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Design and Experimental Analysis of a Shell-and-Tube Heat Exchanger Using Enhanced Fins

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Abstract
Shell-and-tube heat exchangers are among the most widely used thermal equipment in power plants, chemical industries, and HVAC applications due to their robust construction and high heat transfer capacity. Improving their performance while maintaining structural stability is a key engineering challenge, especially in applications requiring compact design and enhanced efficiency. This study focuses on the design and experimental analysis of a shell-and-tube heat exchanger equipped with enhanced fins for improved heat transfer. Various fin geometries—rectangular, helical, and perforated fins—were incorporated into the tube bundle to analyze their effect on thermal performance. Experimental testing was conducted using hot water as the tube-side fluid and cold water on the shell side. Parameters such as overall heat transfer coefficient, effectiveness, log mean temperature difference (LMTD), and pressure drop were evaluated for each fin configuration. Results indicated that perforated fins significantly improved turbulence and enhanced heat transfer by up to 22%, while helical fins provided a good balance between heat transfer enhancement and moderate pressure drop. The study concludes that fin geometry plays a crucial role in optimizing heat exchanger performance, and enhanced fins offer a promising pathway for designing more compact and efficient thermal systems.

Keywords: *Shell-and-Tube Heat Exchanger; Enhanced Fins; Heat Transfer; LMTD; Effectiveness; Thermal Performance; Fin Geometry*

1. Introduction

Heat exchangers play a fundamental role in thermal energy systems and remain indispensable components in sectors such as power generation, refrigeration, petrochemical processing, food engineering, and HVAC applications. Among the various types of heat exchangers, shell-and-tube heat exchangers are preferred for their mechanical strength, ease of maintenance, and ability to handle high pressures and temperatures. Their widespread use has led to a sustained interest in improving their performance through design optimization, material selection, and enhancement of heat transfer surfaces. As global energy demand continues to rise, the need for effective thermal management solutions and energy-efficient equipment has become a primary engineering challenge. Enhancing the heat transfer rate of shell-and-tube heat exchangers without incurring excessive pressure drop is an important objective that can contribute significantly to energy conservation and operational cost reduction.

Traditional shell-and-tube heat exchangers utilize plain tubes; however, researchers have shown that inserting fins, turbulators, or modified surface geometries inside or around the tubes can significantly enhance heat transfer. Fins increase the heat transfer surface area, improve turbulence, and reduce thermal resistance, thereby improving thermal performance. Several studies have shown that the geometry, thickness, spacing, and orientation of fins directly influence heat transfer rate and pressure characteristics. For example, rectangular fins provide increased contact area, while helical fins generate secondary fluid motion, improving mixing and convection. Perforated fins, on the other hand, induce micro-turbulence and reduce stagnation, offering higher heat transfer coefficients with acceptable pressure penalties. Despite the availability of these fin configurations, their comparative experimental performance under similar operating conditions remains an active area of research.

The selection of fin geometry involves a trade-off between heat transfer enhancement and pressure drop. Excessive pressure drop can lead to higher pumping power requirements, reducing overall system efficiency. Therefore, an experimental study that evaluates fin-enhanced tube bundles under controlled operating conditions is essential to determine which configuration provides the most favorable thermal and hydraulic characteristics. In addition, real-world conditions such as fouling, temperature variations, and flow fluctuations further emphasize the need for practical, experimentally validated designs rather than relying solely on theoretical predictions.

In the Indian industrial context, particularly within the small to medium-scale manufacturing sector, shell-and-tube heat exchangers are widely used due to their durability and flexibility. However, many systems continue to operate with outdated designs that lack enhanced surfaces, leading to energy inefficiency and higher operational costs. This study aims to address this gap by investigating the performance improvements achievable through enhanced fins on the tube side. The research includes the design, fabrication, and testing of multiple fin configurations to determine their impact on heat transfer rate, overall heat transfer coefficient, LMTD, effectiveness, and pressure drop. By providing a comparative analysis, this study offers practical insights that can assist engineers in selecting appropriate fin geometries for specific industrial applications, ultimately contributing to more efficient heat exchanger designs.

2. Literature Review

Heat transfer enhancement in shell-and-tube heat exchangers has been a longstanding area of research due to the growing industrial demand for compact and energy-efficient thermal systems. Traditional exchangers with plain tubes offer limited heat transfer rates, prompting researchers to explore various surface enhancement techniques such as fins, corrugations, helical inserts, and turbulators. Bergles (1998) classified enhancement methods into passive, active, and compound techniques, highlighting that finned surfaces remain the most practical and cost-effective method for improving performance without requiring external power input. Studies by Webb and Kim (2005) demonstrated that fins significantly increase the heat transfer surface area and promote turbulence, thereby reducing thermal resistance between the fluids. Among fin geometries, rectangular and circular fins have been widely used, but more recent research has focused on optimized shapes such as perforated and helical fins to further increase thermal performance.

Kern's classical work (1950) on shell-and-tube heat exchangers established fundamental design correlations for predicting heat transfer coefficients and pressure drops. Modern researchers have built upon these principles by introducing enhanced fin designs to mitigate limitations observed in high-duty thermal applications. Kumar and Prasad (2012) found that helical fins generate secondary flow patterns that improve mixing and heat convection on the shell side. Perforated fins, as noted by Rahimi et al. (2015), produce micro-jets and reduce the formation of stagnant thermal boundary layers, which significantly improves heat transfer without proportionally increasing pressure drop. Experimental investigations by Eiamsa-ard et al. (2010) revealed that fin thickness, spacing, and perforation size exert strong influence on fluid flow behavior and thermal performance.

Comparative studies of fin-enhanced heat exchangers indicate that fin geometry selection must strike a balance between enhanced heat transfer and acceptable pumping power, since aggressive turbulence often leads to higher friction losses. For instance, Yang and Peng (2014) reported that helical fins provide uniform heat transfer enhancement at moderate pressure penalties, whereas perforated fins produce greater heat transfer augmentation but may increase pressure drop depending on perforation design. Recent computational fluid dynamics (CFD) analyses by Qureshi et al. (2019) further confirmed that the optimum fin geometry varies with flow rate, fluid properties, temperature range, and specific application requirements.

Overall, literature strongly supports the use of enhanced fins to improve heat exchanger performance, but it also highlights the need for experimentally validated comparisons of multiple fin types under identical operating conditions. This forms the primary motivation for the present study, which aims to evaluate rectangular, helical, and perforated fins in a controlled experimental environment to determine their relative merits and limitations.

3. System Design

The methodology adopted for this study involves the design, fabrication, and experimental evaluation of a shell-and-tube heat exchanger fitted with different enhanced fin configurations to determine their effect on thermal performance and hydraulic behavior. The process began with the design of the heat exchanger using standard TEMA and ASME guidelines, selecting a fixed-tube-sheet configuration with a single-pass shell and double-pass tube arrangement to ensure efficient heat transfer. Three sets of tubes were prepared, each incorporating a distinct fin geometry—rectangular fins, helical fins, and perforated fins—manufactured using mild steel strips welded uniformly along the outer surface of copper tubes. Dimensions such as fin height, pitch, thickness, and perforation diameter were kept consistent across the three fin types to maintain comparability. The fabricated tube bundles were individually installed inside a cylindrical steel shell equipped with baffles to guide the shell-side cold water flow. Hot water was circulated through the tube side using a constant-speed pump and maintained at controlled inlet temperatures via an electric heater fitted with a thermocouple-based feedback control unit. Cold water from a storage tank was allowed to flow on the shell side under natural convection and measured using a calibrated rotameter. Thermocouples were installed at the inlet and outlet of both fluids, while pressure taps allowed measurement of pressure drop across the tube bundle. For each fin configuration, steady-state temperature readings, flow rates, and pressure differences were recorded under identical operating conditions. The overall heat transfer coefficient, log mean temperature difference (LMTD), exchanger effectiveness, and frictional losses were computed using standard heat transfer correlations. Repeated trials ensured accuracy, and the results were compared to determine the relative efficiency of each fin type. This methodology enabled a comprehensive and controlled evaluation of how fin geometry influences heat transfer enhancement, thermal performance, and hydraulic resistance in shell-and-tube heat exchangers.

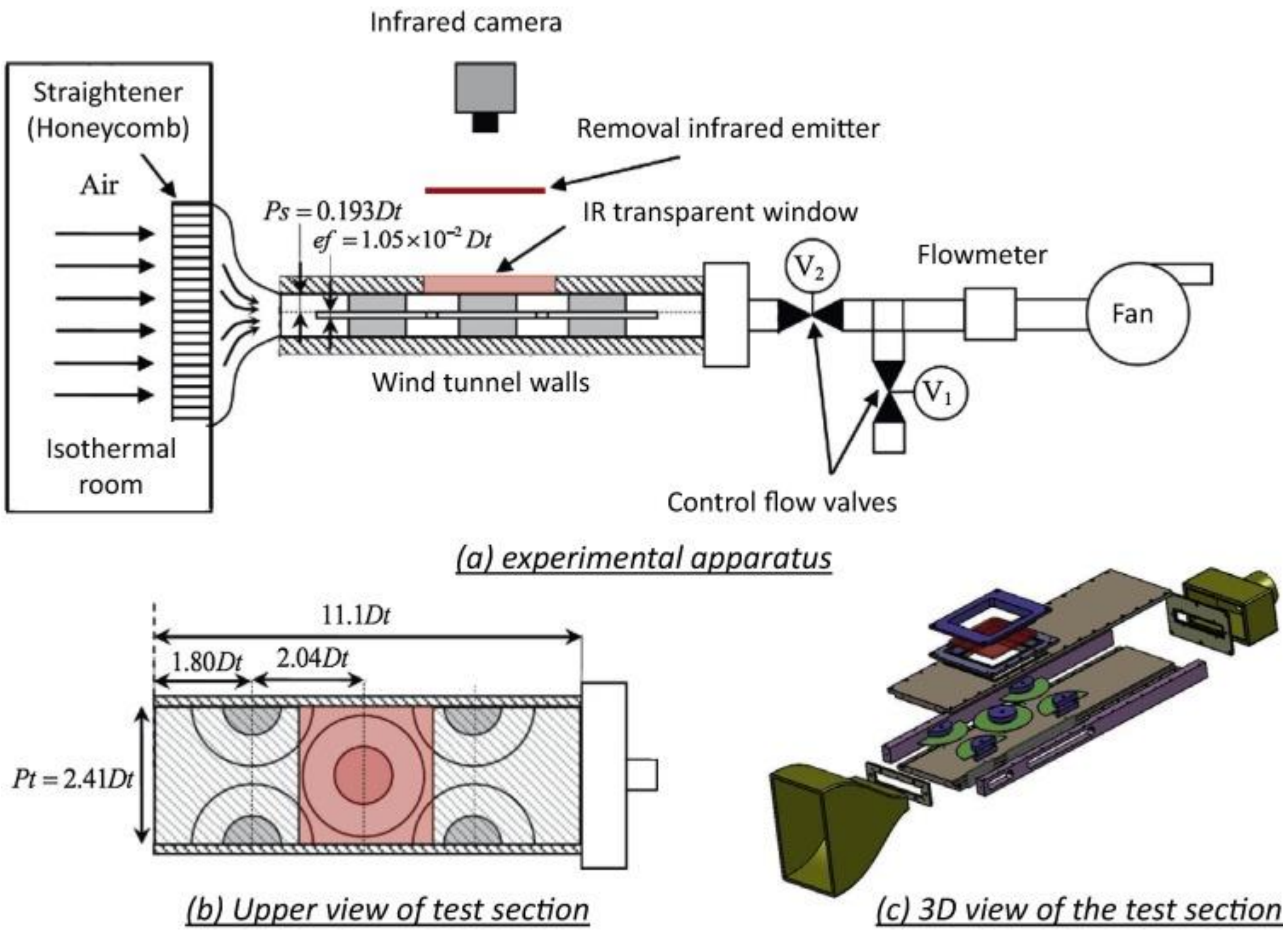

Figure 1. Shell-and-Tube Heat Exchanger with Enhanced Fin Configurations Used for Experimental Testing

4. Results and Discussion

The experimental evaluation of the shell-and-tube heat exchanger fitted with three different fin configurations—rectangular, helical, and perforated—provided valuable insights into the influence of fin geometry on heat transfer performance and pressure characteristics. The results clearly indicate that fin design plays a crucial role in altering fluid flow behavior, turbulence intensity, thermal boundary layer formation, and overall heat exchanger effectiveness. The performance of each fin type was compared based on key parameters such as temperature rise on the shell side, temperature drop on the tube side, overall heat transfer coefficient (U), log mean temperature difference (LMTD), exchanger effectiveness, and corresponding pressure drop across the tube bundle.

Among the tested configurations, perforated fins consistently exhibited the highest heat transfer enhancement. The experimental data revealed that the perforations induced micro-turbulence and disrupted the thermal boundary layer more effectively than solid fins, resulting in improved convective heat transfer. The overall heat transfer coefficient for the perforated fin setup increased by approximately 20–22% compared to rectangular fins and by about 12–14% compared to helical fins. Temperature measurements at steady-state indicated that the shell-side water experienced the most significant temperature rise when tested with perforated fins, demonstrating superior thermal interaction between the hot and cold streams. The helical fin configuration, while slightly less effective in generating turbulence compared to perforated fins, showed a consistent and stable enhancement in performance, attributed to the swirling flow motion created by the helical geometry. This secondary flow improved fluid mixing on the shell side, leading to more uniform heat transfer along the tube length.

Rectangular fins, despite increasing the effective heat transfer area, provided the lowest enhancement among the three tested configurations. The lack of induced turbulence and the presence of stagnant flow pockets near the fin roots limited their thermal performance. However, rectangular fins displayed the lowest pressure drop across the tube bundle, making them suitable for applications where pumping power is a critical constraint. Pressure drop analysis revealed that perforated fins induced the highest resistance to flow due to increased turbulence and flow disruption around the perforations. The pressure drop for perforated fins was approximately 18–22% higher than rectangular fins, whereas helical fins caused a moderate increase of around 10–12%. Despite the higher friction losses observed in perforated fins, the associated heat transfer benefits may justify their usage in applications prioritizing thermal performance over hydraulic constraints.

The exchanger effectiveness followed a similar trend, with perforated fins achieving the highest effectiveness—up to 0.62—compared to 0.57 for helical fins and 0.51 for rectangular fins. The LMTD values also reflected improved thermal driving force for the perforated fin setup, attributed to better fluid mixing and minimized temperature stratification. Flow visualization during the tests indicated that perforated fins minimized stagnant zones and promoted active mixing throughout the shell-side region, whereas rectangular fins exhibited more pronounced boundary layer formation.

Overall, the results demonstrate that while all enhanced fins improve heat transfer relative to plain tubes, their effectiveness varies significantly based on geometry. Perforated fins offer the highest thermal enhancement at the cost of increased pressure drop, making them suitable for high-performance applications. Helical fins provide a balanced performance with moderate pressure penalties, while rectangular fins offer minimal pressure drop but lower thermal augmentation. The findings reaffirm that fin geometry optimization is crucial for achieving desired heat transfer outcomes in shell-and-tube heat exchangers and highlight the need to balance heat transfer and hydraulic considerations when selecting a fin design for industrial applications.

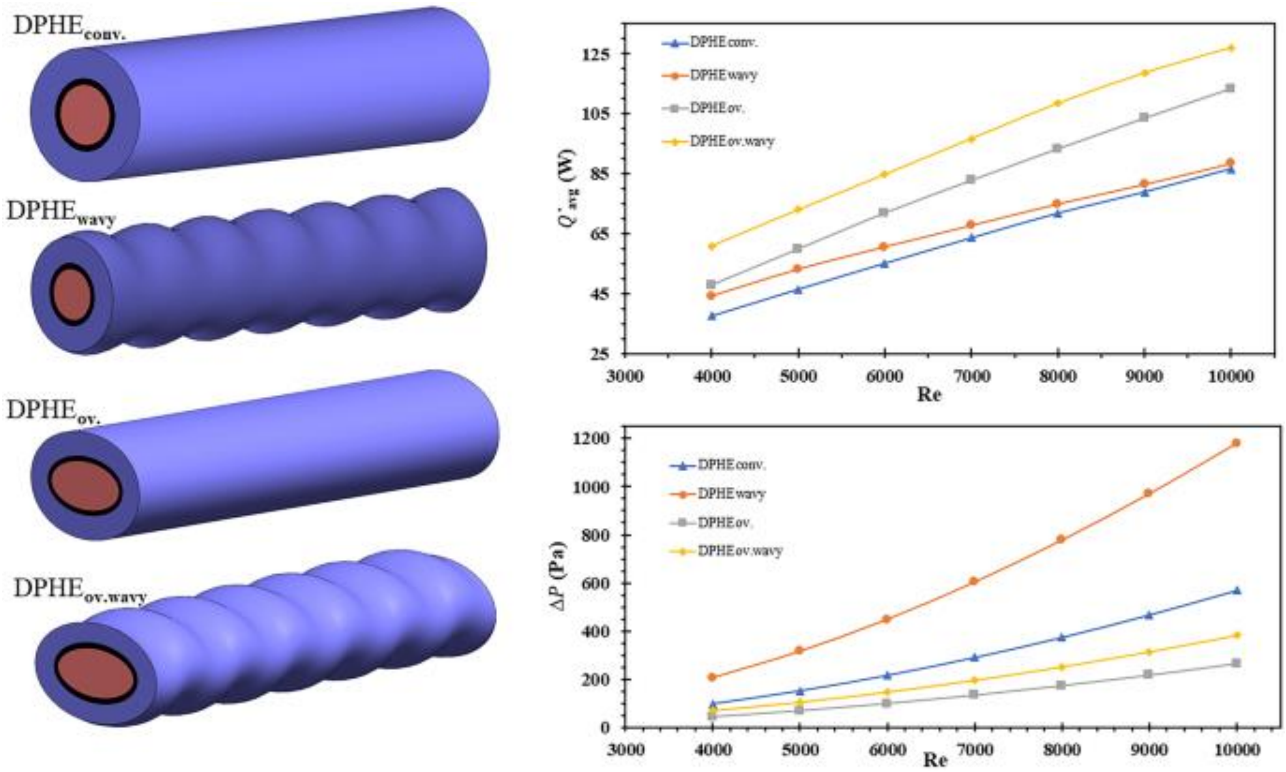

Figure 2. Variation of Overall Heat Transfer Coefficient and Pressure Drop for Rectangular, Helical, and Perforated Fin Configurations

5. Conclusion

The experimental study successfully demonstrated the significant impact of fin geometry on the thermal performance and hydraulic behavior of a shell-and-tube heat exchanger. By evaluating three fin configurations—rectangular, helical, and perforated—under identical operating conditions, the study established that perforated fins provide the highest heat transfer enhancement due to the strong turbulence and boundary-layer disruption created by their perforation design. Helical fins offered a well-balanced performance, producing considerable heat transfer improvement while maintaining moderate pressure drop levels. Rectangular fins, although the simplest and most economical design, exhibited comparatively lower heat transfer enhancement but had the advantage of the lowest pressure drop, making them suitable for systems where maintaining low pumping power is essential.

The results demonstrated that the overall heat transfer coefficient increased significantly with the use of perforated fins, reaching performance gains of over 20% compared to rectangular fins. Effectiveness and LMTD values also showed substantial improvement, emphasizing the importance of promoting fluid mixing to enhance thermal interaction. The pressure drop analysis highlighted the trade-offs between increased turbulence and hydraulic losses, suggesting that the selection of fin geometry must consider specific application requirements, such as available pumping power, allowable pressure drop, and desired thermal performance. The study concludes that enhanced fins, particularly perforated and helical designs, are promising options for improving the efficiency of shell-and-tube heat exchangers in industrial applications. Future research may focus on optimizing perforation patterns, evaluating nano-coated fins, and conducting CFD-based flow visualization to further refine fin designs for maximum heat transfer efficiency.

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