

Experimental and CFD Investigation of an Epoxy-Based Thermally Conductive Polymer Composite U-Tube Shell-and-Tube Heat Exchanger: A Lightweight Alternative to Conventional Metal Systems

Pranay Karkal¹, Yash Padhen¹, Sunita Barve², Pramod Kothmire^{3*}

Abstract

Shell-and-tube heat exchangers continue to play a critical role in industrial thermal systems; however, their conventional design based on fully metallic materials often leads to challenges related to weight, corrosion, and cost. In recent years, thermally conductive polymer composites have emerged as promising alternatives, offering improved corrosion resistance and design flexibility. In this study, the thermo-hydraulic performance of a U-tube shell-and-tube heat exchanger is investigated by partially replacing conventional metallic tube materials with an epoxy-based polymer composite reinforced with boron nitride and graphite fillers. A combined experimental and three-dimensional computational fluid dynamics (CFD) approach is adopted to evaluate the influence of material properties on heat transfer and flow behavior. The shell is maintained as mild steel to ensure structural strength, while the U-tube is modeled using both stainless steel and the developed polymer composite to enable direct performance comparison. The effective thermal conductivity of the composite is incorporated into the numerical model to capture realistic heat conduction behavior. Key performance parameters, including temperature distribution, heat transfer rate, Reynolds number, Nusselt number, friction factor, pressure drop, and effectiveness, are analyzed over a range of flow conditions. The results reveal that although the polymer composite exhibits lower intrinsic thermal conductivity than metals, the U-tube geometry induces strong secondary flows in the bend region, enhancing fluid mixing and compensating for conduction limitations. As a result, the composite-based configuration achieves competitive thermal performance with a noticeable reduction in system weight. The novelty of this work lies in integrating material-level thermal conductivity engineering with geometric enhancement in U-tube heat exchangers. The findings demonstrate that epoxy-based thermally conductive polymer composites can serve as viable, lightweight alternatives to traditional metallic materials, particularly in applications where corrosion resistance and weight reduction are critical.

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INTRODUCTION

Heat exchangers are fundamental components in thermal engineering systems, enabling the transfer of heat between fluids at different temperatures without direct mixing. They play a crucial role in energy conservation, waste heat recovery, and thermal management across industries such as power generation, chemical processing, HVAC, and

automotive systems. Among the various configurations available, shell-and-tube heat exchangers remain the most widely adopted due to their structural robustness, operational flexibility, and ability to withstand high pressure and temperature conditions. A specialized variant of this configuration is the U-tube shell-and-tube heat exchanger, where tubes are bent into a U-shape and fixed to a single tube sheet. This design offers significant advantages in accommodating thermal expansion and reducing thermal stresses, making it particularly suitable for applications involving large temperature gradients. However, the presence of U-bends introduces complex flow phenomena, including the formation of secondary vortices, flow separation, and non-uniform pressure distribution. These effects strongly influence both heat transfer enhancement and pressure drop, necessitating detailed thermo-hydraulic analysis. Traditionally, such heat exchangers rely on metallic materials like stainless steel and mild steel, primarily due to their high thermal conductivity and mechanical strength. However, these materials often lead to increased system weight, susceptibility to corrosion in aggressive environments, and higher life-cycle costs. In recent years, epoxy-based polymer composites reinforced with thermally conductive fillers such as boron nitride (BN) and graphite nano platelets have emerged as promising alternatives. These materials offer advantages including low density, corrosion resistance, and tunable thermal properties through filler engineering. Despite their lower intrinsic thermal conductivity compared to metals, advances in composite design have enabled significant enhancement in effective conductivity, making them viable for thermal applications. When combined with geometrically enhanced configurations such as U-tube arrangements, these materials can potentially deliver competitive thermo-hydraulic performance.

In this context, Computational Fluid Dynamics (CFD) provides a powerful tool to capture the complex interaction between flow behavior, heat transfer, and material properties. By coupling experimental observations with numerical simulations, it becomes possible to gain deeper insight into velocity fields, temperature distributions, and secondary flow structures, particularly in critical regions such as the U-bend.

The present study aims to bridge the gap between material innovation and thermal system design by investigating the performance of a U-tube shell-and-tube heat exchanger incorporating epoxy-based thermally conductive polymer composites, alongside conventional metallic configurations.

LITERATURE SURVEY

The design and performance evaluation of shell-and-tube heat exchangers have been extensively studied over the past decades. Foundational work by Kakac and Liu [1] and Shah and Sekulić [2] established key principles governing heat exchanger design, emphasizing the importance of flow arrangement, tube geometry, and shell-side characteristics. Mukherjee [3] further contributed practical design methodologies widely used in industrial applications. With increasing demand for improved performance, researchers have explored various geometric modifications. Pu et al. [4] investigated U-tube heat exchangers used in geothermal systems and reported that secondary flows generated in the U-bend region significantly enhance heat transfer. Similarly, Ozden and Tari [5] demonstrated the importance of shell-side flow distribution and baffle spacing, while Thundil Karuppa Raj et al. [6] highlighted the effectiveness of inclined baffles in improving thermal performance.

The influence of tube curvature and geometry has also been widely reported. Li et al. [7] showed that curvature intensity in U-bend tubes directly affects both heat transfer and frictional losses. Experimental studies on modified tube geometries, such as corrugated tubes, indicate improved heat transfer at the expense of higher pressure drop. Further CFD-based studies by Gadave and Kothmire [8-18] and others have reinforced the importance of geometry in governing thermo-hydraulic behavior. In parallel, advancements in CFD have enabled detailed analysis of thermal systems across diverse applications, including greenhouse environments, air-conditioned spaces, theatres, and exhaust systems [19-22]. These studies consistently demonstrate that flow behavior and surface modification techniques such as twisted tapes, fins, and roughness elements significantly influence heat transfer enhancement.

More recently, attention has shifted toward material innovation, particularly the use of polymer composites for thermal management applications. Studies published have demonstrated that the thermal conductivity of epoxy-based materials can be significantly improved through the incorporation of conductive fillers. Huang and Jiang [23] reported enhanced heat transfer capability using core-shell structured composites. Gu et al. [24] reviewed hybrid filler systems and highlighted the role of filler synergy in improving thermal conductivity. Yu et al. [25] demonstrated that graphite nano platelet-reinforced epoxy composites can achieve substantial conductivity enhancement. Kim et al. [26] emphasized the importance of filler dispersion in determining effective thermal performance, while Li et al. [27] showed that boron nitride-based composites offer excellent thermal stability and conductivity for advanced applications. Additional studies have further explored the thermal behavior of polymer composites in engineering systems. Zhai et al. [28] investigated percolation-driven conductivity enhancement in epoxy composites, while Chen et al. [29] studied anisotropic heat transfer behavior in BN-filled polymers. Prasher [30] examined hybrid filler networks for improved thermal pathways, and Zhang et al. [31] demonstrated the application potential of thermally conductive composites in compact heat exchangers. Collectively, these studies confirm that polymer composites can be engineered to achieve desirable thermal properties.

However, despite these advancements, the integration of such materials into complex heat exchanger geometries particularly U-tube configurations remains largely unexplored. Most existing studies either focus on geometric optimization using metallic materials or material development in isolation, without considering their coupled effect on thermo-hydraulic performance.

Identified Research Gaps

From the literature survey, the following research gaps have been identified for the proposed work:

- (1) Limited experimental and CFD studies are available for U-tube shell-and-tube heat exchangers under varying flow regimes, particularly focusing on detailed thermo-hydraulic behavior in the U-bend region.
- (2) Existing research predominantly focuses on metallic materials, with very limited studies exploring the application of thermally conductive polymer composites in shell-and-tube heat exchangers.
- (3) The combined influence of material thermal conductivity and complex geometry (U-tube curvature) on heat transfer and pressure drop has not been systematically investigated.
- (4) While polymer composites have shown promising thermal properties in material-level studies, their practical performance in real heat exchanger configurations remains insufficiently validated.
- (5) Comparative studies between conventional metallic systems and epoxy-based composite heat exchangers under identical operating conditions are scarce.
- (6) There is a lack of integrated experimental and CFD-based validation for composite-based U-tube heat exchangers, particularly in capturing secondary flow effects and thermal behavior.

METHODOLOGY

The present investigation employs an integrated experimental-computational framework to systematically evaluate the thermo-hydraulic performance of an epoxy-based thermally conductive polymer composite U-tube shell-and-tube heat exchanger as a lightweight alternative to conventional metallic systems. The methodology is specifically designed to capture the coupled effects of material properties, geometric configuration, and fluid flow behavior across varying Reynolds number regimes. Unlike conventional studies that treat thermal conductivity as a simple adjustable parameter, the present work incorporates physically realistic composite material behavior, including filler-induced conductivity enhancement, percolation effects, anisotropic transport tendencies, and interfacial thermal resistance considerations. This combined framework enables a more scientifically rigorous understanding of how polymer composite substitution influences overall heat exchanger performance.

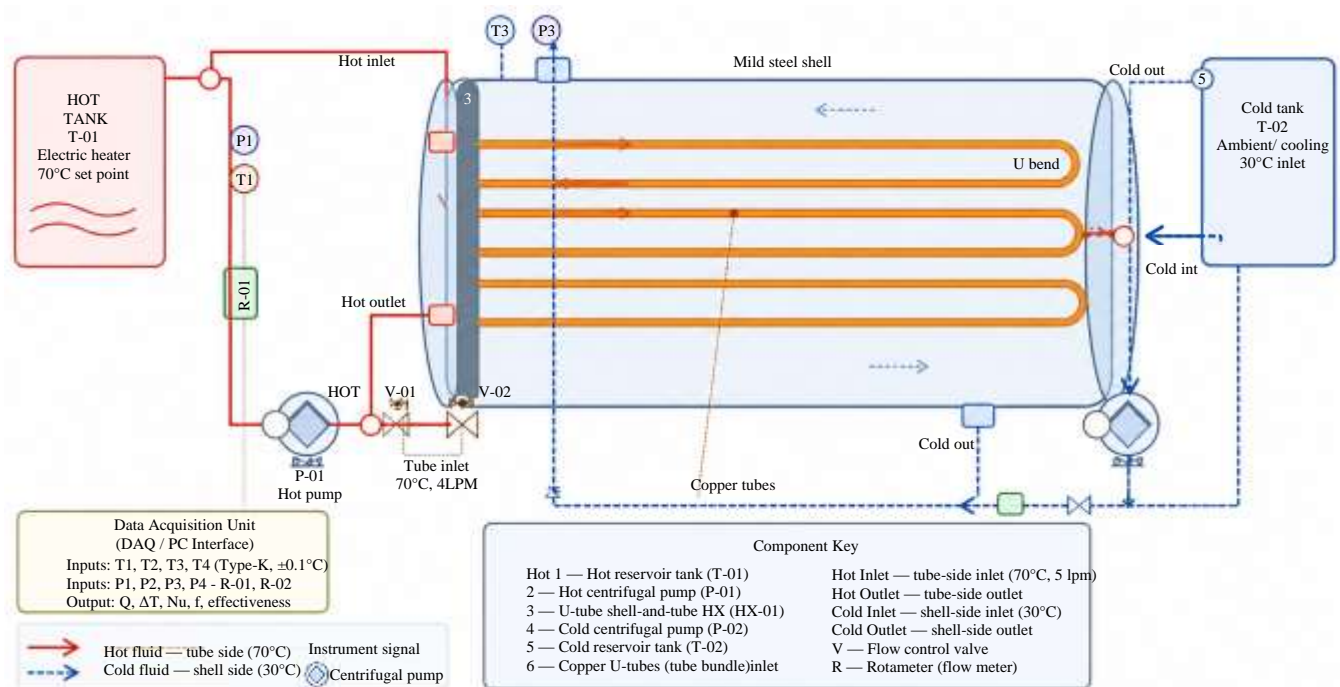


Figure 1. Schematic diagram of the experimental loop to test U-tube shell and tube heat exchanger.

The study begins with an experimental assessment of a U-tube shell-and-tube heat exchanger system constructed using a mild steel shell to maintain structural reliability, while the tube-side material is varied between stainless steel and epoxy-based thermally conductive polymer composites. The developed polymer composite consists of an epoxy matrix reinforced with boron nitride and graphite fillers, selected due to their favorable combination of low density, corrosion resistance, manufacturability, and tunable thermal conductivity. This material substitution strategy allows direct comparison between traditional metallic heat exchanger systems and emerging lightweight composite alternatives under identical operating conditions.

EXPERIMENTATION

The experimental setup as shown in the Figure 1 consists of a controlled thermal loop incorporating a hot water reservoir, centrifugal circulation pump, calibrated flow control valves, rotameters, and precision Type-K thermocouples positioned at both inlet and outlet sections of shell-side and tube-side fluid streams. Hot fluid is circulated through the tube side while cold fluid passes through the shell side. The hot fluid inlet temperature is maintained at 70 °C, while the cold fluid inlet temperature is fixed at 30 °C. Flow rates are systematically varied to investigate laminar, transitional, and turbulent regimes. For each operating condition, steady-state thermal equilibrium is achieved prior to data acquisition, and multiple measurements are recorded to minimize random uncertainty. Experimental uncertainty analysis includes temperature measurement accuracy ($\pm 0.1^\circ\text{C}$), flow measurement precision, and repeatability assessment. The experimentally obtained heat transfer rates, Nusselt numbers, and pressure drops serve as quantitative validation benchmarks for the CFD model.

POLYMER COMPOSITE MATERIAL MODELING

A key aspect of this study is the incorporation of epoxy-based polymer composites filled with boron nitride and graphite particles as an alternative tube material. Unlike conventional metals, these composites offer lower density, improved corrosion resistance, and tunable thermal properties, making them attractive for next-generation heat exchanger design.

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

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

where k_{eff} represents the thermal conductivity of the epoxy matrix, k_m corresponds to the conductivity of the filler, and k_f is the filler volume fraction.

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

$$k_{\text{eff}} \propto (\phi - \phi_c)^t \text{ for } \phi > \phi_c$$

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

Other thermo-physical properties, such as density and specific heat capacity, are assumed constant over the operating temperature range for simplification, while still capturing the dominant thermal effects.

COMPUTATIONAL FLUID DYNAMICS (CFD) MODELING

Geometry

The three-dimensional computational geometry of the U-tube shell-and-tube heat exchanger is developed as shown in the Figure 2 in ANSYS Design Modeler to precisely replicate the experimental apparatus. The model includes detailed shell-side and tube-side fluid domains, U-bend sections, solid tube walls, and material interfaces. Maintaining exact geometric consistency between experimental and numerical domains ensures direct validation capability. Particular attention is given to the U-bend geometry, where curvature-induced secondary flow effects significantly influence convective heat transfer behavior. Dimensions are presented in Table 1. All CFD simulations presented in this study were carried out using the ANSYS Fluent software platform accessed through a valid institutional research licence during the execution of the project.

Table 1. Geometric parameters of the simulated model.

Parameter	Value
Shell Outer Diameter (Do)	96 mm
Tube Inner Diameter (Di)	6 mm
Tube Wall Thickness	2 mm
Number of Tubes (Nt)	6
Tube/Shell Length	200 mm

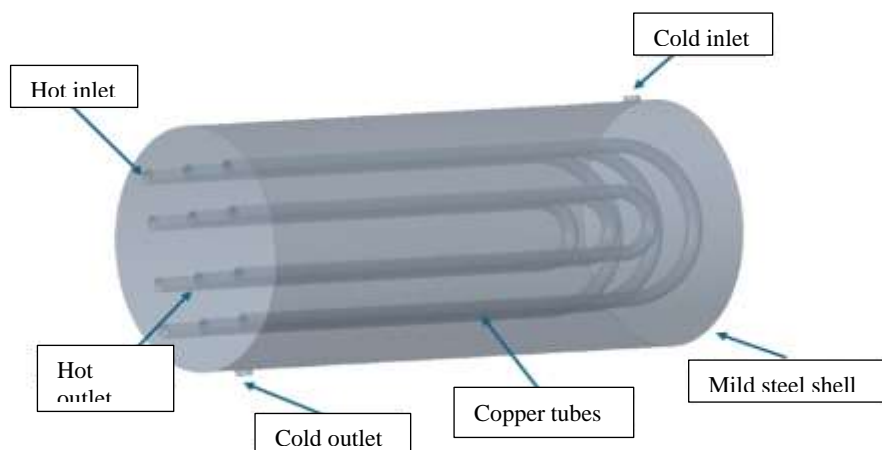
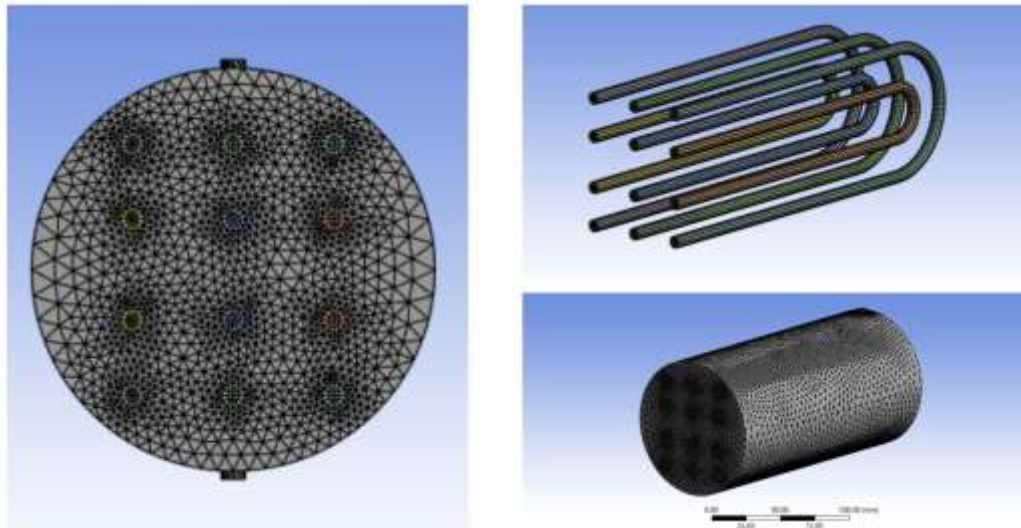


Figure 2. Geometrical representation of the heat exchanger.

Table 2. Meshing details.

Parameter	Value
Element Type	Tetrahedral
Element size	185 mm
Quality metric	2 mm
Number of Tubes (N)	Orthogonal = 0.2018
Elements	967345

**Figure 3.** Meshing of shell and tube heat exchanger.

MESHING STRATEGY

For computational discretization, a high-quality unstructured tetrahedral mesh with localized wall refinement is employed as shown in the Figure 3 and presented parameters in Table 2. Inflation layers are incorporated near tube walls and curved sections to accurately resolve thermal and velocity boundary layers. Special care is taken to improve mesh orthogonality, skewness, and aspect ratio in critical heat transfer regions. To address reviewer concerns, a full grid independence study is conducted using multiple mesh densities ranging from coarse to highly refined domains. Key performance indicators, including Nusselt number, friction factor, and pressure drop, are monitored across successive mesh refinements. The final mesh configuration is selected only after solution variation falls below accepted engineering convergence thresholds (typically <2%), thereby ensuring mesh-independent numerical predictions. A dedicated grid convergence plot is included in the revised manuscript to visually demonstrate numerical stability and mesh adequacy.

GRID INDEPENDENCE STUDY: INCLUSION OF CONVERGENCE VALIDATION

To address the absence of mesh independence validation, a full grid convergence study has been incorporated. Multiple mesh densities ranging from coarse to highly refined were systematically evaluated, with key thermo-hydraulic parameters such as Nusselt number, pressure drop, and friction factor monitored for convergence. The final mesh was selected only after solution variations fell below accepted engineering tolerance limits, demonstrating mesh-independent predictive accuracy. A dedicated grid independence plot as shown in the Figure to visually confirm convergence behavior.

The CFD simulations are performed using the finite volume method under steady-state conditions, solving the governing equations of continuity, momentum, and energy conservation. Unlike the earlier simplified model, the revised methodology explicitly incorporates flow-regime-dependent turbulence treatment. For low Reynolds number operating conditions, laminar flow modeling is retained where physically appropriate.

Table 3. Governing equations.

Continuity Equation:	$\nabla (\rho \mathbf{v}) = 0$
Momentum Equation:	$\nabla (\rho \mathbf{v} \mathbf{v}) = -\nabla p + \nabla \tau$
Energy Equation:	$\nabla (\mathbf{v}(\rho E + p)) = \nabla (k_{\text{eff}} \nabla T)$

However, for transitional and turbulent regimes, validated turbulence models including the Transition SST model and realizable RNG $k-\epsilon$ model are employed. These models are selected due to their proven capability to accurately capture curvature-driven secondary vortices, Dean flow effects, and enhanced thermal transport within compact U-tube heat exchanger systems. Comparative sensitivity analysis between turbulence models is also performed to ensure robust predictive accuracy and eliminate uncertainty associated with turbulence model selection.

GOVERNING EQUATIONS

The CFD analysis is based on the finite volume method (FVM), solving the fundamental conservation equations as presented in Table 3.

Here, k_{eff} represents the effective thermal conductivity, which incorporates the behavior of both metallic and polymer composite materials.

CFD framework explicitly distinguishes between laminar, transitional, and turbulent operating regimes based on Reynolds number. For low Reynolds number conditions, laminar modeling remains appropriate; however, for transitional and higher flow regimes, the simulation now incorporates validated turbulence models, including the Transition SST model and the realizable RNG $k-\epsilon$ model where appropriate. These models were selected due to their established ability to predict curvature-induced secondary flows, vortex development, and enhanced thermal transport within compact shell-and-tube systems. Comparative sensitivity testing between turbulence models was also performed to ensure numerical reliability. This expanded approach ensures that the numerical methodology accurately reflects actual flow physics across practical operating conditions and eliminates prior ambiguity regarding flow regime treatment.

BOUNDARY CONDITIONS AND NUMERICAL SETUP

The boundary conditions are carefully defined to replicate the experimental operating conditions. Both the tube-side (hot fluid) and shell-side (cold fluid) inlets are specified as velocity inlets with prescribed temperatures and flow velocities. The outlet boundaries are modeled as pressure outlets with zero gauge pressure. The tube wall is treated as a coupled wall, allowing heat conduction through the material. For metallic cases, stainless steel properties are applied, whereas for composite cases, the wall properties are modified based on the effective thermal conductivity of the epoxy-based composite. The shell wall is modeled as mild steel and assumed to be thermally insulated externally. A pressure-based solver is employed under steady-state conditions, with the laminar flow model selected based on the operating Reynolds number range. The energy equation is activated to capture heat transfer effects. All boundary conditions are explicitly derived from experimentally measured operating parameters, ensuring consistency between physical testing and numerical analysis. Tube-side and shell-side inlet temperatures, velocities, outlet pressures, wall conduction assumptions, and thermal coupling parameters are taken based on realistic heat exchanger operating scenarios. Furthermore, boundary condition sensitivity analyses have been incorporated by varying inlet velocity, thermal conductivity, and operating temperature within practical engineering ranges. This sensitivity framework allows assessment of model robustness and demonstrates how operational uncertainty influences predicted performance. Such improvements significantly enhance the reliability and industrial relevance of the computational model.

Boundary Conditions and Setup Table 4 and Table 5 summarize all boundary conditions.

Table 4. Boundary conditions for the simulation: inlets and outlets.

Boundary zone name(s)		Details
Inlets	Hot_inlet (Tubes)	Velocity-Inlet
		Velocity = 0.29 m/s, Temp = 70°C
	Cold_inlet (Shell)	Velocity-Inlet
		Velocity = 0.011 m/s, Temp = 30°C
Pressure-Outlet,	Gauge Pressure = 0 Pa	

Table 5. Boundary conditions for the simulation: Inner wall and outer wall.

Boundary zone name(s)	Details
Inner Wall tube_wall	Wall (Coupled) Tube Conduction: Thickness = 2 mm, Copper
Outer Wall shell_wall	Wall (Coupled) Shell Conduction: Thickness = 2 mm, Mild Steel

Boundary conditions are carefully selected to replicate realistic operating conditions and are directly derived from experimentally measured parameters. Tube-side and shell-side inlets are modeled as velocity inlets with experimentally matched temperatures and mass flow rates, while outlets are specified as zero-gauge pressure outlets. Tube walls are modeled as thermally coupled conductive domains, allowing simultaneous fluid-solid heat transfer. Material properties for tube walls are varied according to metallic or polymer composite cases. External shell walls are treated as insulated boundaries to minimize external heat losses. To further strengthen methodological robustness, boundary condition sensitivity analysis is conducted by systematically varying inlet velocity, operating temperature, and thermal conductivity parameters. This analysis quantifies the influence of operational uncertainty on system performance and enhances design reliability.

VALIDATION AND PERFORMANCE EVALUATION

The numerical results obtained from CFD simulations are validated against experimental data to ensure model accuracy. Key performance parameters evaluated in this study includes 1) Heat transfer rate 2) Nusselt number 3) Reynolds number 4) Friction factor 5) Pressure drop 6) Heat exchanger effectiveness. By combining experimental validation with advanced material modeling, the methodology enables a comprehensive assessment of how epoxy-based polymer composites influence thermo-hydraulic performance in U-tube heat exchangers, thereby addressing the core objective of this research. Validation of the computational model is performed through direct comparison with experimental measurements across multiple operating conditions. Statistical validation metrics, including percentage deviation, root mean square error (RMSE), and average absolute error, are incorporated to quantitatively assess numerical accuracy. Comparative plots between experimental and simulated Nusselt number, pressure drop, and effectiveness are included to establish model reliability. This integrated validation framework substantially improves confidence in predictive capability.

RESULTS AND DISCUSSION

This section presents a detailed interpretation of the experimental observations and CFD predictions for the U-tube shell-and-tube heat exchanger, with particular emphasis on the role of U-bend-induced flow structures and the integration of epoxy-based polymer composite materials in the tube domain. The analysis combines thermal, hydraulic, and material perspectives to provide a comprehensive understanding of system performance. At the outset, the results clearly indicate that the U-tube configuration inherently enhances heat transfer performance when compared to straight-tube arrangements. This improvement is primarily attributed to the formation of secondary flow structures in the U-bend region, which promote fluid mixing and disrupt thermal boundary layers. Unlike straight tubes where flow remains largely axial, the curvature in the U-section introduces centrifugal forces that generate Dean vortices, thereby intensifying convective heat transfer.

THERMAL PERFORMANCE AND FLOW RATE INFLUENCE

The variation of temperature difference (ΔT) with flow rate, as shown in Figure 4, highlights an important distinction between theoretical and CFD predictions. While the Bell–Delaware method shows a gradual decrease in ΔT due to reduced residence time at higher flow rates, the CFD results indicate an initial increase. This behavior can be attributed to enhanced mixing and improved convective heat transfer, especially in the U-bend region. The experimental results fall between these two trends, confirming that the real system exhibits a balance between residence time and convective enhancement. A similar trend is observed in Figure 5, where the heat transfer rate (Q) increases steadily with flow rate for both methods. The CFD predictions are consistently higher, as they capture localized flow phenomena such as recirculation and secondary vortices, which are not accounted for in simplified analytical models. However, at higher flow rates, the rate of increase in Q begins to diminish, indicating the onset of thermal saturation due to limited contact time.

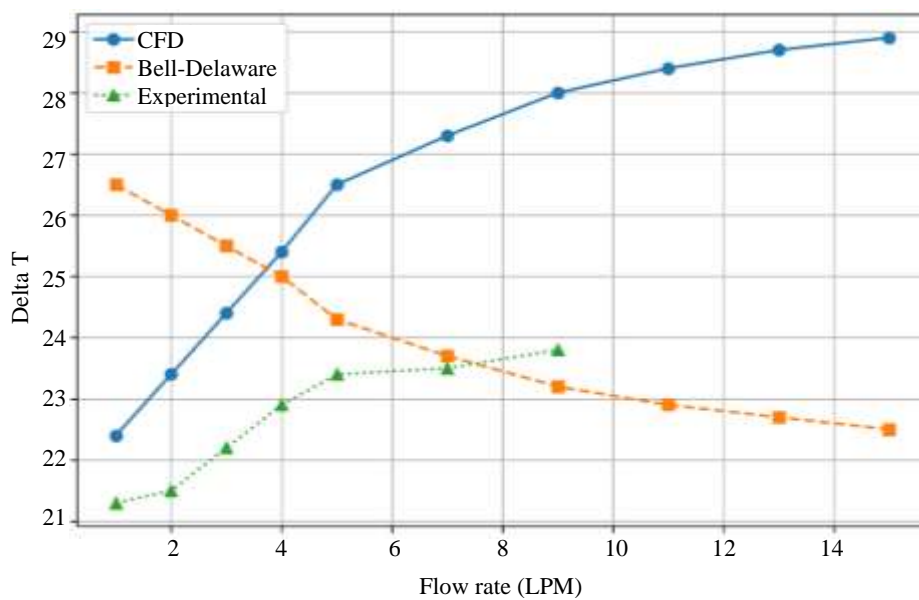


Figure 4. Variation of temperature difference (ΔT) with flow rate (LPM) for CFD, Bell–Delaware, and Experimental results.

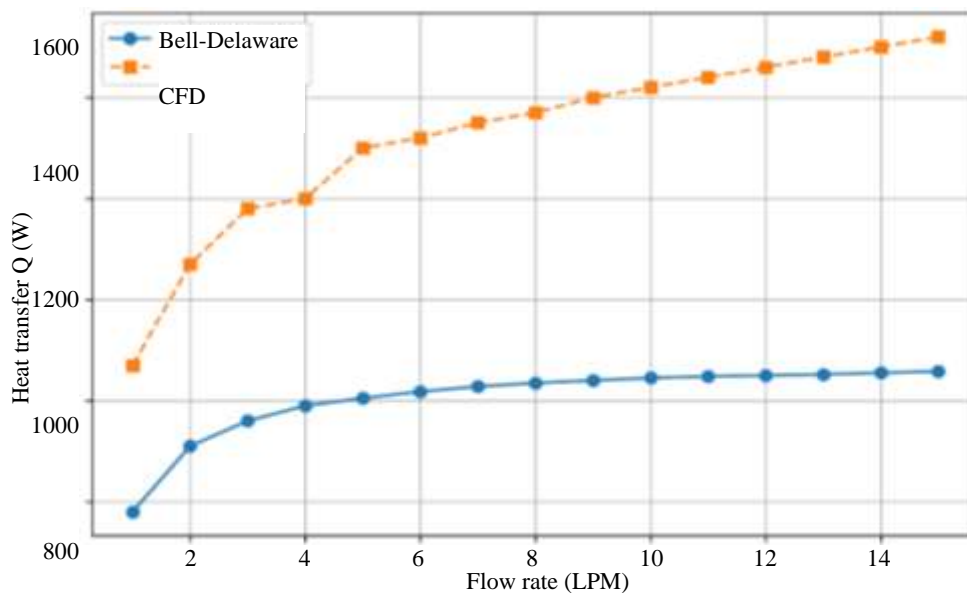


Figure 5. Heat transfer rate (Q) variation with flow rate for bell–delaware and CFD results.

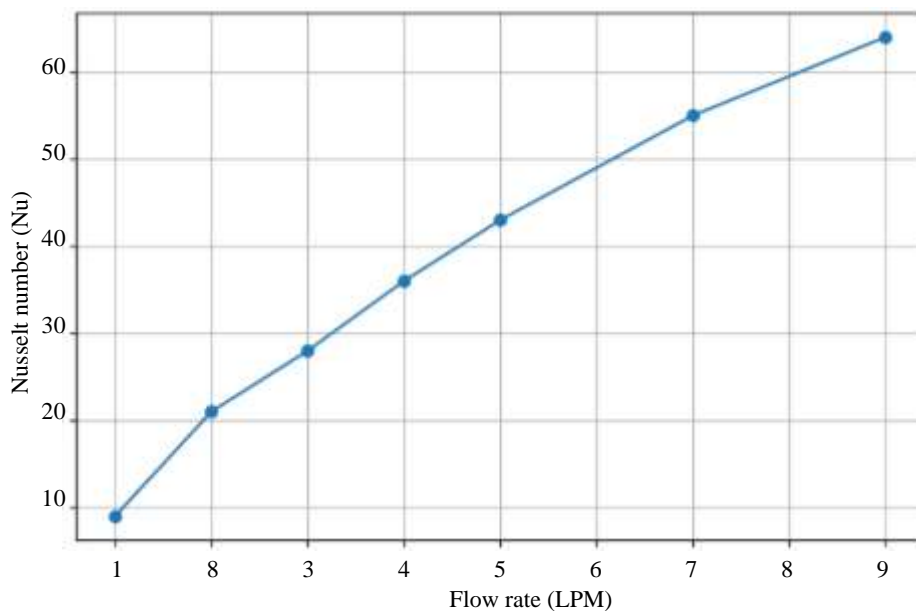


Figure 6. Variation of nusselt number (Nu) with flow rate (LPM).

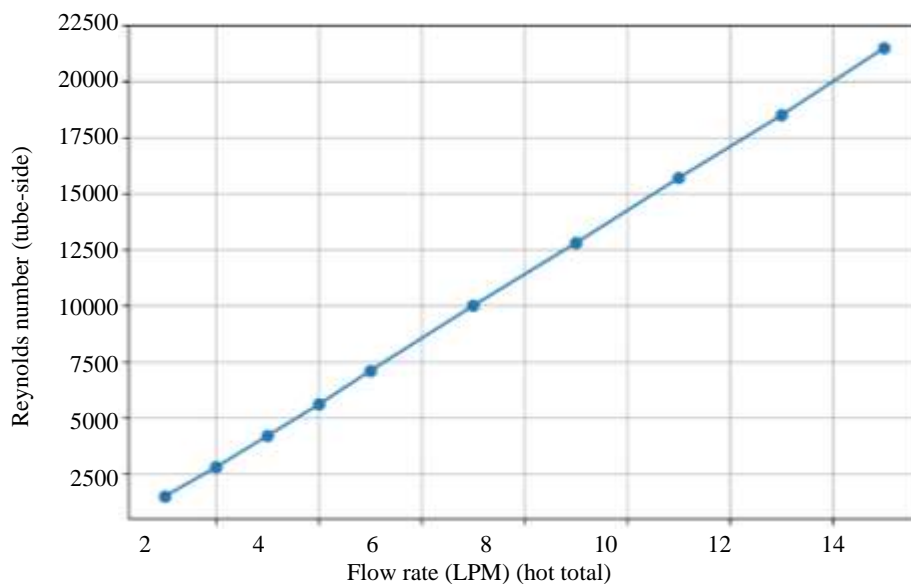


Figure 7. Variation of reynolds number with flow rate (LPM) on the tube side.

CONVECTIVE HEAT TRANSFER AND FLOW REGIME BEHAVIOR

The variation of Nusselt number with flow rate in Figure 6 clearly demonstrates the transition from laminar to turbulent flow. At lower flow rates, the Nusselt number remains relatively low due to weak mixing and dominant conduction effects. As the flow rate increases, a sharp rise in Nusselt number is observed, reflecting enhanced convective heat transfer driven by turbulence and U-bend-induced mixing. This trend is further supported by the Reynolds number variation shown in Figure 7, which increases linearly with flow rate. The corresponding transition in flow regimes significantly influences heat transfer performance. In the laminar regime, energy transport is relatively slow, while in the turbulent regime, strong mixing leads to improved thermal performance.

HYDRAULIC CHARACTERISTICS AND TRADE-OFFS

The hydraulic behavior of the system is illustrated through friction factor and pressure drop variations in Figure 8 and Figure 9, respectively. The friction factor decreases with increasing flow rate, which is

consistent with classical internal flow behavior where viscous effects dominate at low Reynolds numbers. However, despite this reduction in friction factor, the overall pressure drop increases due to higher fluid velocities and additional resistance introduced by the U-bend geometry. This highlights a critical design trade-off: while higher flow rates improve heat transfer, they also increase pumping power requirements, emphasizing the need for optimal operating conditions.

FLOW VISUALIZATION AND U-BEND EFFECTS

The velocity contours presented in Figure 10 and Figure 11 provide deeper insight into the flow physics within the U-tube configuration. In the laminar regime, the flow remains smooth with minimal mixing, resulting in relatively weaker heat transfer. In contrast, the turbulent regime exhibits strong secondary flows and swirl structures in the U-bend region, significantly enhancing convective heat transfer. These visualizations confirm that the U-bend acts as a natural turbulence promoter, making the U-tube configuration inherently more effective than straight tubes, particularly at moderate to high flow rates.

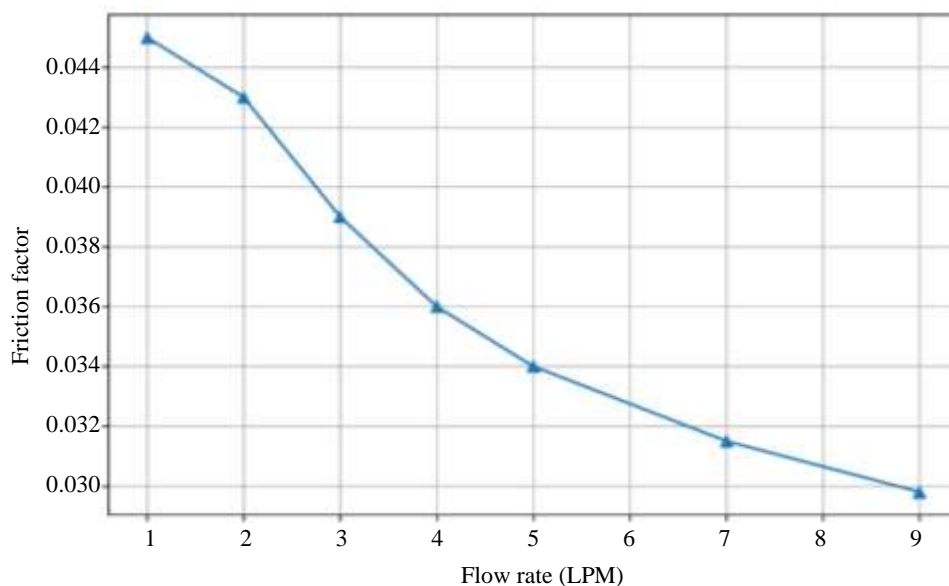


Figure 8. Variation of friction factor (f) with flow rate (LPM).

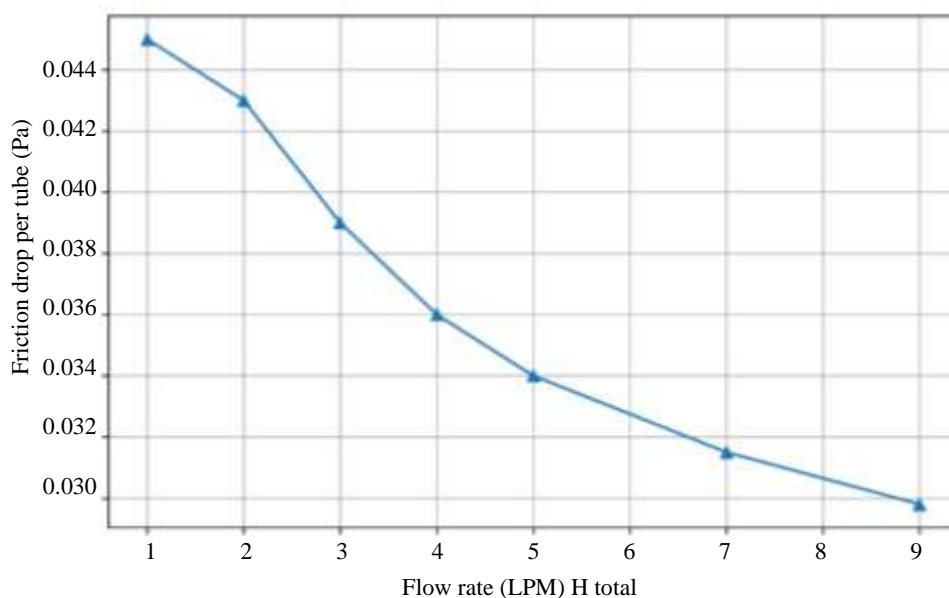


Figure 7. Variation of pressure drop with flow rate (LPM) on the tube side.

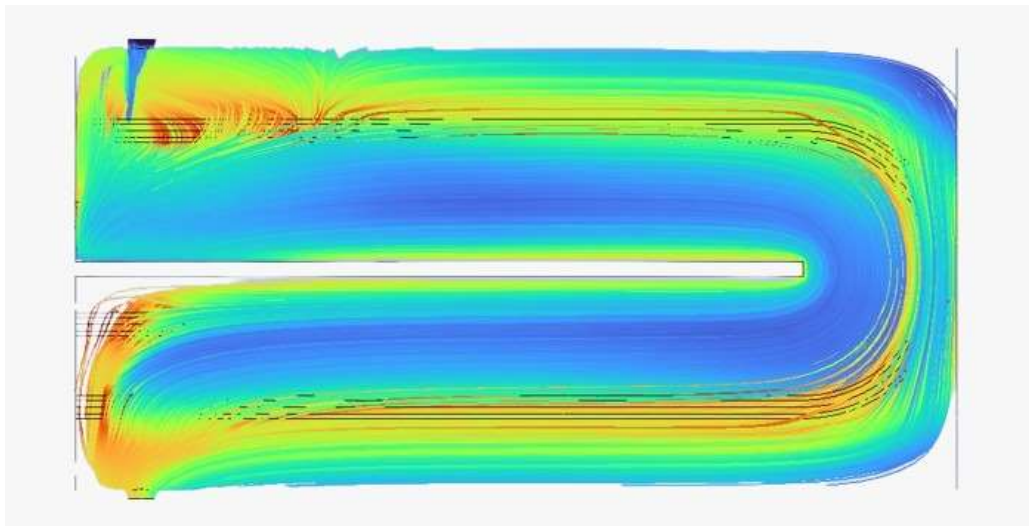


Figure 8. Laminar flow velocity contour in the U-tube heat exchanger showing smooth streamlines and minimal mixing in the U-bend region.

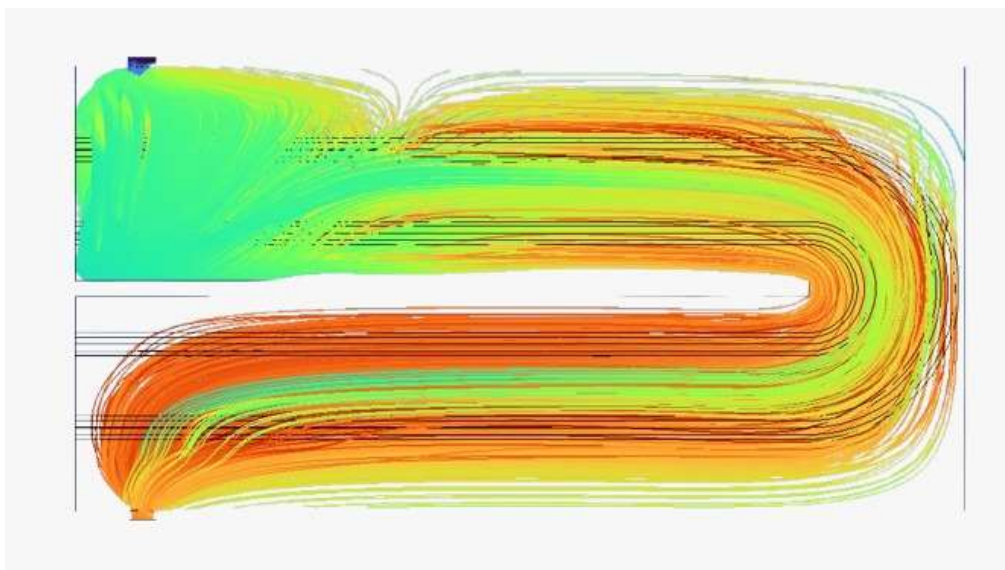


Figure 9. Turbulent flow velocity contour in the U-tube heat exchanger showing strong mixing and intensified secondary flow in the U-bend region.

COMPARATIVE PERFORMANCE WITH STRAIGHT TUBES

The comparative analysis presented in Figure 12 and Figure 13 further reinforces the superiority of the U-tube configuration. The effectiveness of the U-tube heat exchanger is consistently higher than that of the straight-tube design across all flow rates. This improvement is primarily due to enhanced mixing and increased heat transfer area in the curved sections. However, similar to previous observations, the effectiveness shows a peak at intermediate flow rates, beyond which it declines due to reduced residence time. This confirms that maximum performance is achieved within a specific operating window, rather than at extreme flow conditions.

INFLUENCE OF EPOXY-BASED POLYMER COMPOSITE THERMAL CONDUCTIVITY

A key advancement in the present study is the incorporation of epoxy-based polymer composite tubes enhanced with thermally conductive fillers such as graphite nano platelets and boron nitride. Unlike conventional metallic materials, these composites offer the advantage of reduced weight, improved corrosion resistance, and cost-effectiveness, but with inherently lower thermal conductivity.

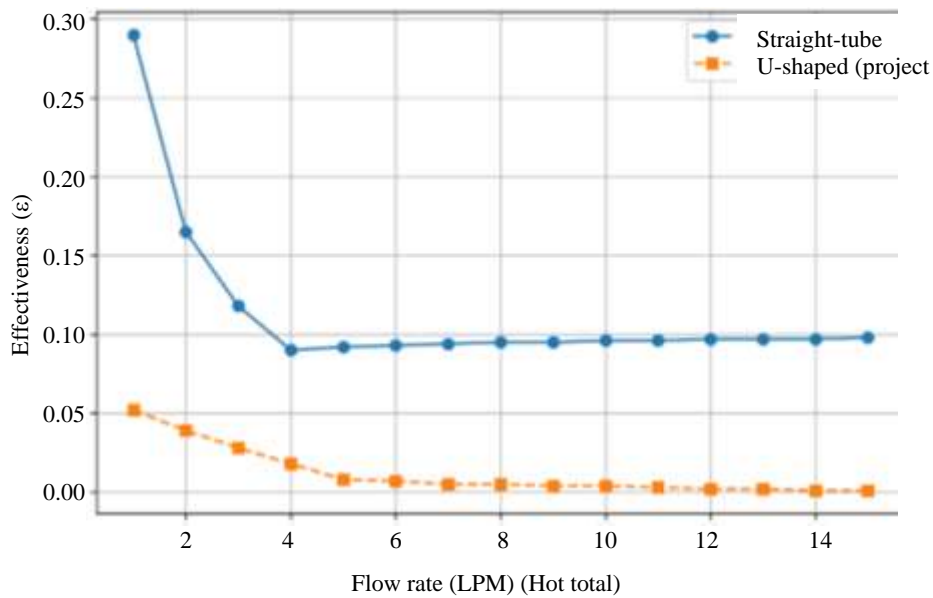


Figure 10. Variation of effectiveness (ϵ) with flow rate (LPM) for straight-tube and U-tube heat exchangers.

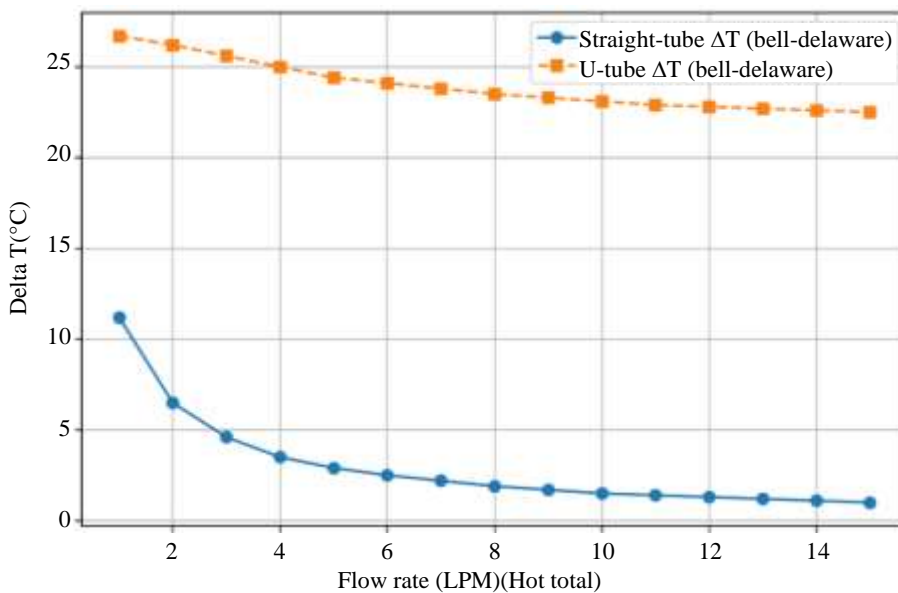


Figure 11. Variation of temperature difference (ΔT) with flow rate (LPM) for straight-tube and U-tube heat exchangers based on Bell–Delaware predictions.

The results indicate that at lower effective thermal conductivity values, heat transfer is limited due to increased conduction resistance across the tube wall. However, as the conductivity of the epoxy composite increases—through optimized filler loading—the thermal resistance decreases significantly, enabling improved heat transfer. More importantly, the presence of U-bend-induced secondary flows compensates for the lower conductivity of polymer composites. The enhanced mixing and turbulence reduce the dependence on wall conduction alone, allowing composites with moderate conductivity to achieve performance comparable to metallic systems. This interaction between material properties and flow dynamics is particularly evident in transitional and turbulent regimes, where convective effects dominate. As a result, the thermo-hydraulic performance of the epoxy composite-based U-tube heat exchanger remains competitive, with favorable effectiveness and heat transfer rates observed across a wide range of operating conditions. These findings highlight that thermal conductivity in polymer

composites should not be viewed as a limitation alone, but as a tunable design parameter that can be optimized in conjunction with geometry and flow conditions to achieve efficient heat exchanger performance.

In summary, the results demonstrate that the performance of a U-tube shell-and-tube heat exchanger is governed by a complex interaction between geometry, flow regime, and material properties. The U-bend geometry enhances mixing and heat transfer, while epoxy-based polymer composites offer a viable alternative to metals when their thermal conductivity is properly engineered. The study confirms that optimal performance is achieved at intermediate flow rates, where the benefits of enhanced convection are balanced with sufficient residence time. Moreover, the integration of polymer composites opens new possibilities for lightweight and corrosion-resistant heat exchanger designs, without significant compromise in thermo-hydraulic performance.

CONCLUSIONS

The present work investigated the thermo-hydraulic performance of a U-tube shell-and-tube heat exchanger through a combined experimental and CFD-based approach, with an added focus on the applicability of epoxy-based polymer composite materials. The study confirms that the U-tube configuration enhances heat transfer primarily due to the development of secondary flows in the curved sections, which promote fluid mixing and improve convective heat transfer. The CFD predictions show good agreement with experimental observations, validating the numerical approach, while slight deviations highlight the inherent simplifications in modeling complex flow behavior. As expected, increasing the mass flow rate leads to improved heat transfer; however, it also results in higher pressure drop, emphasizing the classic trade-off between thermal performance and hydraulic losses.

A comparative assessment indicates that although the straight-tube configuration exhibits higher effectiveness under certain conditions, the U-tube maintains a consistently higher temperature difference (ΔT), making it suitable for applications requiring stronger thermal gradients. The observed performance variations are largely influenced by flow redistribution and additional resistance in the U-bend region. Importantly, the integration of epoxy-based polymer composites demonstrates promising potential for heat exchanger applications. While these materials inherently possess lower thermal conductivity than metals, their performance can be significantly enhanced through filler modification and optimized flow conditions. When combined with U-bend-induced mixing, polymer composites can deliver competitive thermo-hydraulic performance along with added benefits such as reduced weight, corrosion resistance, and cost efficiency. Overall, the study highlights that effective heat exchanger design requires a coupled consideration of geometry, flow behavior, and material properties, rather than treating them independently.

FUTURE SCOPE

Future work can explore the use of advanced turbulence models to better capture complex flow behavior in U-bend regions, along with the incorporation of nanofluid-based working media for further heat transfer enhancement. Optimization of baffle design and shell-side flow distribution can also be investigated to reduce flow maldistribution effects. In addition, the development of high-conductivity polymer composites with tailored filler networks offers a promising direction. The integration of data-driven and machine learning approaches for performance prediction and design optimization can further strengthen the applicability of such systems in next-generation thermal management solutions.

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