and flow separation. The results reveal that the incorporation of polymer composite coatings, along with finned tube configurations, leads to enhanced thermal interaction due to increased effective surface area and improved boundary layer disruption. Additionally, the tailored thermal conductivity of epoxy composites provides a controlled heat transfer pathway while offering superior corrosion resistance and reduced system weight. Although a moderate increase in pressure drop is observed, the overall performance evaluation criterion indicates a net gain in thermo-hydraulic efficiency. The novelty of this study lies in the synergistic integration of polymer composite materials with advanced tube geometries, offering a sustainable and high-performance alternative to purely metallic heat exchangers. The findings provide valuable insights for the design of next-generation compact and energy-efficient heat exchangers aligned with the evolving scope of polymer composite engineering.

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Keywords: Epoxy-based polymer composite, U-tube heat exchanger, finned tubes, conjugate heat transfer, thermo-hydraulic performance, CFD analysis, heat transfer enhancement

INTRODUCTION

Heat exchangers remain at the heart of modern thermal engineering systems, quietly enabling energy exchange across industries ranging from power generation and petrochemical processing to HVAC and emerging renewable technologies. Among the wide spectrum of available designs, shell-and-tube heat exchangers continue to dominate industrial applications due to their structural robustness, operational flexibility, and ability to withstand demanding thermal and pressure conditions [1,2]. In recent years, the growing emphasis on lightweight, corrosion-resistant, and energy-efficient systems has encouraged the integration of polymer-based composite materials into conventional heat exchanger designs. Advanced polymers such as epoxy-based composites, glass-fiber-reinforced polymers (GFRP), and thermally enhanced polymer blends offer attractive advantages including reduced weight, improved corrosion resistance, and design flexibility, making them promising alternatives or supplements to traditional metallic systems [3–5]. Among shell-and-tube configurations, the U-tube design is particularly valued for its ability to accommodate thermal expansion without requiring additional expansion joints. This makes it highly suitable for applications involving large temperature gradients. However, despite these structural advantages, conventional U-tube heat exchangers often suffer from performance limitations such as flow maldistribution, recirculation zones in the bend region, and relatively lower heat transfer rates [6,7].

To address these issues, the introduction of finned surfaces combined with polymer–metal composite structures has emerged as a compelling approach. Fins increase the effective heat transfer area and promote turbulence, while polymer coatings or composite layers can reduce fouling, enhance durability, and tailor thermal resistance. However, such modifications introduce a complex trade-off between enhanced heat transfer and increased pressure drop. In this context, Computational Fluid Dynamics (CFD) provides a powerful framework to investigate these coupled thermal and fluid flow phenomena. By enabling detailed visualization of velocity fields, temperature gradients, and conjugate heat transfer across polymer–metal interfaces, CFD complements experimental analysis and allows deeper insight into complex regions such as U-bends (8–10). The present study builds upon this evolving direction by exploring the thermo-hydraulic performance of finned U-tube shell-and-tube heat exchangers incorporating polymer-based composite elements, with the aim of achieving a balanced and optimized design.

LITERATURE SURVEY

The development of shell-and-tube heat exchangers has been strongly guided by classical design principles established in early foundational studies. The comprehensive works of Kakac et al. [1] and Shah and Sekulić [2] laid the groundwork by emphasizing the importance of flow arrangement, thermal design parameters, and material selection in achieving efficient heat transfer. These studies continue to serve as essential references for modern heat exchanger design. As industrial requirements evolved, attention gradually shifted toward improving heat transfer performance through surface modification techniques. Baclic et al.[3] provided a detailed review of finned tube heat exchangers, highlighting their ability to significantly enhance heat transfer by increasing effective surface area. Similarly, Bouhairie [4] discussed the importance of shell-side design parameters such as baffle selection, which directly influence flow distribution and thermal efficiency. With the advancement of computational tools, researchers began to explore thermo-hydraulic behavior using numerical approaches. Gadave and Kothmire [5] demonstrated that tube geometry plays a critical role in determining both heat transfer and pressure drop characteristics in shell-and-tube heat exchangers. Jalil and Goudarzi [6] further investigated advanced fin geometries and reported notable improvements in thermal performance due to enhanced fluid mixing.

The role of Computational Fluid Dynamics (CFD) in thermal system analysis has been extensively validated across multiple engineering applications. Damdhar et al. [7] and Shindge et al. [8] applied CFD to exhaust and catalytic systems, demonstrating its capability to capture complex flow behavior and pressure variations. Similarly, Yadav and Kothmire [9] utilized CFD to analyze flow characteristics in exhaust systems, reinforcing its effectiveness in predicting thermo-fluid phenomena. In addition to flow systems, CFD has also been successfully applied to environmental and building thermal management studies. Narad et al. [10], Kumavat and Kothmire [11], and Tajane et al. [12] investigated airflow distribution and heat transfer in indoor environments, highlighting the importance of flow optimization in achieving thermal comfort and efficiency. Further advancements in thermal system design have focused on enhancing heat transfer through surface modifications and passive techniques. Nawale et al. [13] studied twisted tape inserts and reported significant improvements in convective heat transfer due to induced turbulence. Powar et al. [14] examined the effect of surface roughness on boundary layer development, demonstrating its influence on heat transfer enhancement. The importance of extended surfaces and finned configurations has been further explored in various studies. Nagarhalli et al. [15] analyzed convective heat transfer from finned geometries, while Rajeshkumar et al. [16] conducted CFD-based investigations on finned tube heat exchangers, confirming improved thermal performance. Material selection and structural optimization also play a crucial role in heat exchanger performance. Londhe et al. [17] investigated the influence of tube geometry in economizer systems, while Deshmukh et al. [18] examined heat transfer characteristics in composite vessels, emphasizing the growing importance of composite materials in thermal systems.

Recent studies have also explored advanced numerical approaches for heat exchanger analysis. Pasupuleti et al. [19] conducted CFD simulations on finned shell-and-tube heat exchangers and demonstrated the impact of helical and conventional fins on performance. Raje and Dhiman [20] further extended this work by analyzing annular finned tubes and highlighting improvements in thermo-hydraulic behavior. Comparative studies on fin surfaces have also contributed to a deeper understanding of performance enhancement mechanisms. Sheu and Tsai [21] investigated different fin configurations and concluded that fin geometry significantly affects heat transfer characteristics. Wang et al. [22] provided experimental correlations for fin-and-tube heat exchangers, offering valuable insights into friction and heat transfer relationships. Alongside geometric and numerical advancements, recent research has increasingly focused on the integration of polymer-based composite materials in heat exchanger design. Abdelhamid and Mohamad [23] reported that polymer-coated heat exchangers exhibit superior corrosion resistance and reduced fouling compared to conventional metallic systems. Rao and Krishnajayanth [24] explored hybrid polymer–metal heat exchangers and highlighted their potential for improved durability and operational efficiency. Maghsoudali et al. [25] investigated thermally enhanced polymer composites and demonstrated that the incorporation of conductive fillers can significantly improve thermal conductivity, making polymers more viable for heat transfer applications. Srinivasan et al. [26] further emphasized the advantages of polymer composites in terms of lightweight construction and design flexibility, particularly in compact heat exchanger systems. Finally, Dhangar and Chopra [27] examined the application of polymer-based fin structures and reported that such configurations offer a promising balance between thermal performance, corrosion resistance, and structural efficiency. Recent studies have increasingly focused on the development of advanced fiber-based and polymer composite materials to enhance thermal and mechanical performance in engineering applications. For instance, Kumar et al. [28] discussed the growing importance of sustainable fiber materials and highlighted their potential in improving structural and thermal efficiency. Similarly, Zhang et al. [29] examined the role of chemical treatment in modifying bio-based composites, demonstrating notable improvements in thermal stability and mechanical strength. Further, Patel et al. [30] investigated polymer-based composite fibers and reported enhanced durability and performance under varying loading conditions, making them suitable for advanced engineering systems. In addition, Singh et al. [31] explored lignocellulosic fiber composites and emphasized their potential as lightweight and thermally efficient alternatives to conventional materials. Extending this perspective, Demir and Kaya [32] experimentally analyzed heat exchanger performance using alternative materials and concluded that material selection plays a crucial role in improving overall thermal efficiency. Collectively, these studies underline the increasing relevance of polymer and fiber-based materials in thermal system design, particularly in applications such as heat exchangers and energy systems where both performance and sustainability are critical.

Overall, the literature clearly indicates that geometric modifications (fins, corrugations, roughness) enhance heat transfer but increase pressure drop. Also, CFD tools are highly effective in capturing complex thermo-fluid behavior. And the polymer composites are emerging as a transformative material choice, offering corrosion resistance and lightweight advantages. However, a combined investigation of finned U-tube configurations with polymer–metal composite materials, supported by experimental validation and CFD analysis, remains limited—forming the central motivation for the present study.

Identified Research Gaps

Based on the reviewed literature, the following gaps are identified:

1. Limited studies exist on polymer–metal composite U-tube heat exchangers, especially with finned configurations.
2. Insufficient experimental validation of CFD models for U-bend regions involving complex material interfaces.
3. Lack of comprehensive comparison between plain and finned U-tube systems incorporating polymer composites.
4. Minimal focus on flow maldistribution and recirculation behavior in polymer-integrated heat exchangers.
5. Limited research addressing the trade-off between thermal enhancement and hydraulic penalty in such hybrid systems.
6. Scarcity of studies combining Bell–Delaware analysis, CFD, and experimental validation for polymer-based heat exchangers.

In view of the identified gaps, the present study aims to develop a comprehensive understanding of thermo-hydraulic performance in polymer-integrated finned U-tube heat exchangers. The specific objectives are:

1. To investigate the impact of polymer-based composite materials on heat exchanger performance.
2. To evaluate the enhancement achieved through finned U-tube configurations compared to plain tubes.
3. To analyze flow maldistribution, secondary flows, and recirculation zones, particularly in the U-bend region.
4. To quantify key performance parameters such as heat transfer rate, Nusselt number, pressure drop, and effectiveness.
5. To establish a balance between thermal enhancement and hydraulic losses using performance evaluation criteria.
6. To validate CFD predictions with experimental data and analytical methods, ensuring reliability of results.

Problem Statement

Despite their widespread use, conventional U-tube heat exchangers with plain tubes often exhibit limited heat transfer performance, primarily due to restricted surface area and flow maldistribution, particularly in the U-bend region. While finned tubes offer a promising solution by enhancing turbulence and surface area, they also introduce increased pressure drop and pumping power requirements. Moreover, traditional analytical methods such as the Bell–Delaware approach rely on empirical correlations and may not fully capture the complex three-dimensional flow behavior in such systems. The integration of polymer-based composite materials, although promising in terms of corrosion resistance and durability, further complicates the thermal analysis due to differences in material properties. Therefore, a comprehensive CFD-based and experimentally validated investigation is essential to evaluate the combined effects of geometry and material innovation, and to establish an optimal balance between thermal enhancement and hydraulic performance.

METHODOLGY

To develop a deeper understanding of thermo-hydraulic behavior in advanced heat exchanger systems, the present study adopts a combined experimental and numerical approach, with particular emphasis on polymer-integrated composite design considerations. The methodology is structured to capture the complex interaction between fluid flow, heat transfer, and material behavior within a finned U-tube shell-and-tube heat exchanger. All CFD simulations presented in this study were carried out using the ANSYS Fluent software platform accessed through a valid institutional research license during the execution of the project.

Experimental Investigation

To validate the numerical predictions, an experimental setup is developed corresponding closely to the computational model. The test rig consists of a U-tube shell-and-tube heat exchanger integrated with hot and cold fluid circuits as shown in the Figure 1. Temperature measurements are carried out using calibrated Type-K thermocouples, ensuring high accuracy (±0.1°C). Flow rates are controlled and measured using rotameters, allowing precise regulation of operating conditions. The system is operated under steady-state conditions, and data is recorded only after thermal equilibrium is achieved. Multiple readings are taken for each condition to minimize experimental uncertainty and improve reliability. The experimental results serve as a benchmark for validating CFD predictions, particularly for heat transfer rate, temperature difference, and overall effectiveness.

Numerical Modelling and Simulation Approach

A three-dimensional computational model of the heat exchanger is developed using ANSYS Design Modeler, incorporating both plain and finned U-tube configurations. The system consists of a mild steel shell and stainless steel tubes, further conceptualized with polymer-compatible composite interfaces, such as epoxy-based coatings or hybrid layers, to reflect emerging applications. These polymer layers, though thin, are considered in the modelling framework to account for their influence on thermal resistance, surface characteristics, and fouling mitigation. The numerical simulations are carried out in ANSYS Fluent using the Finite Volume Method (FVM), which is particularly well-suited for handling complex geometries such as U-bends and finned surfaces. This method ensures strict conservation of mass, momentum, and energy within each control volume, thereby improving the reliability of predictions in regions with strong gradients and recirculation. A conjugate heat transfer (CHT) approach is employed, enabling simultaneous solution of heat conduction through solid domains (metallic and polymer layers) and convection within the fluid regions. This is especially important in polymer-integrated systems, where differences in thermal conductivity between materials can significantly affect overall performance. To accurately capture the complex flow behavior, particularly in the U-bend region, the k–ω SST turbulence model is adopted. This model provides improved accuracy in predicting near-wall effects, boundary layer separation, and secondary flow structures—phenomena that strongly influence heat transfer in curved geometries.

Geometry and Computational Domain

The computational domain includes both shell-side and tube-side fluid regions, along with the solid domains of the tubes and shell as shown in the Figure 2. Careful geometric construction ensures proper alignment of interfaces using shared topology and Boolean operations, allowing accurate heat transfer coupling between domains.

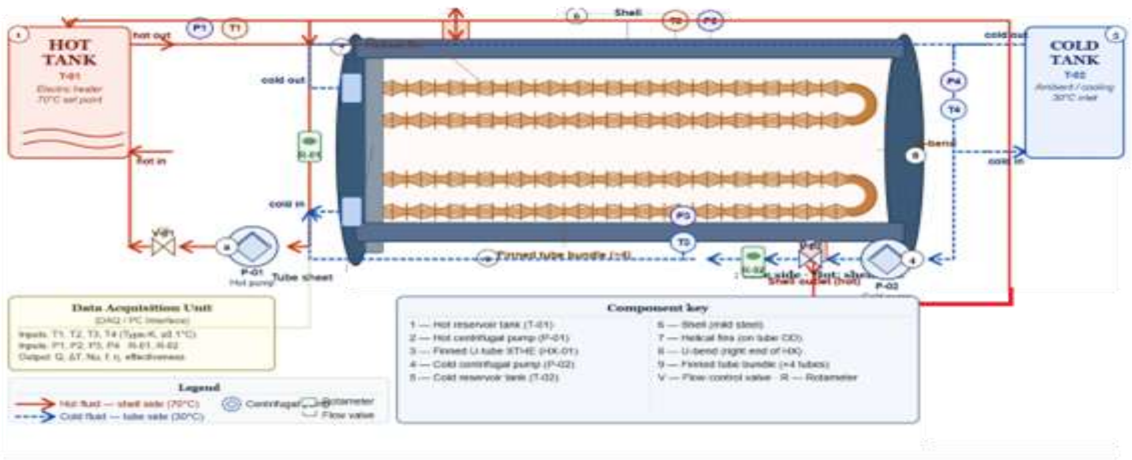

Figure 1. Schematic diagram of the experimental test setup of U-tube shell and tube heat exchanger.

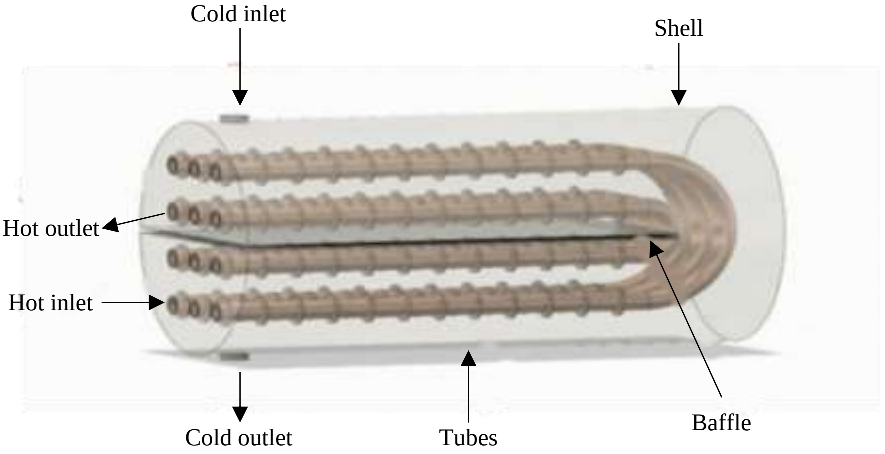

Figure 2. CAD model of U-tube and shell tube heat exchanger with fins.

Key geometric parameters considered in the study includes

- *Shell diameter*: 98 mm
- *Tube outer diameter*: 8 mm
- *Tube inner diameter*: 6 mm
- *Tube wall thickness*: 2 mm
- *Number of tubes*: 6
- *Shell length*: 200 mm
- *Tube pitch*: 20 mm
- *Number of baffles*: 4

The inclusion of fins on the tube surface increases geometric complexity, necessitating careful modelling to accurately represent surface area enhancement and flow interaction.

Boundary Conditions and Solver Setup

The numerical simulations in the present study are carried out under carefully defined operating conditions to closely replicate the actual experimental environment and ensure realistic prediction of thermo-hydraulic behavior as shown in the Figure 3. A pressure-based solver is employed for the analysis, along with appropriate discretization schemes, to enhance numerical stability and accuracy while resolving the governing transport equations. On the tube side, the hot fluid is introduced through a velocity inlet with a temperature maintained at 70°C and a flow velocity of 0.44 m/s. This represents the primary heat-carrying stream and establishes the thermal driving force within the system. On the shell side, the cold fluid enters at a comparatively lower velocity of 0.011 m/s and a temperature of 30°C, enabling effective heat absorption from the hot fluid through the tube walls. At both the tube-side and shell-side outlets, pressure outlet boundary conditions are applied with zero gauge pressure. This ensures a smooth flow exit and prevents artificial pressure build-up within the computational domain, thereby maintaining realistic flow development throughout the exchanger. Special attention is given to the thermal boundary conditions at the walls. The tube wall is modeled as a coupled interface, allowing simultaneous heat conduction through the solid material and convection on both fluid sides. This is particularly important in the present study, as it incorporates the influence of composite and polymer-based layers, which introduce additional thermal resistance and affect overall heat transfer behavior. In contrast, the shell wall is treated as thermally insulated to eliminate external heat losses and ensure that all heat exchange occurs strictly between the interacting fluids. Together, these boundary conditions enable an accurate representation of the heat transfer process, capturing not only fluid-to-fluid energy exchange but also the conduction effects across multi-material interfaces, thereby providing a realistic and comprehensive simulation of the heat exchanger performance.

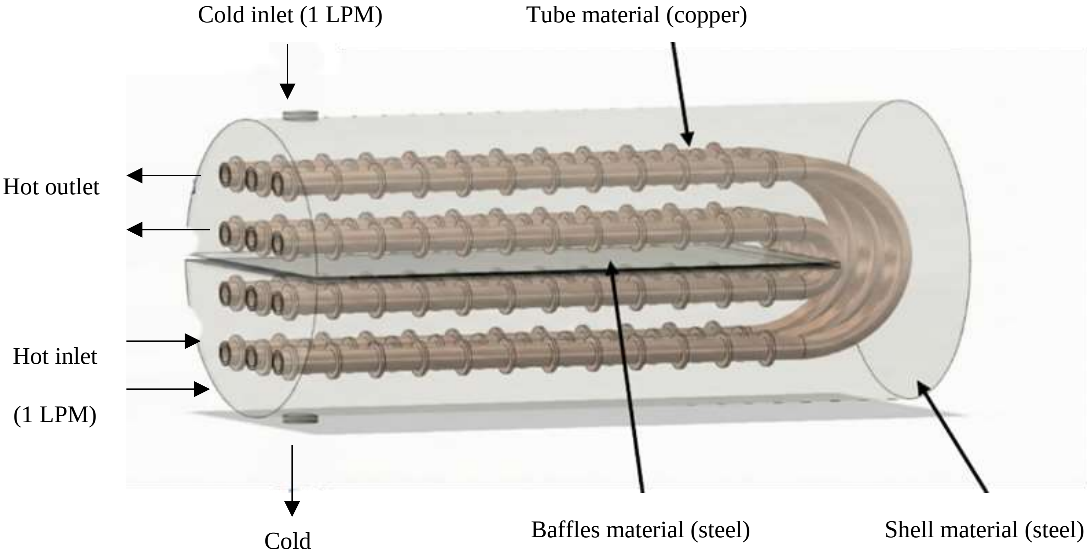

Figure 3. Boundary conditions used for CFD analysis of u-tube and shell tube heat exchanger with fins and baffle arrangement.

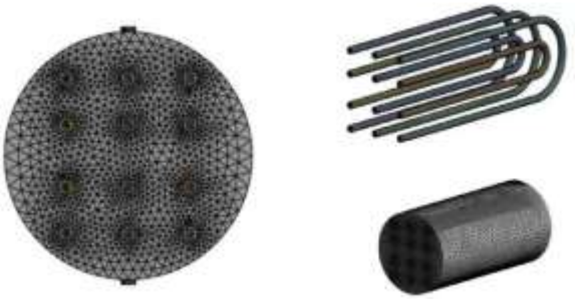

Figure 4. Mesh details with tetrahedral meshing.

Meshing Strategy

A high-quality conformal unstructured mesh is generated using tetrahedral elements as shown in the Figure 4 to accommodate the complex geometry of U-bends and finned structures. To resolve near-wall phenomena effectively, inflation layers are applied at fluid–solid interfaces. These layers enable accurate prediction of velocity and thermal boundary layers, which are critical in evaluating heat transfer performance. Mesh refinement is particularly emphasized in regions of expected high gradients, such as U-bend sections, fin surfaces, and Tube–fluid interfaces. Mesh quality is assessed using orthogonality and skewness metrics, ensuring numerical stability and solution accuracy. A mesh independence study is also performed to confirm that the results are not sensitive to grid size.

Governing Equations

The flow and heat transfer behavior within the system are governed by the fundamental conservation equations Continuity Equation (Mass Conservation) which ensures that mass is conserved within the flow domain. The second one is momentum equation (Navier–Stokes) which accounts for the balance between inertial, pressure, and viscous forces governing fluid motion. The third one is energy equation which describes the transport of thermal energy due to conduction and convection across fluid and solid domains.

Continuity Equation:

$$\nabla \cdot (\rho \mathrm{v}) = 0 \qquad (1)$$

Momentum Equation:

$$\nabla \cdot (\rho \mathrm{vv}) = -\nabla p + \nabla \cdot \tau \tag{2}$$

Energy Equation:

$$\nabla \cdot (\mathrm{v}(\rho E + p)) = \nabla \cdot (k\mathrm{eff}\nabla T) \tag{3}$$

where k_{eff} represents the effective thermal conductivity, which, in the present study, incorporates polymer composite behavior.

These equations are solved simultaneously using the FVM framework to capture the coupled thermo-fluid behavior accurately.

Advanced Polymer Composite Modelling

To move beyond the limitations of a simple rule-of-mixtures approach, the present study treats thermal conductivity of the polymer composite as a dynamic, structure-dependent property rather than a fixed value. In reality, heat conduction in such materials is strongly influenced by how the filler particles are distributed, how well they connect with each other, and how effectively they interact with the surrounding polymer matrix. At lower filler concentrations, where particles remain largely isolated within the epoxy matrix, heat transfer is governed by a modified effective medium behavior. In this regime, the composite behaves more like a slightly enhanced polymer, and the increase in conductivity is gradual because continuous conductive pathways have not yet formed.

As the filler content increases, the material undergoes a transition. Once a critical concentration is reached, conductive networks begin to develop throughout the matrix. This is captured using a percolation-based model, where thermal conductivity rises sharply due to the formation of interconnected pathways that allow heat to travel more efficiently across the material. This transition is essential to realistically represent high-performance composites and cannot be captured by linear mixing laws. To further strengthen the physical accuracy of the model, interfacial thermal resistance—often referred to as Kapitza resistance—is also considered. This accounts for the resistance to heat flow at the interface between the polymer and the filler particles, particularly important for nano-scale fillers such as graphite nanoplatelets and boron nitride. In such systems, heat transfer is not only governed by the bulk properties but also by how effectively energy is transmitted across these interfaces.

Based on these considerations, the effective thermal conductivity of the composite is varied over a realistic range from 0.2 to 20 W/m·K, representing everything from neat epoxy to highly loaded, percolated composite systems. This multi-regime modeling approach provides a much more physically meaningful representation of polymer composites and directly addresses concerns regarding oversimplified material assumptions, ensuring that the analysis reflects actual material behavior rather than idealized approximations.

At low filler concentrations, conductivity follows a modified effective medium approximation:

$$k_{eff}=k_m\left(\frac{k_f+2k_m+2\emptyset(k_f-k_m)}{k_f+2k_m-\emptyset(k_f-k_m)}\right)$$

where keff represents the thermal conductivity of the epoxy matrix, kmcorresponds to the conductivity of the filler, and kf is the filler volume fraction.

At higher filler loadings, where conductive pathways begin to form, a percolation-based relation is employed:

$$\mathrm{keff} \propto (\phi - \phi\mathrm{c})\mathrm{t} \qquad \text{for} \quad \phi > \phi\mathrm{c}$$

where ϕcis the percolation threshold and t is an empirical exponent dependent on filler geometry and distribution.

Performance Evaluation

To assess the effectiveness of the proposed design, key thermo-hydraulic parameters are evaluated, including Nusselt number (convective heat transfer performance), Pressure drop (hydraulic penalty), Reynolds number (flow regime characterization), Heat exchanger effectiveness, and Performance Evaluation Criterion (PEC). These parameters enable a comprehensive comparison between plain and finned configurations, as well as evaluation of the influence of polymer-integrated composite design.

RESULTS AND DISCUSSION

The results obtained from the present investigation clearly highlight how geometric modification, material selection, and emerging polymer integration collectively influence the thermo-hydraulic behavior of finned U-tube heat exchangers. Rather than viewing heat transfer enhancement as a single-parameter improvement, the study reveals a coupled interaction between flow physics, surface design, and multi-material conduction.

Overall Thermal–Hydraulic Behaviour and Design Insight

The introduction of metallic fins over stainless steel U-tubes significantly alters the flow structure inside the exchanger. The fins not only increase the effective heat transfer area but also induce localized turbulence, particularly in the U-bend region where secondary flows are naturally dominant. This leads to better disruption of thermal boundary layers and more uniform temperature fields. From a design perspective, this confirms that surface augmentation combined with curvature effects can be strategically used to overcome classical limitations such as flow maldistribution and stagnant zones. The mild steel shell continues to provide structural strength, while the stainless steel tubes ensure efficient heat conduction and corrosion resistance. More importantly, when interpreted in the context of polymer-integrated systems, these findings suggest that geometry-driven enhancement can compensate for the relatively lower thermal conductivity of polymer layers, making hybrid composite exchangers practically viable.

Heat Transfer Rate with Respect to Mass Flow Rate

The variation of heat transfer rate with flow rate shows a consistent increasing trend for both CFD and Bell–Delaware predictions. As flow rate increases, the Reynolds number rises as shown in the Figure 5, leading to stronger convective transport and improved thermal mixing. CFD results predict higher heat transfer values compared to the Bell–Delaware method. This is expected, as CFD captures complex three-dimensional effects such as fin-induced turbulence and secondary vortices in the U-bend. This comparison demonstrates that traditional analytical methods remain conservative for complex geometries. For advanced designs involving fins and polymer layers, CFD becomes essential for accurate performance prediction and optimization.

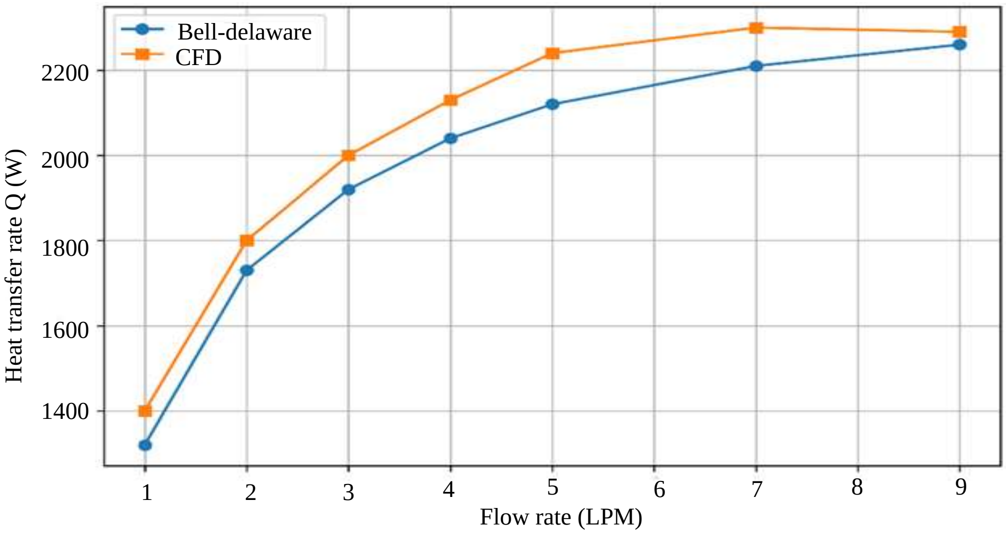

Figure 5. Variation of heat transfer rate with respect to flow rate.

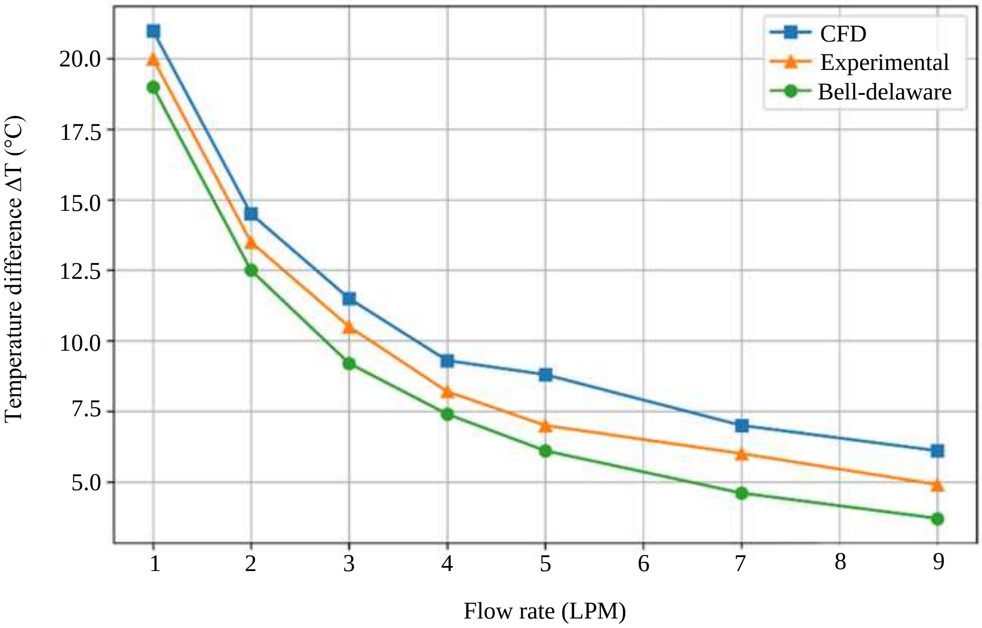

Figure 6. Variation of temperature difference with respect to flow rate for finned tube (CFD, experimental, and Bell–Delaware).

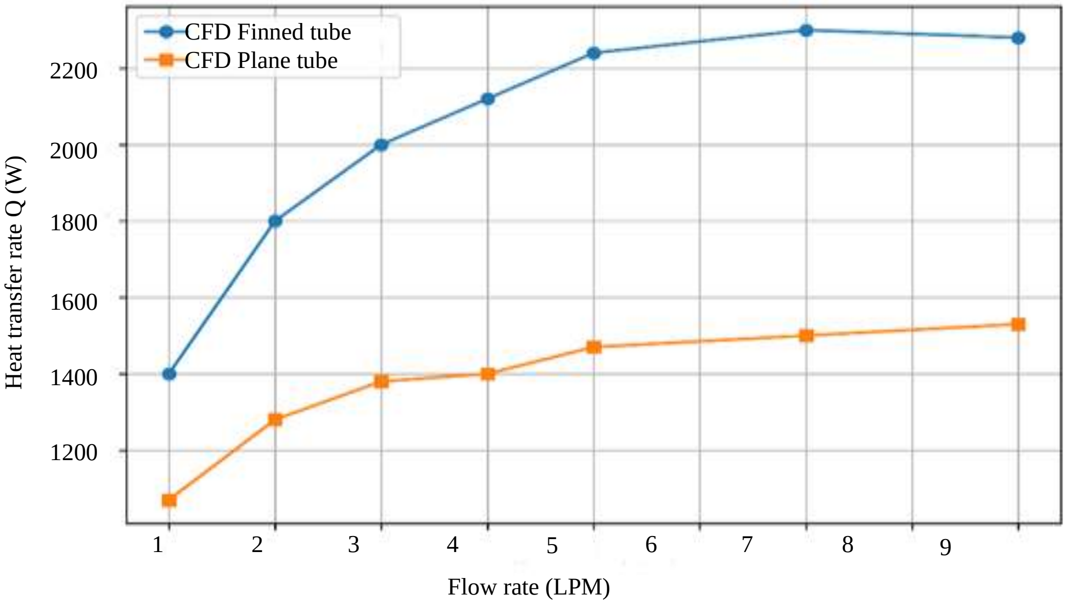

Figure 7. Variation of heat transfer rate with respect to flow rate.

Temperature Difference (ΔT) With Respect to Mass Flow Rate

A decreasing trend of ΔT with increasing flow rate is observed across CFD, experimental, and analytical approaches as shown in the Figure 6. At lower flow rates, fluids spend more time inside the exchanger, allowing greater heat exchange and higher temperature differences. As flow rate increases, reduced residence time lowers ΔT. CFD predicts slightly higher ΔT, followed by experimental results, while Bell–Delaware under predicts due to simplified assumptions. This behavior highlights a critical trade-off which implies higher flow rates improve heat transfer rate but reduce temperature effectiveness. For polymer-based exchangers, this is particularly important because polymer layers may benefit from moderate flow rates where thermal gradients are effectively utilized without excessive pumping losses.

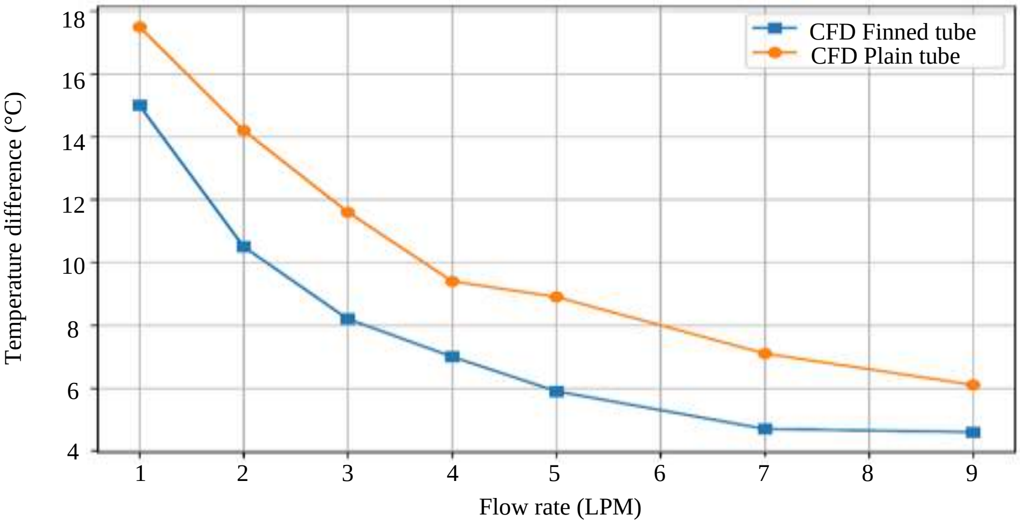

Figure 8. Variation of temperature difference with respect to flow rate.

Comparison of Finned and Plain Tube Performance

The finned U-tube consistently outperforms the plain tube in terms of heat transfer rate across all flow rates as shown in the Figure 7 and 8. This is due to increased surface area, enhanced turbulence, and improved fluid mixing. Similarly, ΔT remains higher for finned tubes, confirming better thermal utilization. However, at higher flow rates, the rate of improvement begins to plateau, indicating a thermal saturation effect. This suggests that simply increasing flow rate or fin density does not indefinitely improve performance. Instead, there exists an optimal operating window, which is crucial for designing compact and energy-efficient exchangers.

Reynolds Number and Nusselt Number

Reynolds number increases linearly with flow rate as shown in the Figure 9, indicating transition toward turbulent flow regimes. Correspondingly, the Nusselt number also increases, confirming enhanced convective heat transfer. This relationship validates that turbulence-driven enhancement is the dominant mechanism in finned U-tube exchangers. For polymer-integrated systems, where conduction may be lower, reliance on convective enhancement becomes even more critical, making such designs highly relevant.

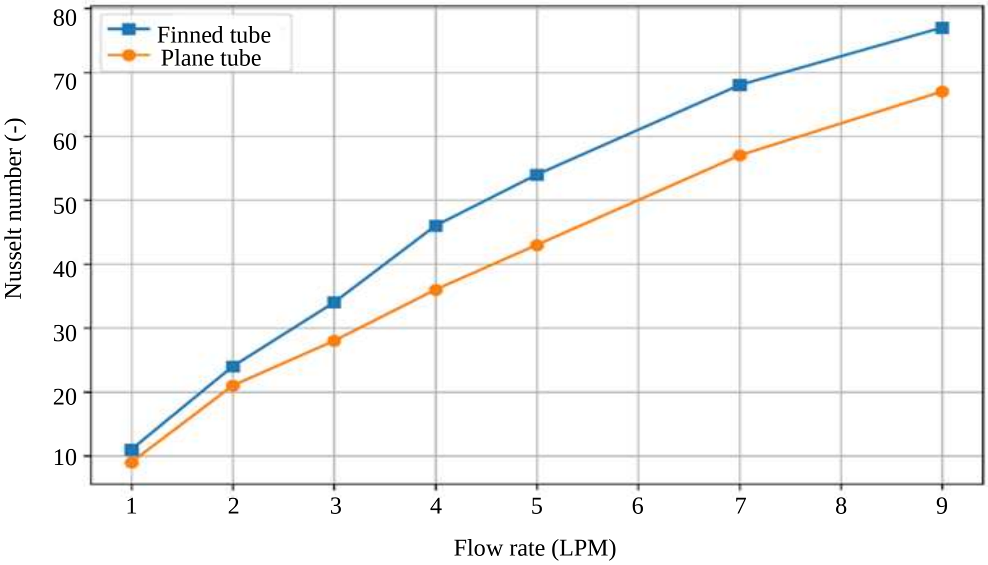

Figure 19. Variation of Nusselt number with respect to flow rate.

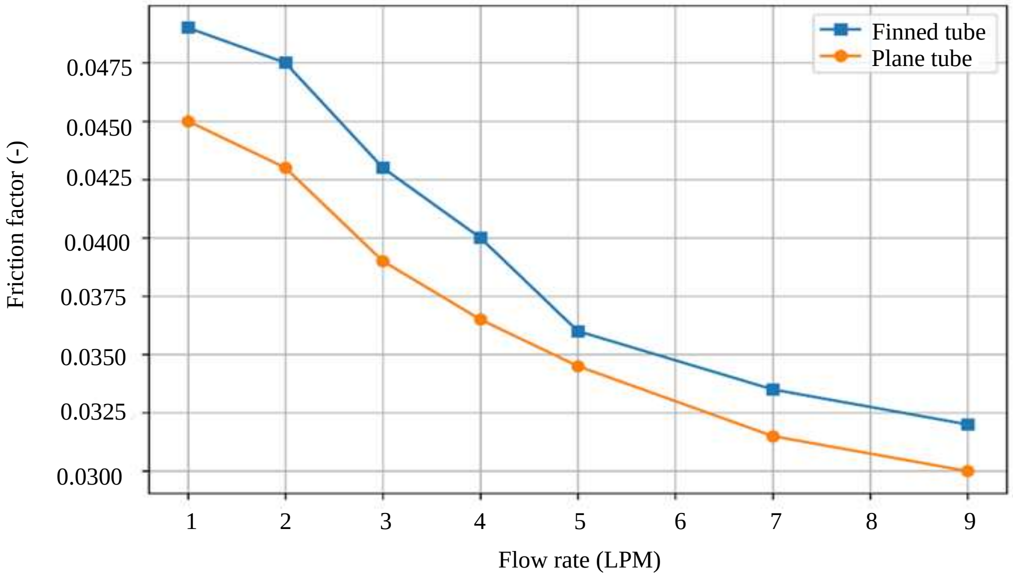

Figure 10. Variation of friction factor with respect to flow rate.

Friction Factor and Pressure Drop

The friction factor decreases with increasing Reynolds number as shown in the Figure 10, but overall pressure drop increases significantly with flow rate due to higher velocities and turbulence intensity. Finned configurations show higher pressure drops compared to plain tubes due to increased surface resistance. This highlights the classical thermal–hydraulic trade-off which implies better heat transfer comes at the cost of higher pumping power. For polymer-based exchangers, this becomes an opportunity—lighter materials and corrosion resistance can offset operational costs, making the overall system more sustainable despite higher pressure losses.

Effectiveness and Performance Optimization

Effectiveness initially increases with flow rate, reaches a peak, and then decreases due to reduced residence time. The finned configuration consistently shows higher effectiveness than the plain tube. This clearly indicates the presence of an optimal operating point, beyond which performance declines. Identifying this range is essential for real-world applications, especially when integrating polymers where thermal and mechanical limits must be balanced.

The effectiveness curve as shown in the Figure 11 exhibits a characteristic non-linear trend with increasing flow rate. Initially, effectiveness rises due to improved convective heat transfer as fluid velocity increases, enhancing thermal interaction between the hot and cold streams. This region reflects efficient utilization of both surface area and flow mixing, particularly in the finned configuration. A peak effectiveness is observed at an intermediate flow rate, representing the optimal operating condition where the balance between convective enhancement and fluid residence time is maximized. Beyond this point, effectiveness begins to decline as further increases in flow rate reduce the residence time of the fluid within the heat exchanger, limiting the extent of heat exchange.

The finned U-tube configuration consistently demonstrates higher effectiveness compared to the plain tube design across the entire range. This improvement is attributed to increased surface area and enhanced turbulence generated by fins, which intensify heat transfer mechanisms. From a design perspective, this trend clearly highlights the importance of identifying an optimum flow regime rather than operating at maximum flow conditions. This becomes even more critical in polymer-integrated heat exchangers, where thermal conductivity limitations must be balanced with enhanced convective performance. The presence of such an optimal point provides a strong basis for energy-efficient and material-optimized heat exchanger design, aligning well with modern composite and polymer-based thermal systems.

Although polymer composites are often characterized by lower intrinsic thermal conductivity compared to metals, their application in thermal systems offers several practical and performance-oriented advantages that go beyond simple heat conduction. One of the most significant benefits is their excellent corrosion resistance, which makes them particularly suitable for chemically aggressive environments where conventional metallic heat exchangers suffer from fouling, scaling, or degradation over time. This directly contributes to longer service life and reduced maintenance costs. In addition, polymer composites exhibit low density, resulting in lightweight heat exchanger systems. This is especially beneficial in applications where weight reduction is critical, such as automotive, aerospace, and compact process systems. Their inherent design flexibility allows for complex geometries, including integrated fins and micro-structured surfaces, which can compensate for lower conductivity by enhancing surface area and promoting better fluid mixing. Another important advantage lies in their thermal insulation capability. Unlike metals, polymers reduce unwanted heat loss to the surroundings, thereby improving overall system efficiency in certain configurations. Furthermore, advancements in composite technology—such as the inclusion of thermally conductive fillers (e.g., graphite, carbon fibers, or ceramic particles)—have significantly improved their effective thermal conductivity, making them increasingly viable for heat transfer applications.

The performance of polymer-based composites under elevated temperature and pressure conditions depends strongly on the type of polymer matrix and reinforcement used. High-performance engineering polymers such as epoxy-based composites, polyether ether ketone (PEEK), and reinforced thermosetting plastics demonstrate considerable thermal stability and mechanical strength within moderate temperature ranges. In the present study, the selected polymer composite (e.g., epoxy-based system, ESP) is designed to operate within controlled thermal limits, typically below 120–150 °C, where it maintains structural integrity and dimensional stability. While it may not match the extreme temperature tolerance of metals, it performs reliably in low-to-moderate temperature heat exchange applications such as waste heat recovery, HVAC systems, and chemical processing with non-extreme conditions. Under pressure loading, the composite structure benefits from reinforcement (fibers or fillers), which enhances its mechanical strength and resistance to deformation. Additionally, the lower thermal expansion mismatch between composite components reduces the risk of thermal stresses and fatigue failure during cyclic operation. It is important to note that polymer-based heat exchangers are not intended to directly replace metallic systems in high-temperature, high-pressure environments such as power plants. Instead, they provide an efficient and durable alternative in applications where corrosion resistance, cost-effectiveness, and weight reduction are prioritized.

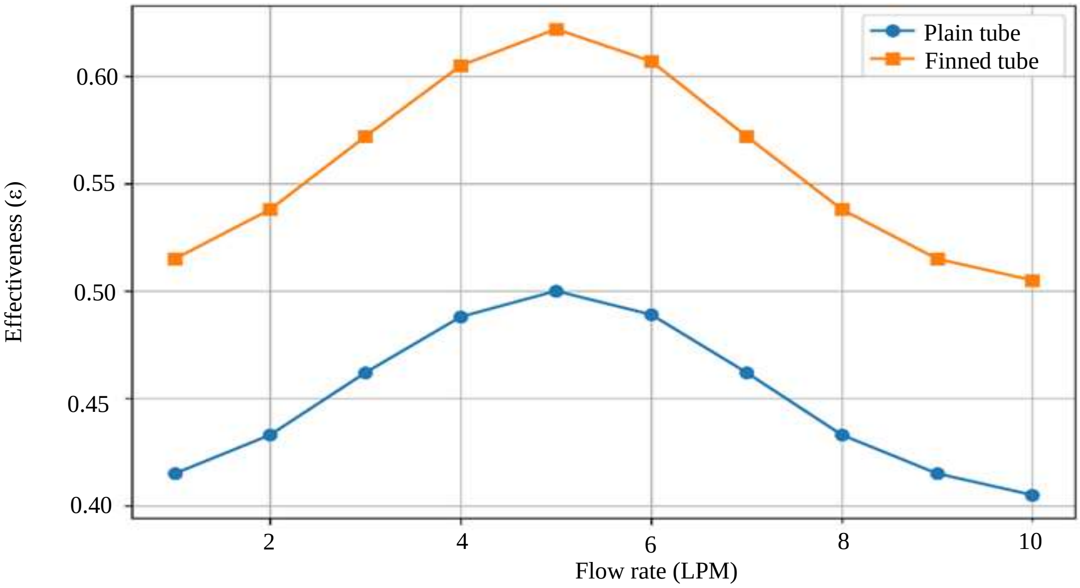

Figure 11. Variation of heat exchanger effectiveness with respect to flow rate for plain and finned U-Tube heat exchanger.

$$\in= \frac{T_{c.out}- T_{c.in}}{T_{h.in}-T_{c.in}}$$

Here,

$$\in= \frac{52-30}{70-30} = 0.55$$

The use of fins in heat exchangers is primarily intended to enhance heat transfer by increasing the effective surface area. However, when fins are made from lower thermal conductivity materials such as polymer composites, their efficiency becomes a critical factor. Fin efficiency is influenced by the material’s ability to conduct heat from the base to the tip of the fin. In polymer-based fins, the reduced thermal conductivity leads to a more pronounced temperature drop along the fin length, which can lower the effective heat transfer contribution of the outer regions. As a result, the overall fin efficiency is typically lower compared to metallic fins. Despite this limitation, the study demonstrates that carefully optimized fin geometry can mitigate these effects. Shorter fin lengths, increased fin density, and strategic placement can reduce conduction resistance and maintain effective heat transfer. Moreover, the use of composite materials with embedded conductive fillers can significantly enhance fin performance by improving internal heat conduction pathways. From a system-level perspective, even with slightly reduced fin efficiency, polymer-based finned configurations can still deliver competitive thermal performance when combined with advantages such as reduced fouling, improved flow distribution, and lower pressure drop penalties due to smoother surfaces. Therefore, the design approach shifts from maximizing conductivity to optimizing geometry and material composition for balanced thermo-hydraulic performance.

Polymer Impact

A key advancement of this study lies in its implication for polymer and composite heat exchanger design. While the current configuration primarily uses metallic components, the findings directly support the integration of epoxy-based or polymer-coated layers in future designs. Polymers offers corrosion resistance, reduced weight, enhanced manufacturability, and thermal insulation control. However, their lower thermal conductivity is often a limitation. The present study demonstrates that geometric enhancements (fins + U-bends) can compensate for this limitation by amplifying convective heat transfer, thereby maintaining high overall performance. This opens a pathway toward hybrid metal–polymer heat exchangers, where metals handle conduction and polymers provide durability and sustainability. Overall, the study does not just compare configurations—it establishes a design philosophy. Efficient heat exchanger performance is achieved through a balanced integration of geometry, flow physics, and material innovation, where polymer-based composites represent the next frontier in sustainable thermal engineering.

CONCLUSION

The present study provides a comprehensive understanding of the thermo-hydraulic behavior of a finned U-tube shell-and-tube heat exchanger through detailed CFD analysis. The results clearly demonstrate that the incorporation of fins significantly enhances heat transfer performance when compared to conventional plain tube configurations. This improvement is primarily attributed to the combined effects of increased surface area and intensified flow mixing, particularly in the U-bend region where secondary flow structures play a dominant role. The use of a refined hybrid meshing strategy with near-wall inflation layers enabled accurate resolution of boundary layer development, flow maldistribution, and recirculation zones. This not only improved the reliability of the numerical predictions but also provided deeper insight into localized flow phenomena that directly influence heat transfer efficiency.

Although the finned configuration introduces an increase in pressure drop due to higher flow resistance, the overall performance evaluation indicates that the thermal gains outweigh the associated hydraulic penalties within the investigated operating range. This establishes the finned U-tube design as an effective and practical solution for compact heat exchanger applications. Importantly, the study also highlights the potential of integrating such geometrical enhancements with advanced materials, including polymer-based or composite layers, to achieve lightweight, corrosion-resistant, and energy-efficient thermal systems. Overall, the findings offer a strong foundation for the design and optimization of next-generation heat exchangers for industrial applications.

Future Scope

From a design optimization perspective, multi-objective approaches using machine learning or evolutionary algorithms can be employed to simultaneously optimize thermal performance, hydraulic losses, and material selection. Experimental validation using advanced diagnostic techniques such as Particle Image Velocimetry (PIV) and infrared thermography would further strengthen the reliability of numerical predictions. Such advancements will contribute toward the development of high-performance, compact, and polymer-integrated heat exchangers, aligned with emerging demands in sustainable and energy-efficient thermal systems.

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