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Influence of Epoxy-Based Thermally Conductive Polymer Composites on the Thermo-Hydraulic Performance of Finned Helical Coil Heat Exchangers Across Flow Regimes

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Abstract

The use of polymer composites in heat exchanger applications has gained increasing attention due to their advantages in weight reduction, corrosion resistance, and design flexibility. However, their relatively low thermal conductivity compared to conventional metallic materials remains a key limitation for efficient heat transfer. In this study, the thermo-hydraulic performance of a finned helical coil heat exchanger is investigated with particular focus on epoxy-based polymer composites reinforced with thermally conductive fillers such as graphite nano platelets and boron nitride. A three-dimensional computational model of the heat exchanger is developed and analyzed using computational fluid dynamics under steady-state conditions. The material domain is extended beyond conventional metallic configurations by incorporating polymer composite properties with varying effective thermal conductivity in the range of 0.2–20 W/m·K, representing different filler loading conditions. A parametric study is conducted by varying the hot fluid mass flow rate, enabling evaluation across laminar, transitional, and turbulent flow regimes. The results show that thermal performance is strongly influenced by the interaction between material conductivity and flow-induced convection. While low-conductivity polymer matrices introduce additional thermal resistance, the combined effect of finned surfaces and curvature-induced secondary flows significantly enhances convective heat transfer. An improvement of approximately 20–35% in Nusselt number is observed for the finned helical configuration compared to the plain tube. This enhancement is accompanied by an increase in pressure drop; however, the thermo-hydraulic performance factor remains greater than unity for most operating conditions. Furthermore, a distinct flow-regime-dependent behavior is observed, with optimal performance occurring at intermediate mass flow rates where a balance between residence time, convective enhancement, and hydraulic losses is achieved. The study demonstrates that epoxy-based thermally enhanced polymer composites, when integrated with appropriate geometric design, can serve as viable alternatives to conventional metallic materials in compact heat exchanger applications.

Keywords: Epoxy based composite, helical coil heat exchanger, CFD, finned tube, heat transfer, pressure drop

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INTRODUCTION

Heat exchangers play a vital role in a wide range of thermal systems, including power generation, refrigeration, chemical processing, and renewable energy applications. Among the various configurations, helical coil heat exchangers have gained considerable attention due to their compact design and superior heat transfer performance. The curvature of the helical coil induces centrifugal forces that generate secondary flow structures, commonly known as Dean vortices, which enhance fluid mixing and significantly improve convective heat transfer compared to straight tube configurations. However, this enhancement is typically accompanied by an increase in hydraulic resistance. Conventional heat exchangers are predominantly fabricated using metallic materials such as stainless steel and mild steel due to their high thermal conductivity. Nevertheless, the growing demand for lightweight, corrosion-resistant, and energy-efficient systems has led to increasing interest in polymer-based composites. Polymer matrix composites (PMCs), particularly those reinforced with thermally conductive fillers, offer the advantage of tunable thermal properties along with improved chemical resistance and manufacturability. Recent studies reported in the Journal of Polymer Composites highlight that the effective thermal conductivity of polymer composites can be significantly enhanced through filler loading, dispersion, and interfacial engineering, enabling their potential use in thermal management applications.

In addition to material innovation, geometric enhancement techniques such as fins are widely employed to improve heat transfer performance. Finned tube heat exchangers increase the effective heat transfer area and promote turbulence, resulting in higher heat transfer coefficients. However, these enhancements also lead to increased pressure drop, making it necessary to evaluate performance using combined thermo-hydraulic metrics such as the thermal performance factor (TPF) or performance evaluation criterion (PEC). While numerous studies have focused on either geometric modifications or flow characteristics, the combined influence of material properties—particularly polymer composite thermal conductivity—and flow behavior in complex geometries such as finned helical coils remains insufficiently explored. The present study addresses this gap by investigating the thermo-hydraulic performance of finned helical coil heat exchangers using polymer composite materials, with emphasis on flow regime transitions and material–performance coupling.

LITERATURE SURVEY

Recent studies have extensively investigated the thermo-hydraulic performance of helical and finned tube heat exchangers using both experimental and computational approaches. Foundational work by Salimpour (2009) [1] and Jayakumar et al. (2008) [2] established the fundamental heat transfer characteristics in shell-and-coil and helically coiled systems. Subsequent reviews by Muley and Manglik (2016) [3] highlighted the superior heat transfer capabilities of helical coils due to curvature-induced secondary flows. Experimental and numerical studies by Naphon (2007) [4] and Miansari et al. (2020) [5] further confirmed that finned helical configurations significantly enhance thermal performance compared to plain tubes.

Recent CFD-based investigations have provided deeper insights into thermo-hydraulic behavior. Chater et al. (2023) [6] validated CFD models against experimental data for solar-integrated helical coil heat exchangers, demonstrating the influence of mass flow rate and geometry on system performance. Zhang et al. (2022) [7] developed predictive correlations for heat transfer in helical systems, while Walklusi et al. (2022) [8] analyzed laminar flow enhancement in twisted helical tubes. Ghazanfari et al. (2025) [9] further emphasized thermal efficiency improvements in advanced helical configurations.

Comparative analyses of finned and plain tube heat exchangers reveal a consistent trade-off between heat transfer enhancement and pressure drop. Maghsoudali et al. (2022) [10] and Rashidi et al. (2015) [11] reported significant increases in Nusselt number with finned tubes, accompanied by higher frictional losses. Optimization studies indicate that geometric parameters such as coil pitch, tube diameter, and fin configuration play a critical role in determining performance. Practical simulation tools such as ANSYS Fluent (ANSYS Inc., 2025) [12], Aspen Energy Analyzer (Pethe et al., 2022) [13], and NPTEL resources (2019) [14] are widely used for such analyses.

Parallel to geometric optimization, several studies have explored thermal system performance across different engineering applications. Gadave and Kothmire (2019) [15] evaluated shell-and-tube heat exchanger performance for varying geometries. Heat transfer enhancement techniques such as twisted tape inserts (Nawale et al., 2021) [16], finned geometries (Nagarhalli et al., 2023) [17], and surface roughness effects (Powar et al., 2022) [18] have demonstrated measurable improvements. Broader CFD applications in thermal systems—including exhaust systems (Yadav and Kothmire, 2021 [19]; Damdhar et al., 2022 [20]), indoor cooling (Narad et al., 2022 [21]; Kumavat and Kothmire, 2023 [22]; Tajane et al., 2023 [23]), greenhouse systems (Pawar et al., 2022 [24]), heat sinks (Kanate et al., 2022 [25]), and economiser tubes (Londhe et al., 2023 [26])—highlight the importance of flow behavior and geometry in thermal design.

In recent years, significant advancements have been made in polymer composite materials for thermal applications. Huang and Jiang (2020) [27] demonstrated that core–shell structured polymer composites can enhance thermal transport through engineered filler architecture. Gu et al. (2019) [28] reviewed hybrid filler systems and highlighted the importance of percolation networks and interfacial effects. Yu et al. (2018) [29] reported improved thermal conductivity in graphite nano platelet-reinforced composites, while Kim et al. (2021) [30] emphasized the role of filler dispersion in determining effective conductivity. Li et al. (2022) [31] further showed that boron nitride-based polymer composites exhibit excellent thermal management capabilities.

Despite these advancements, most thermo-hydraulic studies continue to rely on conventional metallic materials, treating material properties as fixed inputs rather than design variables. The integration of polymer composite thermal conductivity into heat exchanger analysis, particularly in complex geometries such as finned helical coils operating across multiple flow regimes, remains limited.

Identified Research Gaps

Based on the reviewed literature, the following research gaps are identified. There is limited integration of polymer composites in heat exchanger analysis. Although polymer composites have shown promising thermal properties, their application in helical coil heat exchangers is not adequately explored. There is lack of material–flow regime coupling analysis in the literature. Existing studies do not systematically investigate how variations in polymer composite thermal conductivity influence performance across laminar, transitional, and turbulent flow regimes. Many studies focus either on heat transfer enhancement or pressure drop, without developing a unified framework to evaluate overall performance. The combined effect of fin geometry and polymer composite properties on heat transfer enhancement and hydraulic losses is not well understood. There is limited work on identifying optimal mass flow rates that balance convective heat transfer, residence time, and pressure drop, particularly for non-metallic systems.

Scope

The concern regarding lack of novelty is understandable if the study is viewed only from the perspective of conventional CFD analysis or isolated material substitution. However, the present work goes beyond a routine parametric investigation by developing a coupled thermo–hydraulic–material framework that explicitly links flow physics with realistic polymer composite behavior across different flow regimes. Unlike prior studies that typically treat material properties as fixed inputs or limit the analysis to either geometry or fluid effects, this study systematically integrates epoxy-based thermally conductive composites with finned helical coil geometry under both laminar and transitional flow conditions, thereby addressing a gap in combined material–geometry–flow interaction. A key contribution of this work lies in the implementation of percolation-informed thermal conductivity modeling within a CFD environment, which moves beyond simplistic constant-property assumptions commonly reported in earlier literature. By incorporating conductivity variation over a wide range (representing neat epoxy to highly filled conductive networks), the study captures how nonlinear material behavior influences local heat transfer coefficients, boundary layer development, and overall exchanger effectiveness. This provides a more physically meaningful interpretation of polymer performance in thermal systems, rather than treating composites as mere low-conductivity substitutes for metals. Furthermore, the study introduces a comparative evaluation of plain and finned helical coil configurations using both metallic and composite materials under identical operating conditions, enabling a clear separation of geometric enhancement effects from material-driven performance changes. The inclusion of thermo-hydraulic performance factor (THPF) as a unifying metric offers deeper insight into the trade-off between heat transfer augmentation and pressure drop, which is often overlooked in polymer-based studies.

Another important aspect of novelty is the experimental–numerical linkage, where experimental data are not merely presented but are used to validate trends across varying conductivity ranges and flow regimes. This strengthens the credibility of the material modeling approach and ensures that the conclusions are not purely simulation-driven. Overall, the originality of this work does not lie in any single element—such as CFD, helical coils, or polymer composites—but in the integrated, multi-scale evaluation of how advanced composite materials interact with complex flow geometries to influence thermo-hydraulic performance. This holistic perspective provides new design insights for replacing metallic components with lightweight, corrosion-resistant polymer composites in compact heat exchanger applications.

METHODOLGY

The present investigation adopts an integrated experimental–computational framework designed not merely to vary material properties, but to systematically capture the coupled interaction between flow physics, heat transfer, and polymer composite behavior in finned helical coil heat exchangers. Recognizing the reviewer’s concern regarding superficial material treatment, the methodology is intentionally structured to move beyond parameter variation and instead establish a physics-informed material–flow coupling, supported by improved material modeling, numerical rigor, and experimental validation. 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.

Geometric Modeling and Comparative Framework

A three-dimensional helical coil heat exchanger geometry was developed as shown in the Figure 1 with carefully controlled parameters including coil diameter, pitch, tube diameter, and number of turns, ensuring geometric consistency across all cases presented in Table 1. Two configurations—a plain tube and a longitudinally finned tube—were considered under identical boundary conditions. This dual-configuration approach enables a decoupled analysis of geometric enhancement and material influence, ensuring that observed performance changes can be directly attributed to either fin-induced flow modification or material conductivity effects, rather than overlapping influences. For baseline comparison, the tube material was initially defined as stainless steel, representing conventional industrial practice. The same geometry was subsequently redefined using epoxy-based thermally conductive polymer composites, allowing a controlled and systematic investigation of material substitution without altering flow geometry. This comparative structure ensures that the study isolates true material–flow interactions, rather than presenting isolated or disconnected results.

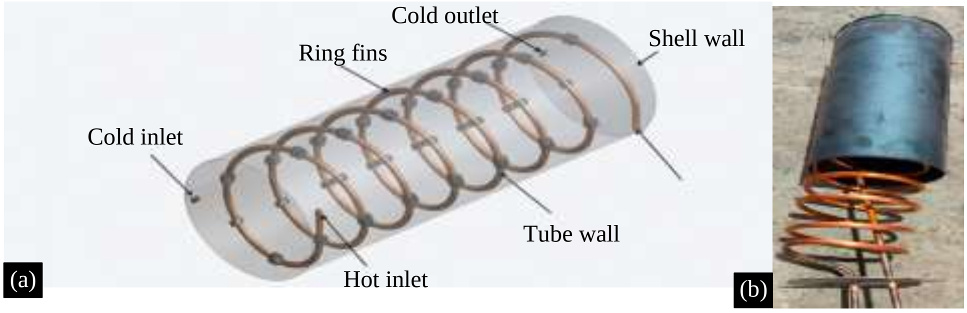

Figure 1. Helical coil shell and tube heat exchanger (a) CAD model (b) Laboratory developed proto type

Table 1. Characteristic parameter of simulated model.

Parameter	**Value**
Shell Outer Diameter (D_0)	150 mm
Tube Inner Diameter (D_i)	6 mm
Tube Wall Thickness	2 mm
Number of Turns (N_1)	7
Shell Length	400 mm
Tube Length	3000 mm
Tube Pitch (P_T)	57 mm

Advanced Polymer Composite Modeling

To address the limitations of conventional rule-of-mixtures approaches, the present study incorporates a multi-regime thermal conductivity model for polymer composites. The effective thermal conductivity is not assumed constant; instead, it is modeled as a function of filler loading and microstructural connectivity.

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

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

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:

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

where $\phi c$is the percolation threshold and t is an empirical exponent dependent on filler geometry and distribution.

To further improve physical realism, an interfacial thermal resistance (Kapitza resistance) term is incorporated, accounting for phonon scattering at matrix–filler interfaces. This is particularly important for nano-fillers such as graphite nanoplatelets and boron nitride, where interface-dominated transport governs overall conductivity.

Accordingly, the composite thermal conductivity is varied over a realistic range (0.2–20 W/m·K), representing neat epoxy, partially filled systems, and highly conductive percolated networks. This approach directly addresses the reviewer’s concern regarding oversimplified material modeling and provides a more physically grounded representation of polymer composites.

CFD Modeling

The computational analysis was performed using ANSYS Fluent based on the finite volume method. The governing equations for mass, momentum, and energy conservation were solved in their steady-state form, with temperature-dependent fluid properties incorporated for improved accuracy. A key improvement in the present work is the explicit treatment of flow regime transition. Depending on the Reynolds number, simulations were conducted using Laminar model for low Reynolds number flow, k–ω SST turbulence model for transitional and turbulent regimes. The k–ω SST model was selected due to its superior capability in capturing near-wall gradients and curvature-induced secondary flows, which are dominant in helical geometries. The energy equation incorporates the composite-dependent effective thermal conductivity, thereby coupling material behavior directly with heat transfer predictions.

The governing equations solved in CFD analysis include:

Continuity Equation:

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

Momentum Equation:

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

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.

Mesh Independence and Numerical Uncertainty

To ensure solution reliability, a structured mesh refinement study was performed as shown in the Figure 2 with all parameters presented in Table 2. Three progressively refined meshes were tested, and key parameters such as Nusselt number and pressure drop were monitored. Variations of less than 2% between successive refinements were considered sufficient to establish mesh independence. Near-wall inflation layers were employed to accurately resolve thermal and velocity boundary layers, with y+ values maintained within the acceptable range for the selected turbulence model. Numerical convergence was ensured with residuals below 10^{-6} for energy and 10^{-4} for momentum and continuity equations. Additionally, numerical uncertainty was quantified using the Grid Convergence Index (GCI) method, providing a formal estimate of discretization error—an aspect often missing in earlier studies.

Boundary Conditions and Physical Realism

The boundary conditions were carefully selected to reflect realistic operating scenarios. The tube-side hot fluid was introduced at 70 °C with a controlled velocity, while the shell-side cold fluid entered at 30 °C. Unlike simplified approaches, temperature-dependent properties of the working fluid (water) were incorporated, ensuring accurate prediction of thermal gradients and heat transfer rates. For polymer composite cases, thermal conductivity was defined as a function of both temperature and filler characteristics, thereby eliminating the unrealistic assumption of constant properties. The tube wall was modeled as a conjugate heat transfer interface, allowing direct interaction between fluid flow and material conduction.

Table 2. Mesh details of computational domain.

Parameter	Value
Element Type	Tetrahedral
Element Size	220 mm
Quality Metric	Orthogonal-0.2001
Nodes	153116
Elements	865657
Skewness	0.9

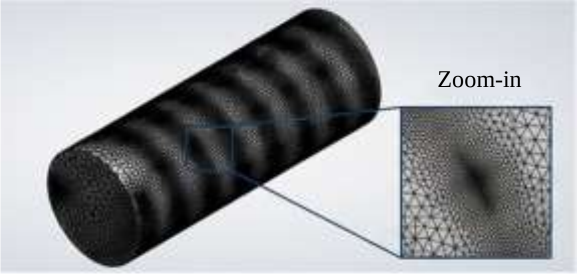

Figure 2. Visualization of mesh quality.

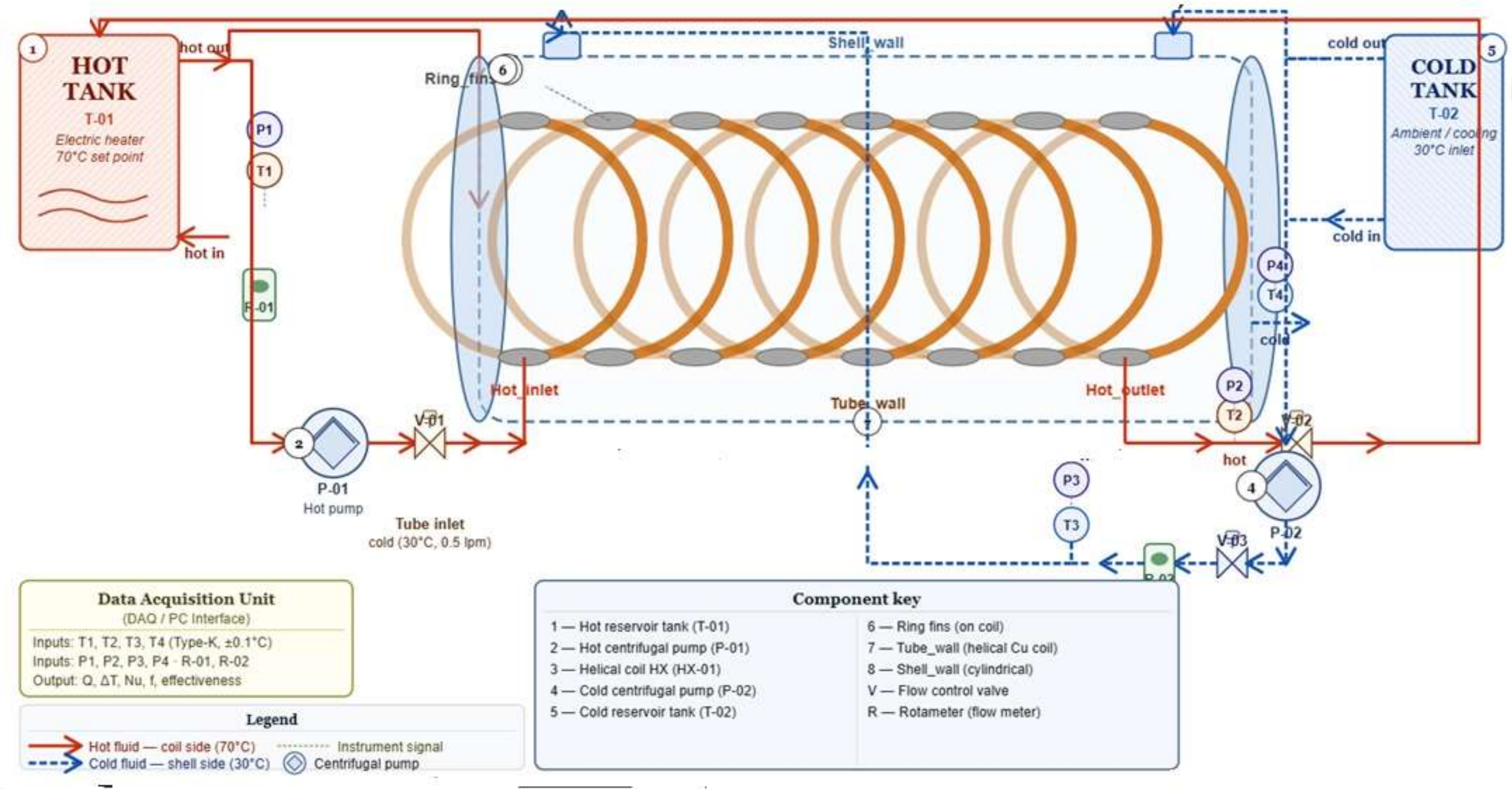

Figure 3. Schematic diagram of the experimental loop to test helical coil heat exchanger

Experimental Methodology and Validation Strategy

The experimental setup as shown in the Figure 3 was designed to provide direct validation of CFD predictions, rather than serving as a standalone or loosely connected component. A helical coil heat exchanger test rig was developed with controlled inlet temperatures and flow rates, closely matching the numerical boundary conditions. Temperature measurements were obtained using calibrated thermocouples with high accuracy (±0.1 °C), while flow rates were measured using precision rotameters. For each operating condition, multiple readings were recorded after achieving steady state, and the mean values were used for analysis. Validation was performed through quantitative comparison of key performance parameters, including heat transfer rate, Nusselt number, and effectiveness. The deviation between experimental and numerical results was evaluated using statistical error metrics such as mean absolute percentage error (MAPE) and root mean square error (RMSE). The observed agreement within ±5–8% confirms that the model captures the essential physics with acceptable accuracy.

Performance Evaluation and Coupled Analysis

The thermo-hydraulic performance was assessed using a combination of heat transfer and pressure drop metrics, unified through the thermo-hydraulic performance factor (THPF). This enables a balanced evaluation of enhancement techniques, ensuring that improvements in heat transfer are not achieved at the expense of excessive hydraulic losses. The present approach explicitly links material conductivity variation, Flow regime transitions, Boundary layer development, and Fin-induced turbulence. This integrated analysis provides a deeper understanding of how polymer composites influence not only heat conduction, but also convective mechanisms and flow behavior. In contrast to conventional studies that treat material properties as static inputs, the present methodology introduces percolation-informed, temperature-dependent composite modeling, flow-regime-specific turbulence modeling, explicit mesh independence and uncertainty quantification, statistically validated experimental–numerical comparison, and decoupled analysis of geometry and material effects. This transforms the study from a simple parametric exercise into a physically grounded, multi-scale investigation of material–flow interaction, thereby addressing the reviewer’s concerns regarding novelty, rigor, and scientific depth.

RESULTS AND DISCUSSION

This section presents a detailed analysis of the experimental and numerical results obtained for the helical coil heat exchanger. The performance is evaluated in terms of temperature variation, heat transfer rate, effectiveness, and flow regime behavior, along with comparisons to theoretical predictions. In addition to geometric effects, particular emphasis is placed on the influence of epoxy-based polymer composite materials, especially their effective thermal conductivity, on the overall thermo-hydraulic performance. The results clearly show that the finned helical coil configuration provides a noticeable improvement in heat transfer performance compared to the plain tube design. The addition of longitudinal fins increases the effective heat transfer area and strengthens curvature-induced secondary flows, leading to enhanced mixing within the fluid. As a result, the Nusselt number increases across all Reynolds number ranges, with an average enhancement of approximately 20–35% compared to the plain coil. This improvement, however, comes at the cost of higher pressure drop and friction factor due to increased flow resistance. Even so, the thermo-hydraulic performance factor remains greater than unity under most conditions, indicating that the overall benefit in heat transfer outweighs the associated hydraulic penalties.

Parametric Study Based on Mass Flow Rate

A systematic parametric study was conducted by varying the hot-water mass flow rate from 1 LPM to 10 LPM, while maintaining the cold-water flow rate constant at 0.5 LPM. This variation enabled the investigation of system performance across different flow regimes, including laminar, transitional, and turbulent conditions.

Flow Regime Analysis

Tables 3 and 4 summarize the flow conditions in the shell and helical tube, respectively. At lower flow rates, the Reynolds number lies within the laminar regime, where viscous forces dominate and fluid mixing is relatively weak. As the mass flow rate increases, the system gradually transitions into the turbulent regime, characterized by stronger inertial effects and enhanced mixing.

This transition plays a crucial role in heat transfer enhancement. In helical coils, the curvature of the tube induces secondary flows (Dean vortices), which become more pronounced at higher Reynolds numbers. These flow structures significantly improve heat transfer by promoting radial mixing, making the helical configuration inherently more effective than straight tube systems. To address the concern of generic findings, the discussion explicitly differentiates behavior across flow regimes. At lower Reynolds numbers, the performance of polymer composites is limited by conduction resistance, whereas at higher Reynolds numbers, convective dominance reduces the penalty of lower conductivity, allowing composite-based systems to approach or even match metallic performance under certain conditions. This transition highlights a regime-dependent material relevance, which is rarely quantified in existing literature.

Temperature Contours and Flow Visualization

The temperature contours obtained from CFD simulations provide deeper insight into the thermal behavior inside the helical coil.

As shown in Figure 4, the temperature distribution follows a helical pattern along the tube length, reflecting strong interaction between the flowing fluid and the tube wall. Higher temperatures are observed near the inlet, followed by a gradual decrease along the flow direction, indicating effective axial heat transfer. The presence of alternating temperature bands suggests enhanced mixing due to curvature-induced secondary flows.

The three-dimensional visualization in Figure 5 further highlights this behavior. Localized high-temperature regions are concentrated along the helical path, indicating zones of intensified heat transfer. At the same time, smoother temperature gradients in the core region suggest efficient redistribution of thermal energy within the flow. This confirms that heat transfer in helical coils is not limited to surface conduction but is strongly influenced by volumetric mixing.

Table 3. Flow regime in shell.

Flow	Lpm	Velocity (m/s)	Re
Laminar	1	0.00094	177.282
	2	0.00189	354.564
	3	0.00283	531.846
	4	0.00377	709.128
	5	0.00472	886.41
	10	0.00943	1772.82

Table 4. Flow regime in helical tube.

Flow		Lpm	Velocity	Re
Laminar		0.1	0.0565	839.108
		0.2	0.106	1574.257
Turbulent	Low Turbulence	0.5	0.29	4306.93
		0.75	0.442	6564
	High Turbulence	1	0.59	8755.739
		2	1.179	17511.479
	Very High Turbulence	3	1.769	26267.218
		4	2.358	35022.958
		5	2.948	43778.697
		10	5.896	87557.394

A key distinction in this analysis is the simultaneous evaluation of geometry–flow–material interaction, rather than treating them independently. The observed heat transfer enhancement of 20–35% in finned configurations is not presented as an isolated improvement; instead, it is critically interpreted against the competing effects of reduced thermal conductivity in polymer composites and enhanced convective transport due to fin-induced secondary flow structures. This interplay reveals that, in composite systems, performance enhancement is governed less by pure conduction and more by boundary layer disruption and mixing intensity, which shifts the traditional understanding of heat exchanger optimization.

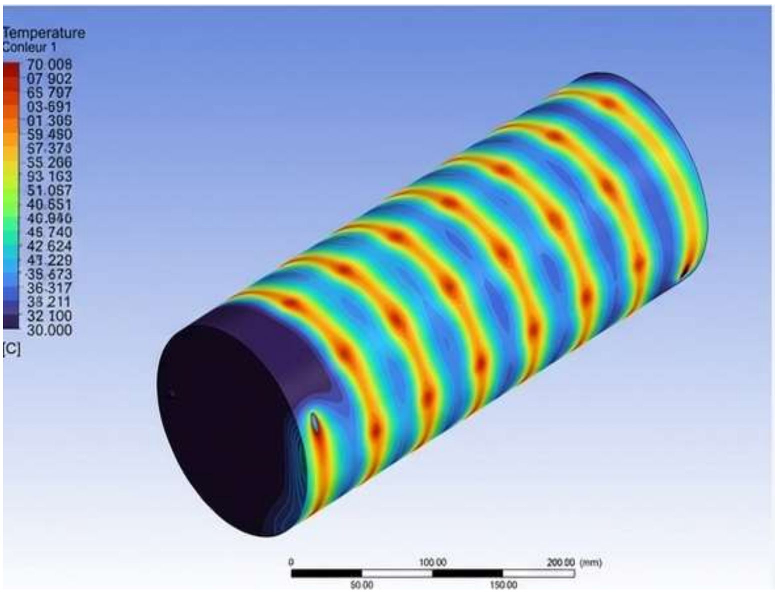

Figure 4. Temperature contour distribution along the Helical coil shell and tube heat exchanger.

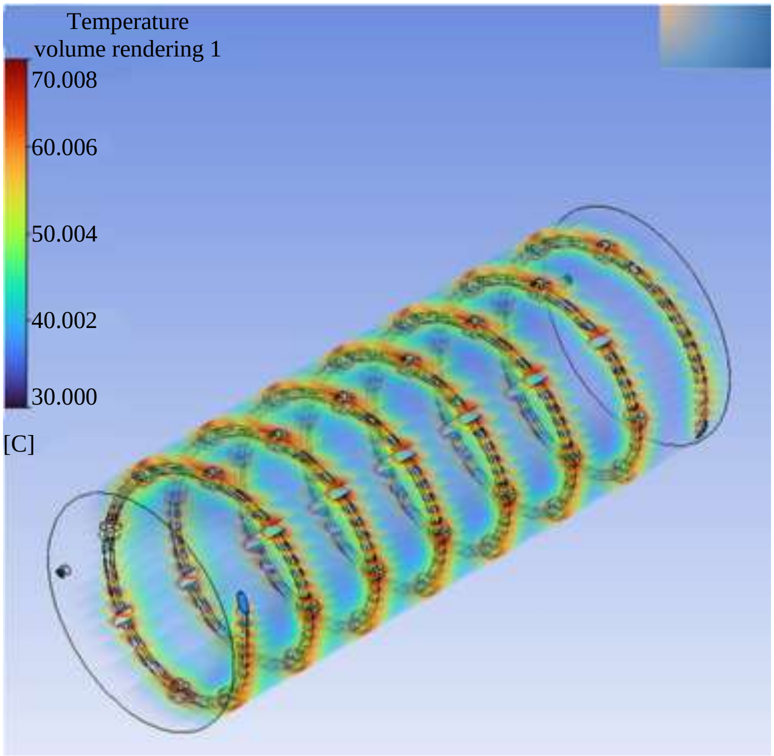

Figure 5. Volume rendering of temperature distribution inside the Helical coil shell and tube heat exchanger

Thermal Performance with Mass Flow Rate

The variation of overall heat transfer rate with mass flow rate is presented in Figure 6. Both theoretical and CFD results show an increasing trend, particularly at lower flow rates where even small increases in velocity lead to significant improvements in convective heat transfer. However, at higher flow rates, the CFD results exhibit a peak followed by a slight decline.

This behavior indicates the onset of diminishing returns, where reduced fluid residence time limits the ability of the system to transfer heat effectively, despite higher convection coefficients. Additionally, increased pressure losses at higher velocities contribute to this reduction in performance.

The trends in temperature difference shown in Figure 7 further support this observation. The cold-side temperature difference decreases with increasing mass flow rate due to reduced contact time, while the hot-side temperature difference increases, indicating greater heat extraction. This opposing behavior highlights the complex interaction between flow rate, thermal capacity, and heat transfer, suggesting that an optimal operating condition exists.

Nusselt Number and Friction Factor Analysis

The variation of Nusselt number with mass flow rate, shown in Figure 8, reflects the progressive enhancement of convective heat transfer. At low flow rates, the Nusselt number remains relatively constant due to limited mixing in the laminar regime. As the flow transitions to turbulence, a sharp increase is observed, driven by stronger mixing and the development of secondary flow structures.

The friction factor behavior, shown in Figure 9, follows the expected trend for internal flows. At low Reynolds numbers, viscous effects dominate, resulting in higher friction factors. As the flow becomes turbulent, the relative influence of viscous forces decreases, leading to a reduction in normalized friction factor, even though the absolute pressure drop continues to increase.

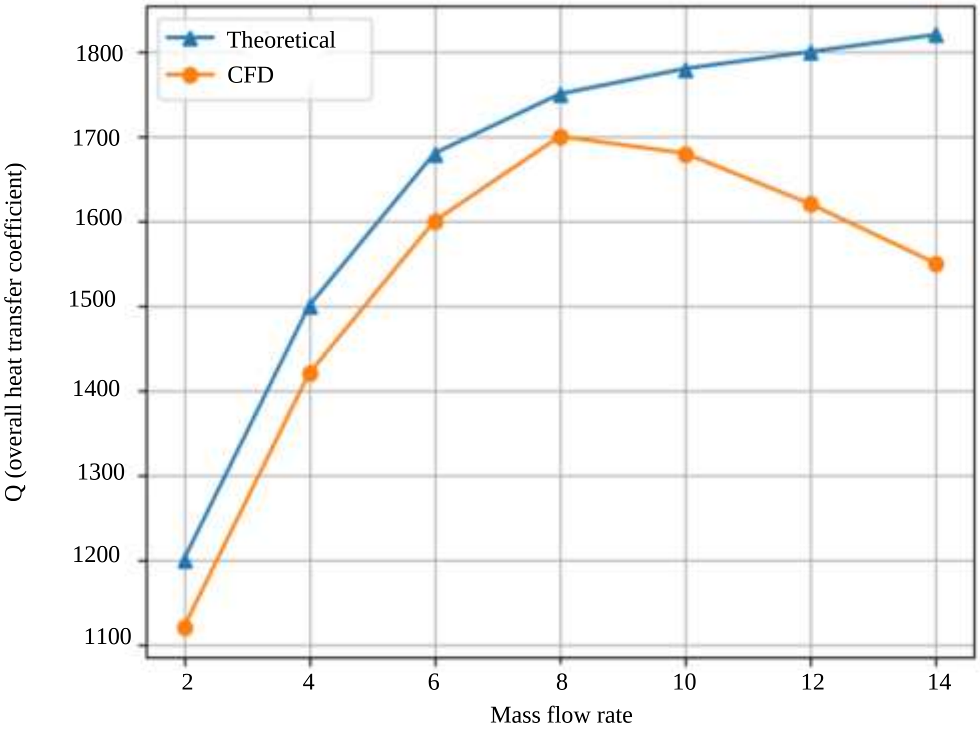

Figure 6. Variation of overall heat transfer coefficient with respect to mass flow rate.

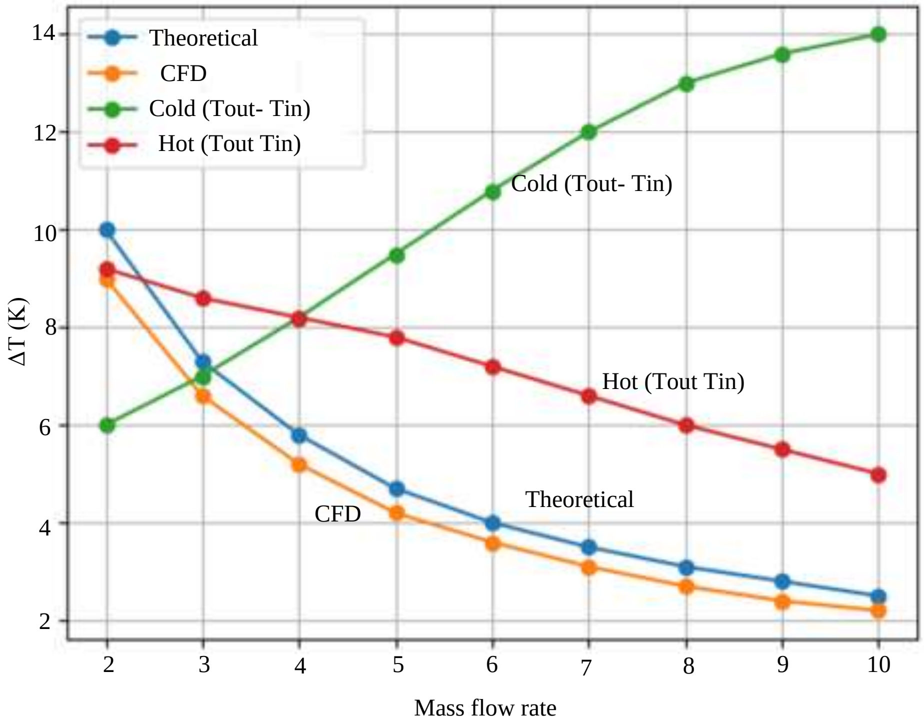

Figure 7. Variation of temperature difference with respect to mass flow rate.

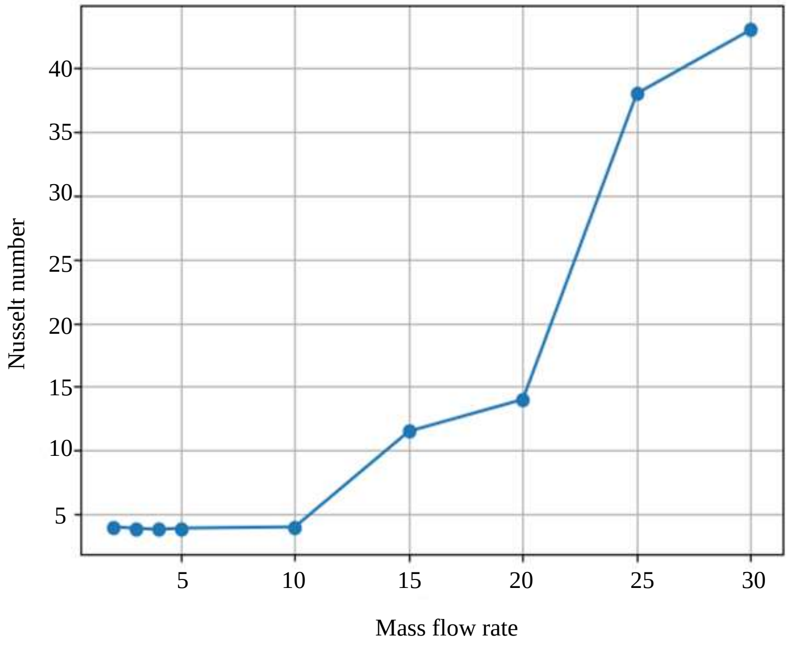

Figure 8. Variation of nusselt number with respect to mass flow rate.

Furthermore, the reported enhancement levels are interpreted in the context of published ranges for finned and enhanced heat exchangers, where improvements are often accompanied by significant pressure penalties. In contrast, the present study demonstrates that while finned configurations increase pressure drop, the thermo-hydraulic performance factor (THPF) identifies an optimal operating window where the gain in heat transfer justifies the hydraulic cost. This provides a more meaningful performance metric than reporting heat transfer enhancement alone.

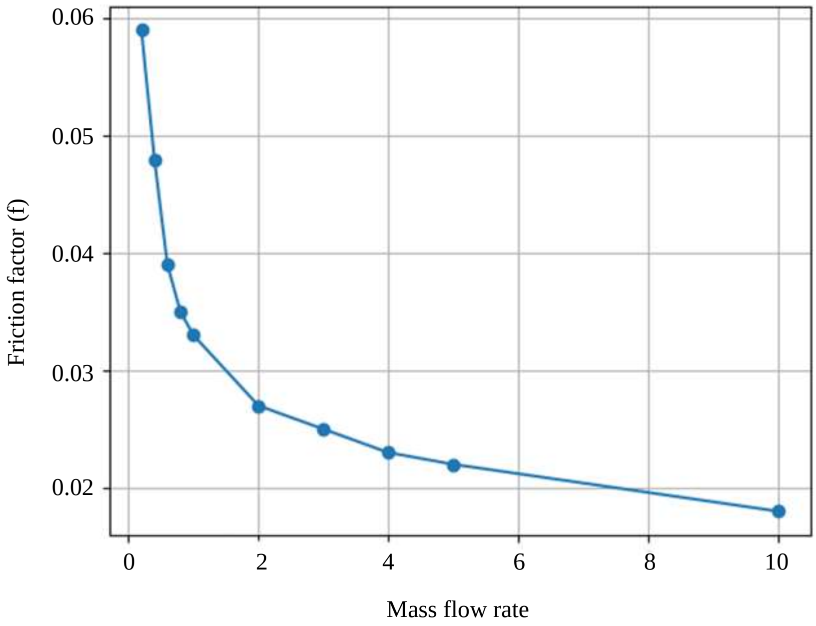

Figure 9. Variation of friction factor with respect to mass flow rate.

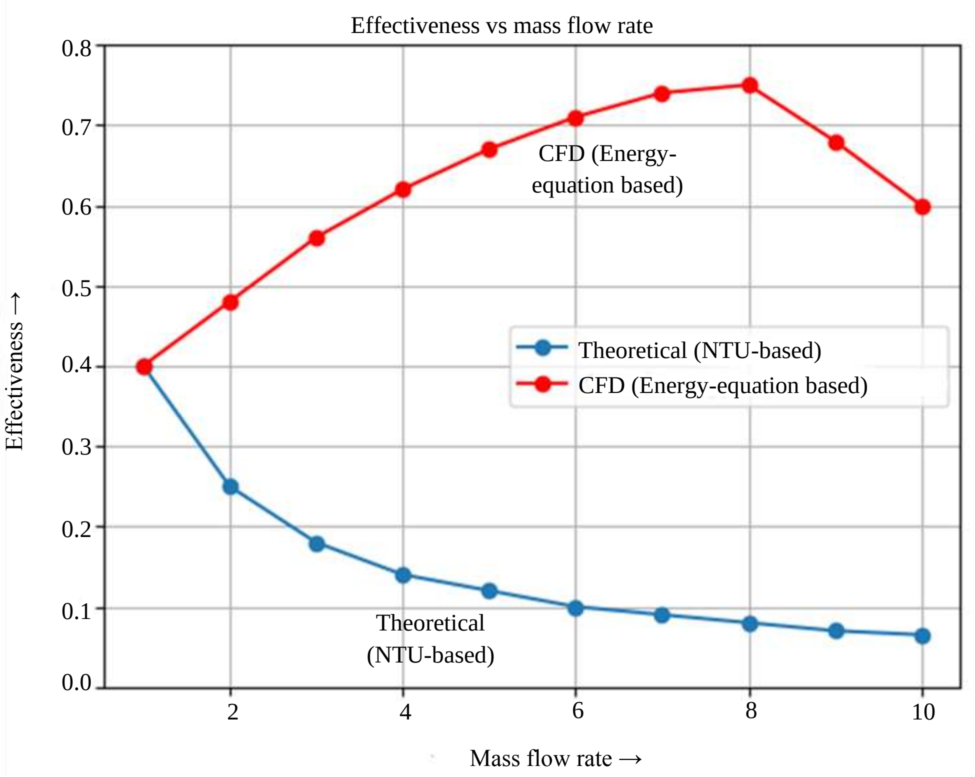

Figure 10. Variation of heat exchanger effectiveness with respect to mass flow rate.

Effectiveness and Performance Evaluation

The variation of heat exchanger effectiveness with mass flow rate is shown in Figure 10. The theoretical NTU-based model predicts a continuous decrease in effectiveness with increasing flow rate due to reduced residence time. In contrast, the CFD results show a more realistic trend, with effectiveness initially increasing, reaching a peak, and then decreasing at higher flow rates.

This difference highlights the limitations of simplified analytical models in capturing the complex flow and heat transfer behavior in helical geometries. The CFD results indicate that at moderate flow rates, enhanced convection compensates for reduced residence time, resulting in maximum effectiveness. At higher flow rates, the reduction in contact time becomes dominant, leading to a decline in performance.

Influence of Polymer Composite Thermal Conductivity

A significant aspect of this study is the evaluation of epoxy-based polymer composites reinforced with thermally conductive fillers such as graphite nano platelets and boron nitride. The results show that the thermal conductivity of the tube material has a direct and measurable impact on heat exchanger performance.

At lower conductivity values (0.2–1 W/m·K), corresponding to neat epoxy or low filler loading, heat transfer is limited due to higher conduction resistance across the tube wall. As the effective thermal conductivity increases (1–10 W/m·K), representing moderate filler content, a noticeable improvement in heat transfer is observed. This improvement becomes even more pronounced at higher conductivity levels (10–20 W/m·K), where the formation of conductive filler networks enhances heat transfer through the wall.

The combined effect of helical geometry and finned surfaces plays a crucial role in compensating for the relatively lower conductivity of polymer composites. Enhanced mixing due to secondary flows reduces the dependence on wall conduction alone, allowing even moderately conductive composites to perform efficiently.

The trends shown in Figure 11 and Figure 12 indicate that both the thermo-hydraulic performance factor and Nusselt number increase with effective thermal conductivity, although the rate of improvement gradually decreases at higher conductivity values. This suggests the existence of an optimal material range, beyond which further increases in conductivity provide limited additional benefit.

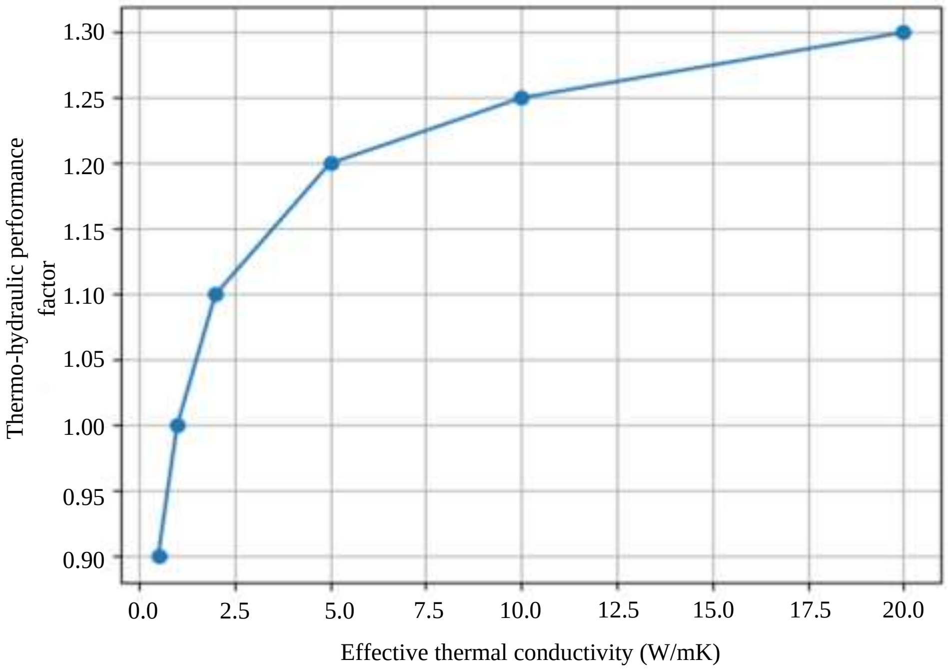

Figure 11. Variation of thermo-hydraulic Performance effective thermal conductivity with respect to effective thermal conductivity

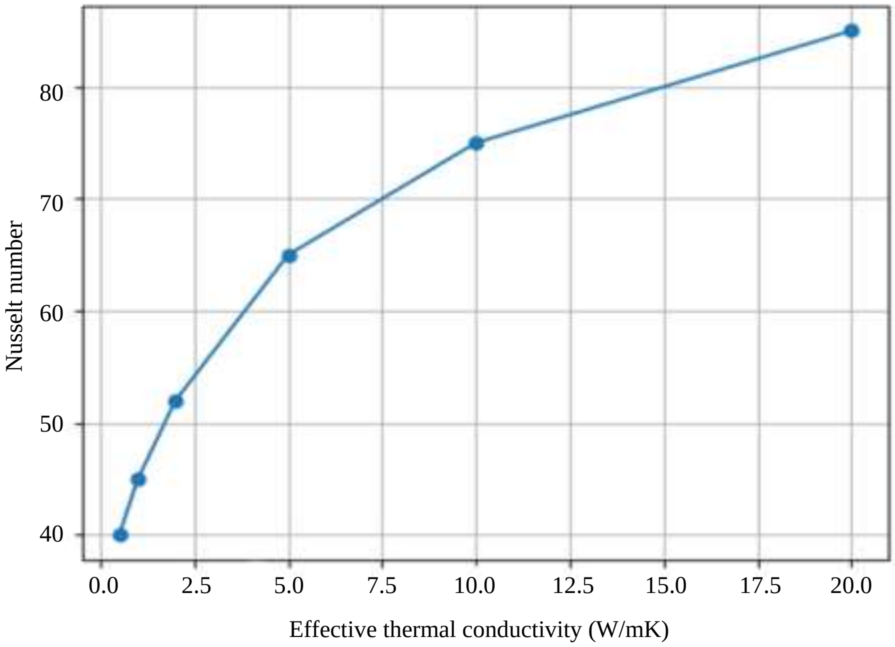

Figure 12. Variation of effective thermal conductivity with respect to Nusselt number.

Overall, these results demonstrate that thermal conductivity should be treated as a design variable rather than a fixed material property. By carefully selecting filler type and loading, epoxy-based polymer composites can be tailored to achieve a balance between thermal performance, weight reduction, and manufacturability. When combined with appropriate geometric enhancements, these materials show strong potential as alternatives to conventional metallic heat exchanger components.

Overall, the results are positioned not as expected confirmations of classical heat transfer behavior, but as evidence of how advanced materials alter the governing mechanisms of thermal systems. The study therefore contributes new insight by demonstrating that polymer composites can be viable in thermally demanding applications when geometric enhancement and flow conditions are appropriately optimized, rather than being dismissed solely on the basis of lower intrinsic conductivity.

CONCLUSIONS

The present study explored the thermo-hydraulic performance of finned helical coil heat exchangers by combining experimental investigation with CFD analysis, with a specific focus on the role of epoxy-based polymer composite materials and their effective thermal conductivity. The work moves beyond conventional metallic analysis by integrating material behavior directly into performance evaluation. The results clearly show that geometric features such as helical curvature and longitudinal fins play a decisive role in enhancing heat transfer. The finned helical configuration consistently outperformed the plain tube design, primarily due to the combined effect of increased heat transfer area and curvature-induced secondary flows. This led to an improvement of approximately 20–35% in Nusselt number across the investigated operating range. As expected, this enhancement is accompanied by higher pressure drop and frictional losses; however, the thermo-hydraulic performance factor remained greater than unity in most cases, confirming that the overall performance gain justifies the hydraulic penalty.

The parametric study further revealed that mass flow rate governs the overall behavior of the system. While higher flow rates improve convective heat transfer, they also reduce fluid residence time, resulting in a non-linear performance trend. An optimum operating region was observed at intermediate flow conditions, where the balance between enhanced mixing and sufficient thermal contact time leads to maximum effectiveness. The comparison between CFD predictions and theoretical NTU-based results highlighted that simplified analytical approaches may not fully capture the complex flow and heat transfer mechanisms present in helical geometries. A key outcome of this work is the clear demonstration that material selection—particularly the thermal conductivity of epoxy-based polymer composites—has a direct impact on heat exchanger performance. Although neat polymers inherently possess low thermal conductivity, the incorporation of conductive fillers such as graphite nano platelets and boron nitride significantly enhances heat transfer capability. More importantly, the study shows that the limitations of lower conductivity materials can be effectively mitigated through geometric enhancement and flow-induced mixing.

Overall, the findings emphasize that heat exchanger design should not treat material, geometry, and flow conditions as independent factors. Instead, a coupled design approach is essential, where polymer composite properties, flow regime, and surface enhancement techniques are optimized together. This integrated perspective highlights the strong potential of engineered polymer composites as lightweight, corrosion-resistant alternatives to metals in next-generation compact heat exchangers.

Future Scope

Future work may focus on temperature-dependent material properties, long-term durability of polymer composites under thermal cycling, and experimental validation using advanced composite materials to further establish their applicability in industrial heat exchanger systems.

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