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Corrugated Tube Shell-and-Tube Heat Exchanger Using Epoxy-Based Polymer Composite Coatings for Lightweight and Efficient Thermal Systems

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Abstract

Corrugated tube geometries are widely recognized for their ability to enhance heat transfer through boundary layer disruption and secondary flow generation. In this study, a combined experimental and computational investigation is carried out to evaluate the thermo-hydraulic performance of a shell-and-tube heat exchanger incorporating corrugated stainless steel tubes integrated with an epoxy-based polymer composite coating and housed within a mild steel shell. Unlike conventional metallic systems, the present work introduces a thin layer of thermally enhanced epoxy composite reinforced with boron nitride fillers on the tube surface to reduce weight, improve corrosion resistance, and tailor thermal conductivity. A three-dimensional Computational Fluid Dynamics (CFD) model based on the finite volume method is developed to simulate conjugate heat transfer, capturing the interaction between fluid flow and composite-coated solid domains. The influence of corrugation geometry, flow rate, and effective thermal conductivity of the epoxy composite on heat transfer rate, Nusselt number, pressure drop, and overall effectiveness is systematically analyzed. Experimental validation is performed under controlled operating conditions to ensure model accuracy. The results demonstrate that corrugated tubes significantly enhance convective heat transfer due to strong flow mixing and periodic boundary layer disruption. The incorporation of epoxy-based polymer composites with optimized filler loading improves thermal performance while offering substantial advantages in terms of weight reduction and material durability. An overall enhancement of 30–55% in heat transfer performance is observed compared to plain metallic tubes, with acceptable pressure drop penalties. The study highlights the novelty of integrating polymer composite coatings with geometric modifications, establishing a coupled material–geometry approach for next-generation compact and energy-efficient heat exchanger design.

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INTRODUCTION

The growing demand for compact, energy-efficient, and durable thermal systems has significantly accelerated research in advanced heat exchanger technologies. Among these, shell-and-tube heat exchangers (STHEs) remain one of the most widely adopted configurations due to their structural robustness, operational flexibility, and suitability for high-pressure and high-temperature environments [1,2]. These systems are extensively used in power generation, chemical processing, HVAC, and thermal energy recovery applications. Despite their widespread use, conventional STHEs employing smooth tubes often suffer from limited heat transfer performance. This limitation primarily arises due to the formation of thick thermal boundary layers and relatively weak fluid mixing, particularly on the shell side. As a result, enhancing convective heat transfer without significantly increasing system complexity has become a critical area of research. To address these challenges, passive heat transfer enhancement techniques—such as fins, twisted tapes, surface roughness, and corrugations—have been widely explored. Among these, corrugated tube geometries offer a promising solution by inducing secondary flows, disrupting boundary layers, and promoting fluid mixing without requiring external energy input.

In parallel, recent advancements in material science have introduced polymer-based composites as viable alternatives to conventional metallic materials in thermal systems. Epoxy-based polymer composites, particularly those reinforced with thermally conductive fillers such as boron nitride and graphite nano platelets, offer tunable thermal conductivity, reduced weight, improved corrosion resistance, and enhanced manufacturability. These attributes make them attractive for next-generation compact heat exchanger designs. However, the integration of such polymer composites with advanced geometries like corrugated tubes introduces complex thermo-hydraulic interactions that require systematic investigation. In this context, Computational Fluid Dynamics (CFD), combined with experimental validation, provides a powerful framework to analyze flow behavior, temperature distribution, and conjugate heat transfer mechanisms in such systems.

The present study therefore focuses on evaluating the coupled effect of corrugated tube geometry and epoxy-based polymer composite coatings on the thermo-hydraulic performance of shell-and-tube heat exchangers, with an emphasis on achieving a balance between heat transfer enhancement and hydraulic losses.

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 the fundamental principles governing heat exchanger design, emphasizing the role of flow configuration, thermal resistance, and surface area in determining performance. Mukherjee [3] further provided practical design guidelines, highlighting real-world constraints such as fouling, pressure drop, and manufacturability. With the increasing demand for enhanced thermal performance, researchers have focused on improving shell-side heat transfer, which is often the limiting factor in overall exchanger efficiency. Early numerical investigations by Pu et al. [4] demonstrated that complex geometries such as U-tube configurations generate secondary flows that improve heat transfer. Similarly, Ozden and Tari [5] used CFD to analyze shell-side flow behavior and highlighted the importance of baffle spacing in improving thermal performance. Thundil Karuppa Raj et al. [6] extended this work by investigating inclined baffle configurations, showing improved flow distribution and heat transfer.

The influence of tube geometry on thermo-hydraulic performance has also been widely explored. Li et al. [7] reported that curvature effects significantly influence both heat transfer and pressure drop characteristics in U-bend tubes. Experimental work by Maheshwari and Trivedi [8] demonstrated that corrugated and modified tube geometries enhance heat transfer due to improved fluid mixing, although at the cost of increased pressure losses. Gadave and Kothmire [9] further confirmed that tube geometry plays a critical role in determining the overall thermo-hydraulic performance of shell-and-tube heat exchangers. Recent studies have increasingly focused on surface modification techniques such as fins and structured surfaces. Raje and Dhiman [10] conducted a detailed CFD analysis of annular finned tubes and showed that geometric parameters significantly influence both heat transfer and friction characteristics. Pasupuleti et al. [11] and Rajeshkumar et al. [12] demonstrated that finned tube configurations offer substantial improvement in heat transfer compared to plain tubes. Jalil and Goudarzi [13] further highlighted that advanced fin geometries, such as nozzle- and diffuser-shaped fins, provide superior performance compared to conventional straight fins.

In parallel, the application of CFD has expanded significantly for analyzing complex thermal systems. Yadav and Kothmire [14], Shindge et al. [15], and Damdhar et al. [16] demonstrated the effectiveness of CFD in predicting flow behavior and pressure losses in engineering applications such as exhaust systems and catalytic converters. Similarly, Nawale et al. [17] and Nagarhalli et al. [18] investigated heat transfer enhancement techniques such as twisted tapes and finned surfaces, confirming improved convective heat transfer. Powar et al. [19] studied the effect of surface roughness on boundary layer development, emphasizing its role in enhancing thermal performance. Further advancements in numerical analysis have enabled the study of diverse thermal systems. Kanate et al. [20] analyzed heat sinks using CFD and demonstrated the importance of geometric optimization, while Londhe et al. [21] and Deshmukh et al. [22] investigated heat transfer in economizer tubes and composite vessels, respectively, highlighting the combined influence of geometry and material properties. These studies collectively establish CFD as a reliable tool for thermo-hydraulic performance evaluation.

Alongside geometric enhancements, material innovation has emerged as a critical factor in modern heat exchanger design. Traditional metallic materials, while offering high thermal conductivity, are often associated with higher weight and susceptibility to corrosion. In this context, polymer composites have gained significant attention due to their lightweight nature, corrosion resistance, and tunable thermal properties. Huang and Jiang [23] investigated core–shell structured polymer composites and demonstrated their effectiveness in thermal management applications. Gu et al. [24] provided a comprehensive review of hybrid filler systems, showing that the incorporation of multiple fillers significantly enhances thermal conductivity. Yu et al. [25] reported that graphite nanoplatelet-reinforced epoxy composites exhibit substantially improved thermal performance. Kim et al. [26] emphasized the importance of filler dispersion in achieving uniform thermal conductivity, while Li et al. [27] demonstrated the effectiveness of boron nitride-based polymer composites in advanced heat transfer applications. More recent studies have further explored the integration of polymer composites into thermal systems. Singh et al. [28] highlighted the role of epoxy-based composites in lightweight heat exchanger applications, while Patel and Mehta [29] demonstrated improved thermo-mechanical performance of polymer-coated heat exchanger surfaces under varying thermal loads.

Despite these extensive investigations, most studies have focused either on geometric enhancement or material innovation independently. The combined effect of corrugated tube geometry and polymer composite materials, particularly in shell-and-tube heat exchangers, remains insufficiently explored. This gap highlights the need for a comprehensive study that integrates both aspects to achieve optimized thermo-hydraulic performance.

Identified Research Gaps

Based on the literature, the following key research gaps are identified:

1. Limited studies are available on the combined effect of corrugated tube geometry and polymer composite materials in shell-and-tube heat exchangers.
2. Experimental validation of CFD models for corrugated geometries integrated with polymer coatings is scarce.
3. The influence of polymer composite thermal conductivity on overall thermo-hydraulic performance is not systematically quantified.
4. Most existing studies focus either on geometry or material enhancement independently, with minimal emphasis on their coupled interaction.
5. There is a lack of comprehensive evaluation using performance parameters such as Nusselt number, friction factor, and Performance Evaluation Criterion (PEC) for composite-based corrugated systems.

In view of the above research gaps, the present study aims to:

1. Investigate corrugated tube geometries as an effective alternative to conventional smooth tubes for enhanced heat transfer.

2. Evaluate the role of epoxy-based polymer composite coatings in improving thermal performance while reducing weight and corrosion effects.
3. Quantify the impact of corrugation on heat transfer enhancement, pressure drop, and pumping power.
4. Perform a comparative thermo-hydraulic assessment between corrugated and plain tube configurations using key performance indicators such as Nusselt number, friction factor, and PEC.
5. Establish a coupled material–geometry design framework for developing efficient, lightweight, and high-performance heat exchangers.

Methodology

The present study adopts a comprehensive approach that integrates geometric modeling, polymer composite material characterization, experimental validation, and computational fluid dynamics (CFD) analysis to evaluate the thermo-hydraulic performance of a corrugated tube shell-and-tube heat exchanger. Particular emphasis is placed on understanding how epoxy-based polymer composite coatings influence heat transfer behavior when coupled with corrugated geometries. 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.

Experimentation

The experimental investigation was carried out using a shell-and-tube heat exchanger configured for both parallel-flow and counter-flow operation, as illustrated in Figure 1. The setup consisted of essential components including a heater, centrifugal pump, flow control valves, rotameters, and thermocouples. Temperature measurements were obtained using calibrated Type-K thermocouples with a wide operating range (–200 °C to 1250 °C). After calibration, an accuracy of ±0.1 °C was achieved, ensuring reliable thermal data acquisition. The flow rates of hot and cold water were measured using rotameters with a range of 0–10 L/min. The hot fluid inlet temperature was maintained at 70 °C, while the cold fluid inlet temperature was fixed at 30 °C. For each operating condition, the system was allowed to reach steady state before recording data. Multiple readings were taken to minimize experimental uncertainty. The experimental results were used to evaluate key performance parameters such as heat transfer rate and effectiveness and to validate CFD predictions.

Computational Fluid Dynamics (CFD) Modeling

The computational analysis was performed using ANSYS Fluent, a widely used CFD solver based on the Finite Volume Method (FVM). The FVM approach ensures conservation of mass, momentum, and energy within each control volume, making it well-suited for complex geometries such as corrugated tubes. The three-dimensional geometry was created in ANSYS Design Modeler, including the shell, corrugated tubes, and fluid domains. Shared topology was applied to ensure proper coupling between solid and fluid regions for conjugate heat transfer analysis.

Geometric Modelling and Material Definition

A three-dimensional model of a shell-and-tube heat exchanger with corrugated stainless steel tubes enclosed within a mild steel shell was developed a shown in the Figure 2. The geometric parameters of the CAD model is presented in Table 1. The corrugations were introduced along the tube length to enhance surface area and induce secondary flow structures. For comparison, a plain tube configuration with identical geometric parameters was also considered. In the baseline configuration, the tubes were modeled using stainless steel and the shell using mild steel. To incorporate material innovation, the tube surface was further modified by introducing a thin epoxy-based polymer composite coating, reinforced with thermally conductive fillers such as boron nitride (BN). This coating was assumed to be uniformly distributed along the corrugated surface, enabling a realistic representation of advanced coated heat exchanger designs. The polymer composite layer was characterized by its effective thermal conductivity, density, and specific heat capacity. Unlike conventional metals, the thermal properties of the epoxy composite were varied parametrically to capture the influence of filler loading and dispersion on heat transfer performance.

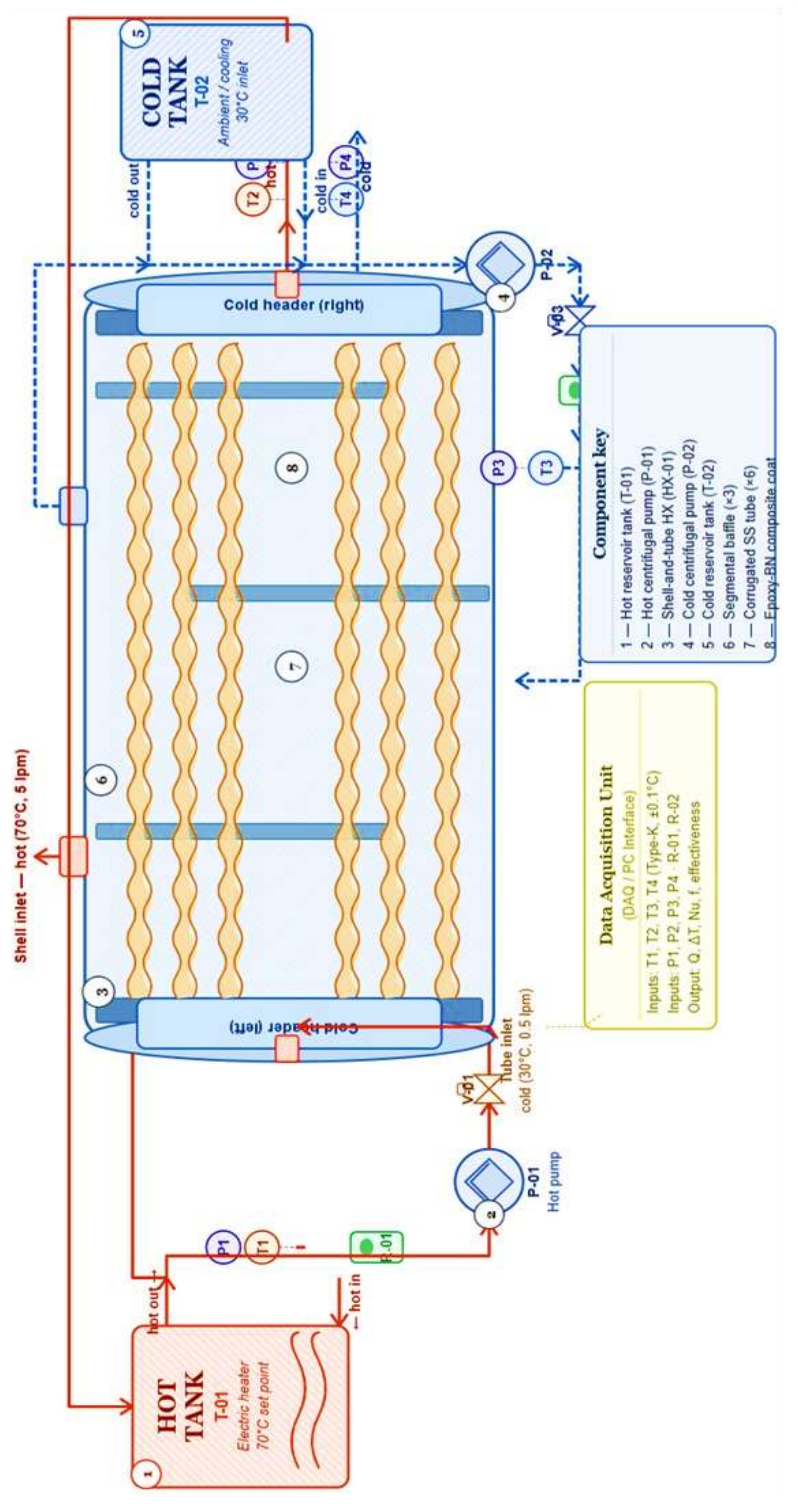

Figure 1. Schematic diagram of the experimental loop to test corrugated tubes shell and tube heat exchanger.

Table 1. Geometric parameters of the simulated model.

Parameter	Value
Shell Inner Diameter (Ds)	50 mm
Tube Outer Diameter (Do)	6 mm
Tube Wall Thickness	2 mm
Tube Inner Diameter (ID)	4 mm
Number of Tubes (Nt)	6
Tube/Shell Length	400 mm
Tube Pitch (PT)	12.5 mm

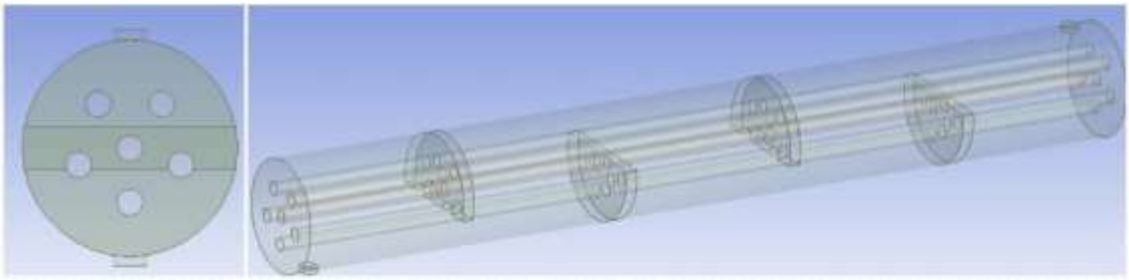

Figure 2. CAD Model designed for straight tube, shell and tube heat exchanger with respect to baffles placed at equal distance.

Table 2. Boundary conditions for the simulation: inlets and outlets

Boundary zone name(s)	Details
Inlets	Hot inlet (Tubes) Velocity =5 lpm, Temp = 30◦ C (299 K)
	Cold inlet (Shell) Velocity = 0.5 lpm, Temp = 70◦ C (323 K)
Outlets	Hot outlet, Cold outlet, Pressure outlet, Gauge Pressure = 0 Pa

Boundary Conditions

The boundary conditions were selected to closely replicate experimental operating conditions. The tube-side inlet was defined as a hot velocity inlet with a uniform velocity of 0.29 m/s and a temperature of 70 °C. The shell-side inlet was specified as a cold velocity inlet with a temperature of 30 °C. Both the tube-side and shell-side outlets were modeled as pressure outlets with zero gauge pressure. The tube wall was treated as a coupled wall, allowing heat conduction through both the metallic substrate and the epoxy-based polymer composite coating. The shell wall was modeled as mild steel with a specified thickness and assumed to be thermally insulated from the surroundings. The boundary conditions used for carrying out numerical simulations are presented in Table2.

Polymer Composite Material Modeling

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:

$keff\propto(\phi-\phi c)t$ for $\phi > \phi c$

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

Mesh Generation

The computational domain was discretized using a high-quality unstructured mesh with tetrahedral elements as shown in the Figure 3 and presented in Table 3. Special attention was given to near-wall regions by incorporating inflation layers to accurately capture velocity and thermal boundary layers, especially around corrugated surfaces where strong gradients are expected. Mesh quality was ensured by maintaining acceptable skewness and orthogonality. A mesh independence study was conducted to confirm that further refinement did not significantly affect the results, ensuring numerical reliability.

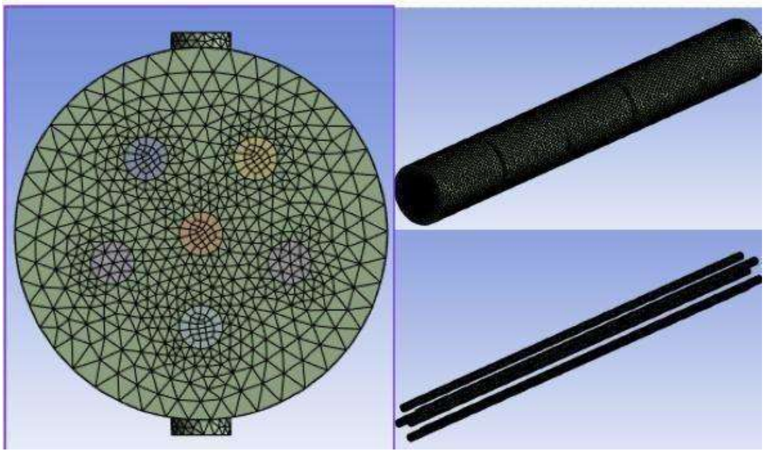

Figure 3. Quad meshing done for CAD model using Ansys meshing.

Table 3. Meshing parameters

Parameter	Specification
Element Type	Quad Dominant
Element Size	14.5mm
Quality Metric	Orthogonal = 0.210

Table 4. Governing equations.

Continuity equation:	$\nabla (\rho \mathrm{v}) = 0$
Momentum Equation:	$\nabla \cdot (\rho \mathrm{vv}) = -\nabla p + \nabla \cdot \tau$
Energy Equation:	$\nabla \cdot (\mathrm{v}(\rho E + p)) = \nabla \cdot (k\mathrm{eff}\nabla T)$

Governing Equations and Solver Settings

The simulations were performed under steady-state conditions by solving the fundamental conservation equations presented in Table 4:

Here, $k$eff represents the effective thermal conductivity, which incorporates the behavior of both metallic and polymer composite materials. Depending on the operating Reynolds number, appropriate laminar or turbulence models were employed to capture flow behavior across different regimes.

Validation and Performance Evaluation

The CFD results were validated against experimental data to ensure model accuracy and reliability. Key performance parameters evaluated include heat transfer rate, Nusselt number, friction factor, pressure drop, and thermo-hydraulic performance factor (THPF). By integrating corrugated geometry with epoxy-based polymer composite coatings, the methodology enables a comprehensive assessment of how material properties and surface modifications interact to influence overall heat exchanger performance, providing a pathway toward lightweight, efficient, and next-generation thermal system design.

RESULTS AND DISCUSSION

The combined experimental and numerical investigation provides a comprehensive understanding of the thermo-hydraulic behavior of the corrugated tube heat exchanger, particularly when integrated with polymer-based material considerations. The results clearly demonstrate that the introduction of corrugations on stainless steel tubes significantly alters the flow structure, leading to the generation of strong secondary vortices and enhanced turbulence intensity. These flow disturbances effectively disrupt the thermal boundary layer, resulting in improved convective heat transfer across the tube surfaces. At the same time, the inherent high thermal conductivity of stainless steel ensures efficient heat conduction from the fluid–solid interface into the tube wall, while the mild steel shell maintains structural integrity and supports uniform heat distribution. This combination of geometric enhancement and material selection leads to a noticeable improvement in overall thermal performance.

Temperature Distribution and Flow Behavior

The temperature contour illustrated in Figure 4 provides clear evidence of effective heat transfer within the exchanger. A pronounced temperature gradient is observed along the flow direction, with higher temperatures near the inlet region gradually decreasing toward the outlet. The rapid transition in color bands, especially in downstream regions, indicates strong convective heat transfer facilitated by turbulence induced by corrugations. Regions exhibiting relatively uniform color suggest localized zones of weaker mixing, whereas sharp gradients confirm active heat exchange zones. Overall, the contour validates that the corrugated configuration enhances thermal interaction between the hot and cold fluids, resulting in efficient energy transfer. The velocity streamline visualization further supports this observation. The presence of segmental baffles creates a zig-zag flow path on the shell side, promoting cross-flow and recirculation. Acceleration of fluid in constricted regions, such as baffle windows and inter-tube spaces, leads to higher local velocities. Conversely, recirculation zones formed downstream of baffles enhance mixing, thereby increasing the local heat transfer coefficient. The combined effect of these phenomena significantly improves the shell-side thermal performance.

Effect of Flow Rate on Thermal Performance

Figures 5 and 6 highlight the influence of volumetric flow rate on heat transfer rate and temperature difference. As the flow rate increases, the heat transfer rate shows a consistent upward trend. This is primarily due to enhanced fluid velocity, which strengthens convective heat transfer mechanisms. The

CFD predictions are consistently higher than those obtained from the Bell–Delaware method, as numerical simulations capture localized turbulence and complex flow interactions more accurately. In contrast, the temperature difference (ΔT) decreases with increasing flow rate. At lower flow rates, the fluid remains in contact with the heat transfer surface for a longer duration, allowing greater thermal exchange and resulting in higher ΔT values. As the flow rate increases, the residence time reduces, leading to a decrease in temperature difference despite an overall increase in heat transfer rate. The close agreement among CFD, experimental, and analytical results confirms the reliability of the adopted methodology.

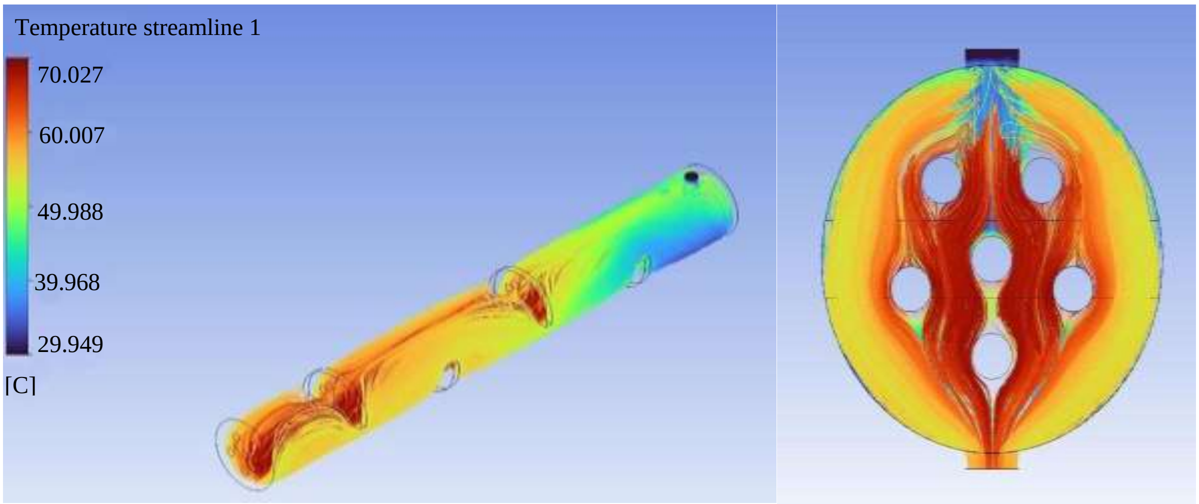

Figure 4. Temperature contour of the Shell-Side flow in a Corrugated tube shell-and-tube heat exchanger.

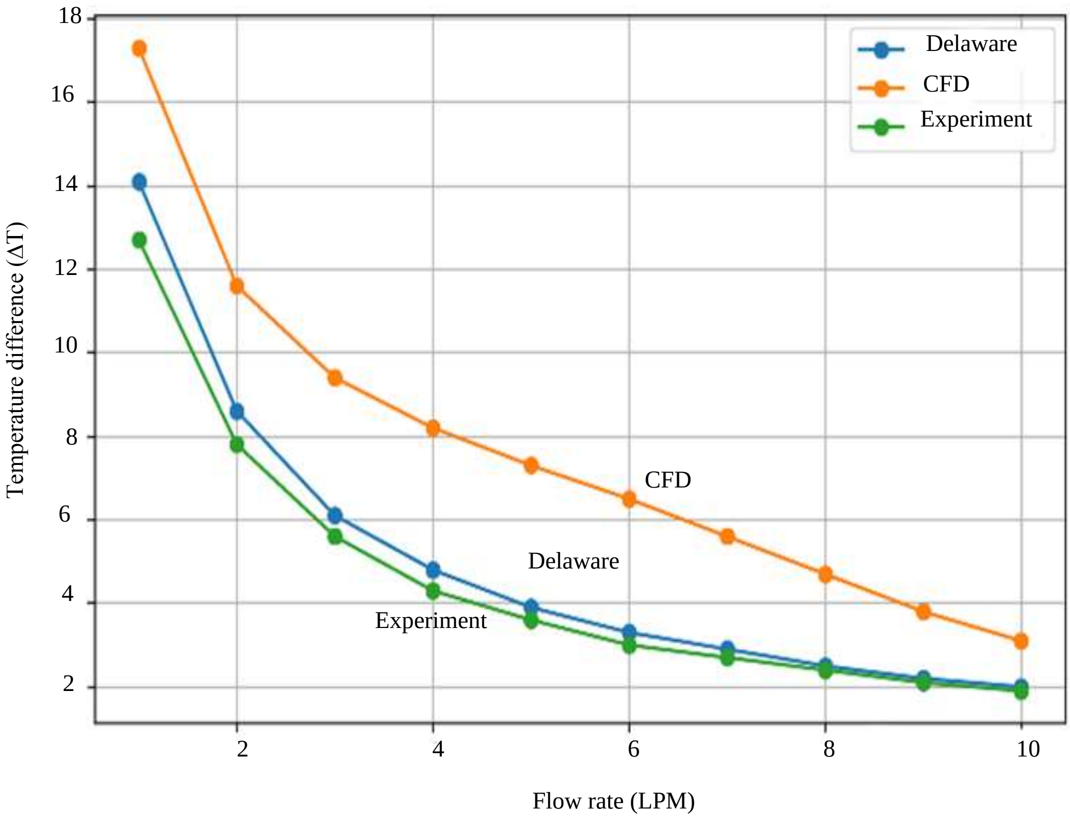

Figure 5. Effect of temperature difference with respect to flow rate.

Flow Characteristics and Heat Transfer Indicators

The variation of Reynolds number with flow rate (Figure 7) shows a nearly linear increase, indicating a transition from laminar to turbulent flow regimes. This transition enhances momentum transport and fluid mixing, which directly contributes to improved heat transfer performance. Similarly, the Nusselt number (Figure 8), representing convective heat transfer strength, increases steadily with flow rate. This confirms that higher flow velocities promote better thermal interaction between the fluid and the tube surface. However, these benefits are accompanied by an increase in hydraulic losses. As shown in Figure 9, the pressure drop rises significantly with flow rate due to increased fluid velocity and frictional resistance introduced by corrugations. This trend aligns with classical fluid mechanics principles, where pressure drop is proportional to the square of velocity. The variation of heat transfer coefficient (Figure 10) further reinforces these findings, showing improved convective performance at higher flow rates. Additionally, the comparison between corrugated and plain tubes clearly demonstrates that corrugated tubes consistently achieve higher heat transfer rates across all operating conditions due to enhanced turbulence and boundary layer disruption.

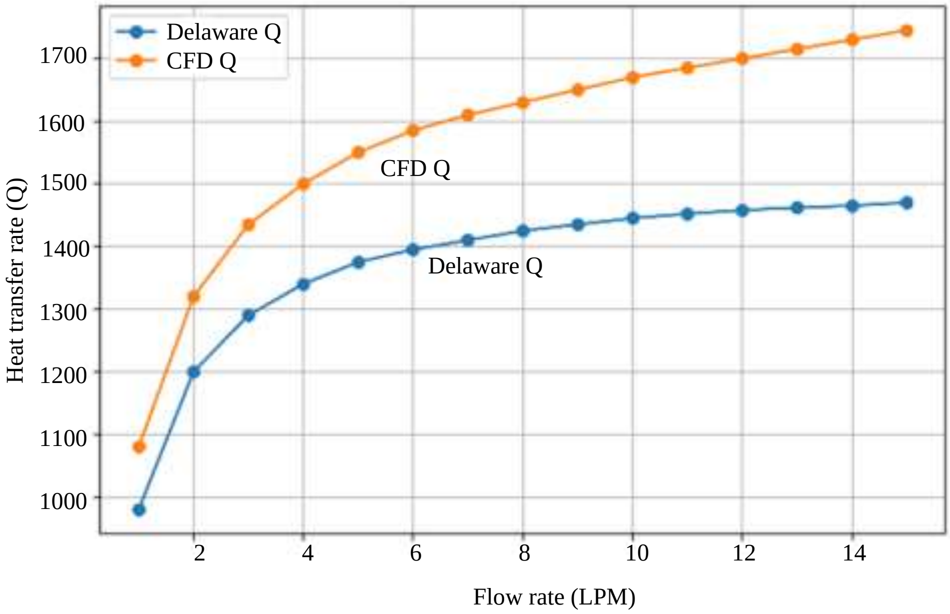

Figure 6. Effect of temperature difference with respect to flow rate.

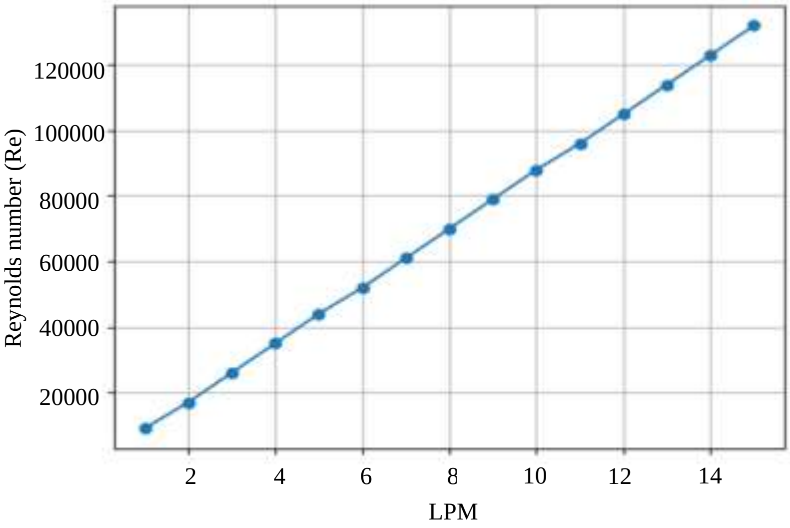

Figure 7. Variation of Reynolds number (Re) with respect to mass flow rate (LPM).

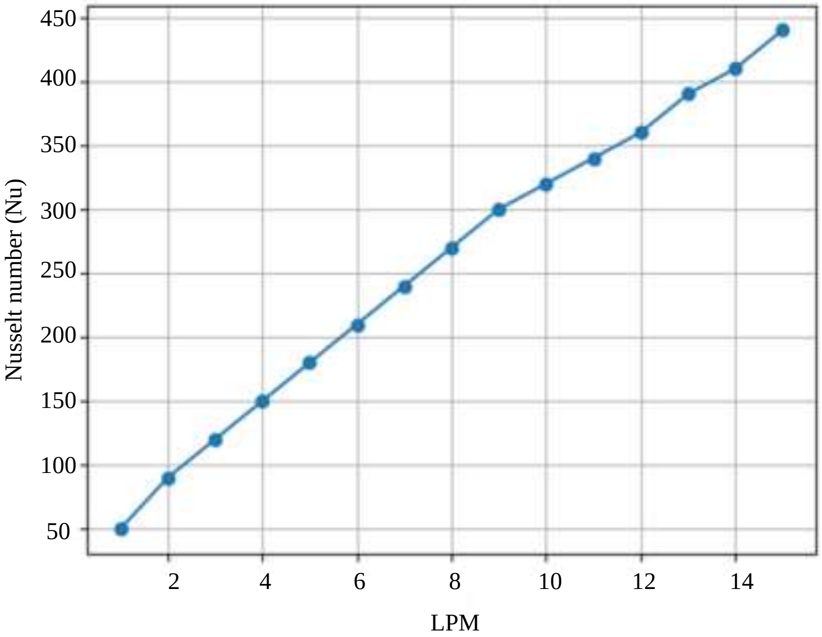

Figure 8. Variation of Nusselt Number with respect to mass flow rate (LPM).

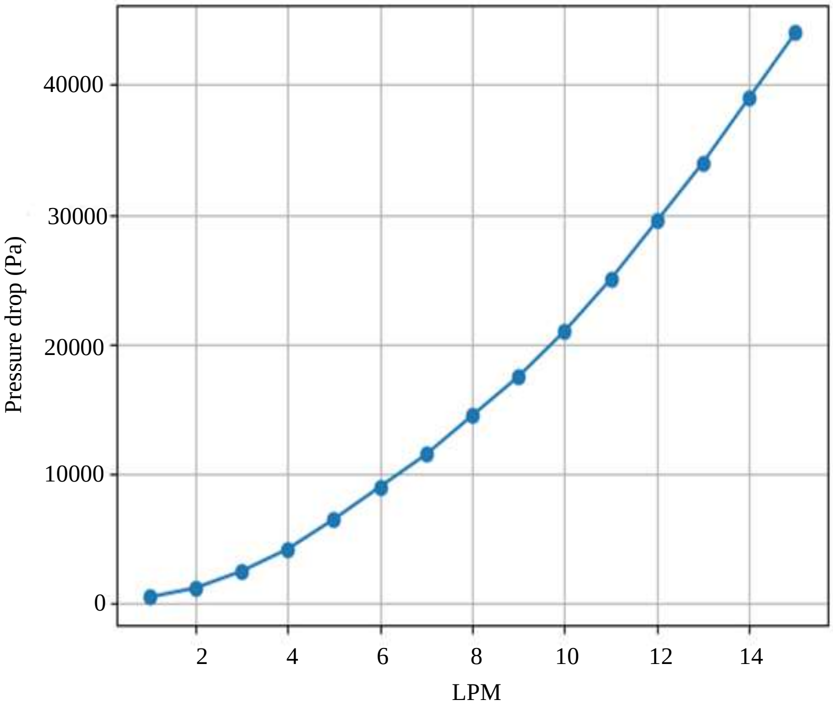

Figure 9. Variation of pressure drop with respect to volumetric flow rate

Effectiveness and Optimal Operating Conditions

Figure 11 presents the variation of heat exchanger effectiveness with flow rate. For both plain and corrugated configurations, effectiveness initially increases with flow rate, reaches an optimum value, and then gradually decreases. This behavior reflects the balance between improved convection and reduced residence time. Importantly, the corrugated tube configuration consistently exhibits higher effectiveness compared to the plain tube. This confirms that geometric modification plays a crucial role in improving thermal performance. However, the existence of an optimal flow range highlights the need for careful design to balance thermal gains with hydraulic penalties.

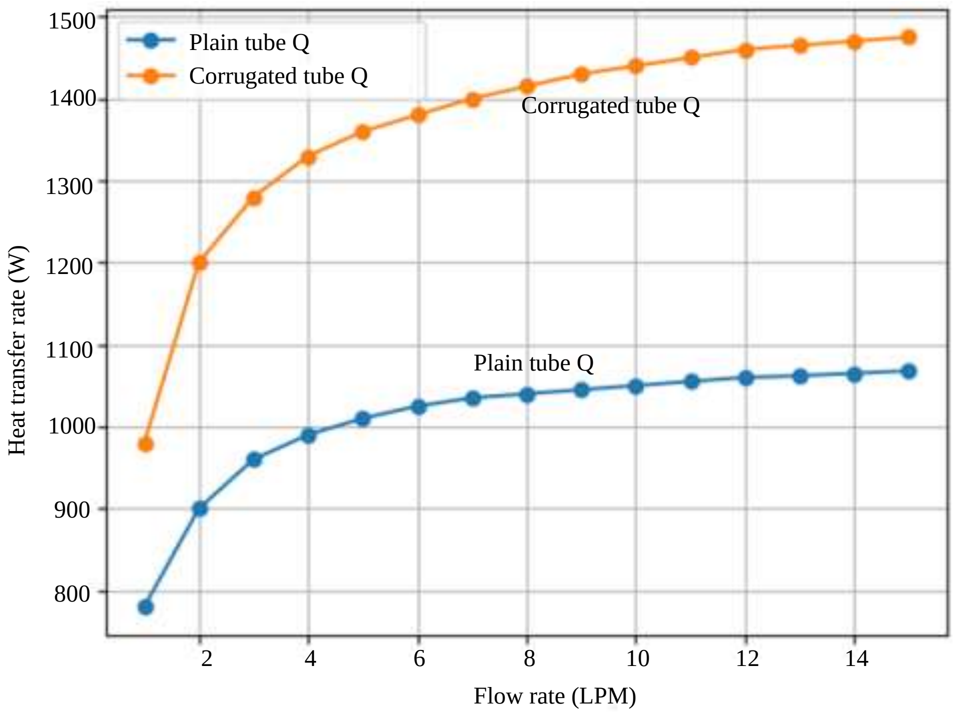

Figure 10. Heat transfer coefficient with respect to mass flow rate (LPM).

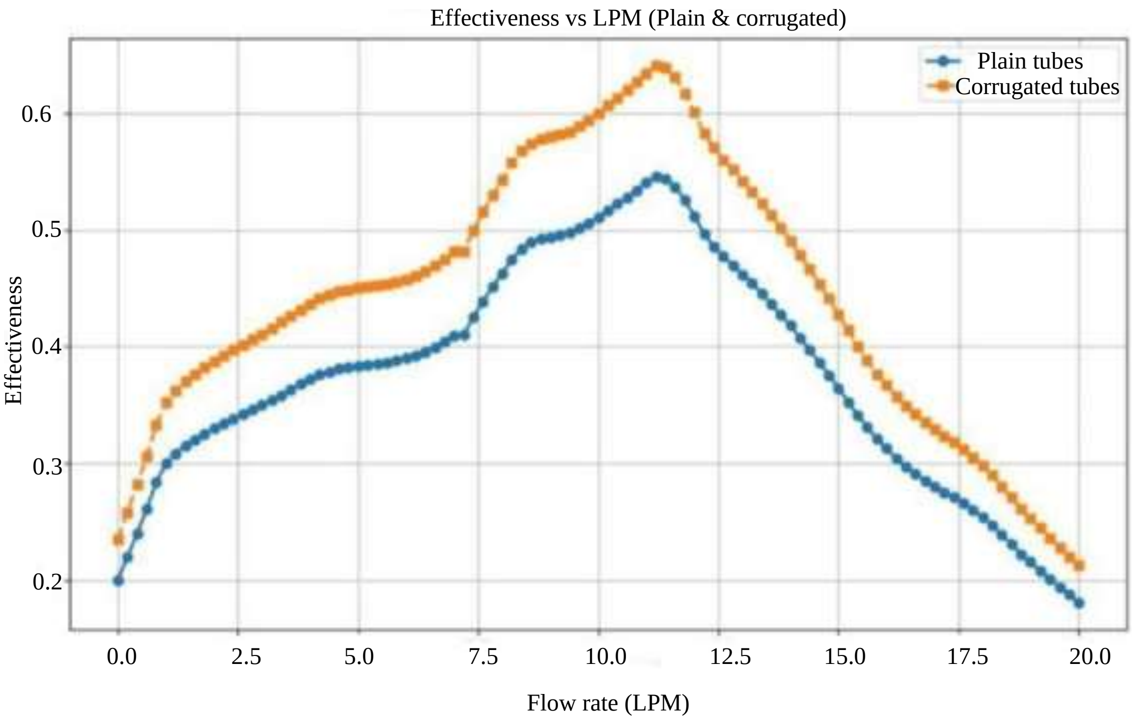

Figure 11. Effectiveness Variation with respect to flow rate for different tube pitch configurations.

Impact of Polymer Integration

A key extension of this study, aligned with the scope of polymer and composite research, lies in the incorporation of epoxy-based polymer composites in heat exchanger design. While the present configuration primarily utilizes metallic materials, the integration of polymer composites—either as coatings, inserts, or hybrid structural elements—introduces new dimensions in performance optimization. Epoxy-based polymer composites offer advantages such as corrosion resistance, reduced weight, and design flexibility. However, their relatively lower thermal conductivity compared to metals introduces additional thermal resistance. When used strategically, such as in selective regions where corrosion protection or insulation is required, polymers can enhance durability without significantly compromising performance. Moreover, polymer composites can be engineered with fillers (e.g., graphene, alumina) to improve their effective thermal conductivity, making them viable alternatives in advanced heat exchanger systems. In corrugated geometries, the combination of enhanced turbulence and tailored material properties can lead to optimized thermo-hydraulic performance. Thus, the study highlights that the future of heat exchanger design lies not only in geometric enhancement but also in intelligent material integration, where polymer composites play a crucial role in achieving lightweight, corrosion-resistant, and energy-efficient thermal systems.

In summary, the results confirm that corrugated tube configurations significantly enhance heat transfer performance due to improved fluid mixing and boundary layer disruption. While this enhancement comes at the cost of increased pressure drop, the overall thermo-hydraulic performance remains superior, especially in moderate to high flow regimes. The integration of polymer composites further opens new avenues for sustainable and high-performance heat exchanger design, aligning well with the evolving scope of advanced composite materials in thermal engineering applications.

CONCLUSIONS

The present investigation clearly establishes that geometric modification of tubes plays a decisive role in improving the thermo-hydraulic performance of shell-and-tube heat exchangers. The use of corrugated tubes enhances fluid mixing and disrupts the thermal boundary layer, leading to a noticeable improvement in heat transfer characteristics compared to conventional plain tubes. Although finned configurations may still offer higher performance due to increased surface area, corrugated tubes provide a balanced enhancement by combining improved convection with relatively simpler manufacturability. It is observed that the heat transfer rate increases consistently with an increase in flow rate; however, the overall efficiency does not follow the same trend indefinitely. Instead, an optimal operating range exists where the combined effects of convection and residence time result in maximum effectiveness. Beyond this range, the reduced contact time between fluid and surface limits thermal exchange despite higher flow velocities. The close agreement between experimental observations, analytical predictions, and CFD simulations confirms the reliability of the numerical framework adopted in this study. Furthermore, the extension toward polymer-based composite integration highlights the potential for developing lightweight, corrosion-resistant, and energy-efficient heat exchangers. Overall, the study demonstrates that corrugated geometries, when combined with advanced material strategies, offer a promising pathway for next-generation compact heat exchanger design.

FUTURE SCOPE

The scope of this work can be meaningfully extended in several directions to further enhance both scientific understanding and practical applicability. Future studies may focus on transient operating conditions to capture real-time thermal behavior under fluctuating loads, which is particularly relevant for industrial applications. The use of alternative working fluids such as nanofluids or phase change materials can be explored to further improve heat transfer performance. Finally, the methodology developed in this study can be extended to more complex configurations, including multi-pass and compact heat exchangers, thereby broadening its applicability to modern thermal systems aligned with polymer and composite engineering advancements.

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