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Geometrical Optimization of Shell-and-Helical Coil Heat Exchangers for Marine Waste Heat Recovery Systems

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ABSTRACT

In maritime transportation and the facilities for ports, reliable and compact thermal components are essential for facilitating sustainable mechanical performance. The article provides a numerical evaluation of the impact of shell size on the thermal efficiency of baffled shell-and-helical coil heat exchangers (HCHEs), commonly utilized in maritime cooling, waste heat recovery, and HVAC systems on ships and offshore platforms. A verified 3D CFD model was created utilizing ANSYS Fluent to simulate steady-state fluid dynamics and thermal transport across three shell diameters (120 mm, 140 mm, and 160 mm) featuring divided baffles and a stationary helical coil. The flow rate of the cold fluid on the shell side ranged from 2 to 6 L/min. Key performance characteristics, such as heat transfer rate, thermal efficacy, and temperature distribution, were evaluated to measure thermohydraulic behavior. The model's reliability was validated by a two-stage technique utilizing experimental data and established numerical standards. The findings indicated that decreasing shell diameter markedly improves heat transmission and thermal efficiency, particularly at reduced flow rates. The compact 120 mm shell configuration frequently surpassed bigger versions, affirming the significance of structural compactness in enhancing thermal performance. These findings offer essential design recommendations for the use of compact heat exchangers into marine and port systems, facilitating advancements in sustainable and efficient maritime transportation.

Nomenclature

T	Temperature, °C
$\dot{m}$	Mass flow rate, kg/s
$\dot{Q}$	Rate of heat transfer, W
ε	Effectiveness
Cp	Specific heat capacity, W/m^2·°C
t	Thickness, mm

Abbreviations

HE	Heat Exchanger
HCHE	Helical Coil Tube Heat Exchanger
CFD	Computational Fluid Dynamics
LMTD	Logarithmic mean temperature difference

1. INTRODUCTION

In a variety of marine and port-based sectors, such as shipboard systems, cargo refrigeration, fuel processing, and energy recovery units, heat exchangers (HE) are essential to thermal energy management. Their capacity to provide efficient heat transfer across fluid streams dramatically affects the energy efficiency, technical dependability, and environmental performance of these systems. In terms of ecologically responsible maritime transportation and eco-friendly port management, improving the efficiency of heat exchangers is essential for decreasing energy consumption, decreasing emissions, and facilitating the global shift towards low-carbon, energy-efficient logistical facilities [1]. HEs form a significant section of a cargo ship's supplementary systems, representing a considerable margin to the vessel's total deadweight [2]. Their incorporation within systems such as engine cooling, waste heat recovery, and ship The heating and cooling system provides them with crucial for guaranteeing energy efficiency and functional dependability in offshore sectors [3].

across the several configurations of heat exchangers, the shell and helical coil design has achieved significance owing to its compact structure and enhanced energy efficiency. This form facilitates fluid flow behaviors, such as Dean vortices, which augment mixing and turbulence, resulting in an improved heat transfer rate relative to conventional straight tube configurations [4,5]. Consequently, the incorporation of a helical coil heat exchanger can significantly enhance the thermal performance of a system. Furthermore, geometric alterations—specifically improvements to the shell diameter—can enhance the exchanger's efficiency by affecting the flow pattern and the surface area used for heat transfer [6][7]. The present research examines the impact of shell diameter variation on the thermodynamic and fluid performance of shell and helical coil heat exchangers (HCHE).

The thermal and hydraulic performance of HCHE is determined by a combination of geometric and flow-related parameters, such as coil diameter, tube diameter, pitch, number of turns, shell diameter, and Reynolds number—each uniquely affecting downstream flow development, turbulence intensity, and boundary layer disruption. A recent numerical study investigated the effects of different HCHEs, revealing that larger coil diameters improve thermal performance by augmenting centrifugal forces, facilitating secondary flow, and enhancing radial fluid mixing, thereby increasing heat transfer rates [8]. A growth in helical tube dimension led to a reduction in the surface heat transfer coefficient and frictional resistance, while facilitating a more substantial overall pressure drop [9]. Investigations indicated that augmenting the helical diameter of the heat transfer fluid tube resulted in a decrease in total melting time, an elevation in the final average temperature of the fluid, and improved energy absorption [10]. It was shown that increasing the inclination angle of the HCHE from horizontal to vertical significantly enhanced thermal performance and reduced pressure drop, with effectiveness improved by over 23% and pressure drop reduced by up to 32.7%, while increasing the Dean number led to higher heat transfer rates but also elevated pressure losses [11]. It was experimentally demonstrated that increasing the inclination angle of the HCHE from horizontal to vertical enhanced the coil Nusselt number and HE effectiveness while reducing the pressure fluctuation, particularly when nanofluids such as Al_2O_3/water and SiO_2/water were used [12]. It was experimentally observed that increasing the coil curvature ratio significantly enhanced the heat transfer performance on both the coil and shell sides of the HE, with average Nusselt numbers rising by up to 160.3% and 224.3% respectively, while also contributing to a noticeable increase in the Fanning friction factor of the helical coil [13]. It was found that variations in curvature ratio had a significant impact on the heat transfer coefficient and pressure drop in the saturated boiling region, while their influence was less pronounced in the subcooled boiling region [9]. It was numerically observed that a lower curvature ratio (di/Dc = 0.142) resulted in a higher rate of heat transfer, whereas a greater curvature ratio (0.166) produced higher Dean and Nusselt numbers within the helical coil, indicating a trade-off between flow development and thermal performance [14]. It was found that decreasing the twist pitch (i.e., reducing the y/d ratio) led to a notable increase in thermal performance, with the highest Nusselt number enhancement observed at the smallest pitch (y/d = 3), confirming that tighter twisting intensifies swirl flow and improves thermal performance [15]. It was numerically demonstrated that introducing

variable radial pitch along the helical tube length significantly enhanced thermal performance improving the performance evaluation criteria (PEC) by up to 10% whereas variations in axial pitch showed minimal effect under the same conditions [16]. In a separate investigation, increasing the external helix diameter of a double coil HCHE was found to significantly enhance thermal performance, with a 33.34% increase in helix diameter resulting in performance improvements of up to 42.86% at Re = 2000 due to greater heat transfer surface area and more effective fluid mixing [17]. Although significant study has been conducted on coil geometry and flow parameters, shell diameter remains a crucial yet inadequately examined design element; its optimization is vital for improving thermal performance and significantly contributes to reducing material consumption, spatial footprint, and overall operational costs, thereby serving as a pivotal factor in the technical and economic efficiency of HCHEs.

While numerous studies have investigated the implementation of baffles in HCHE to improve heat transfer through enhanced shell side turbulence, there has been limited focus on the impact of shell structure, specifically shell diameter, on the thermal and hydraulic performance of baffled configurations. Most current research presumes a constant shell dimension, neglecting its influence on flow dynamics and thermal efficiency.

The present research fills the gap by performing a comprehensive numerical analysis on the impact of different shell sizes (120 mm, 140 mm, and 160 mm) in a baffled HCHE. This study offers novel insights into the influence of shell size on flow structure, turbulence formation, and heat exchange efficiency, which is essential for optimising small thermal systems, particularly in space-restricted marine and offshore locations.

2. MATERIAL AND METHODOLOGY

This research paper utilizes a computational fluid dynamics (CFD) approach to examine the impact of shell diameter fluctuation on the fluid dynamics behavior of a baffled heat exchanger. ANSYS Fluent conducts experiments that facilitate three-dimensional modeling of complex flow and heat transport phenomena across diverse geometric structures and operational situations.

A detailed 3D model of the heat exchanger is developed, incorporating helical coil geometry, segmental baffles, and variable shell diameters. The computational domain includes both the shell-side and tube side fluid regions to accurately capture the interaction between the hot and cold fluids. A structured mesh is generated with local refinement around the coil and baffles to ensure accurate resolution of boundary layers and thermal gradients. To ensure computational accuracy and efficiency, a grid independence study is performed to identify the optimal mesh density.

A turbulence model is selected based on its proven capability to model turbulent flow and secondary motion in coiled geometries. The physical properties of the working fluids are assumed to be temperature based, and appropriate boundary conditions (e.g., constant wall heat flux, inlet velocity, and outlet pressure) are applied to replicate realistic operating conditions.

Model validation is carried out by comparing simulation results with available experimental data and established numerical models from the literature. Key performance parameters such as Nusselt number, pressure drop, and heat exchanger effectiveness are used to assess the accuracy of the model.

Following validation, a parametric analysis is conducted by systematically varying the shell diameter while keeping other geometric parameters (e.g., coil diameter, pitch, number of baffles) constant. The shell diameters considered span a practical design range, ensuring the applicability of results to industrial scenarios.

The results from this study provide actionable insights into how shell diameter influences flow distribution, turbulence intensity, and thermal performance. Ultimately, the findings support design optimization strategies that aim to improve energy efficiency and reduce material and operational costs in baffled HCHEs.

3. NUMERICAL MODEL

In this study, the thermal and flow characteristics of a baffled HCHE were numerically investigated using ANSYS Fluent 19.0. The simulation domain included both the shell and tube sides, with water serving as the working fluid throughout. The fluid was presumed incompressible, and the governing equations for mass, momentum, and energy conservation were resolved utilizing the concept of finite volumes.

To accurately capture turbulence effects, the standard k-ε turbulence model was employed, along with narrow cell near wall to model near-wall behavior. Pressure-velocity coupling was handled using the SIMPLEC algorithm, ensuring stability and convergence of the flow field.

All models were regarded as convergent when the residuals for the momentum and energy equations fell below 10^{-5}, so assuring that the heat acquired by the cold fluid nearly corresponded to the heat relinquished by the hot fluid. The internal energy balance validates the accuracy of the numerical results and ensures appropriate conservation within the simulation domain.

The heat exchanger was modeled with cold water entering the shell side from a bottom inlet at a temperature of 291.8 K, while hot water entered the helical tube from the side inlet at 333.3 K. The shell-side flow rate varied across simulations, ranging from 2 to 6 L/min in 1 L/min increments to assess its effect on performance. In all cases, the tube-side flow rate was held constant at 3 L/min.

3.1. Model Dimension

The heat exchanger comprises a cylindrical shell-and-coil configuration, specifically designed for assistance high-efficiency energy exchange between two fluid streams. The shell section measures 0.340 m in total length, incorporating 0.012 m diameter ports for both inlet and outlet connections. Housed within the shell is a helical tube formed from ¾-inch nominal diameter tubing, wound into a 0.1 m diameter coil with a 0.3 m axial length. This compact helical arrangement maximizes surface area within a confined volume, enhancing convective heat transfer through induced secondary flow patterns. The geometric specifications and structural layout of the unit are illustrated in Figure 1.

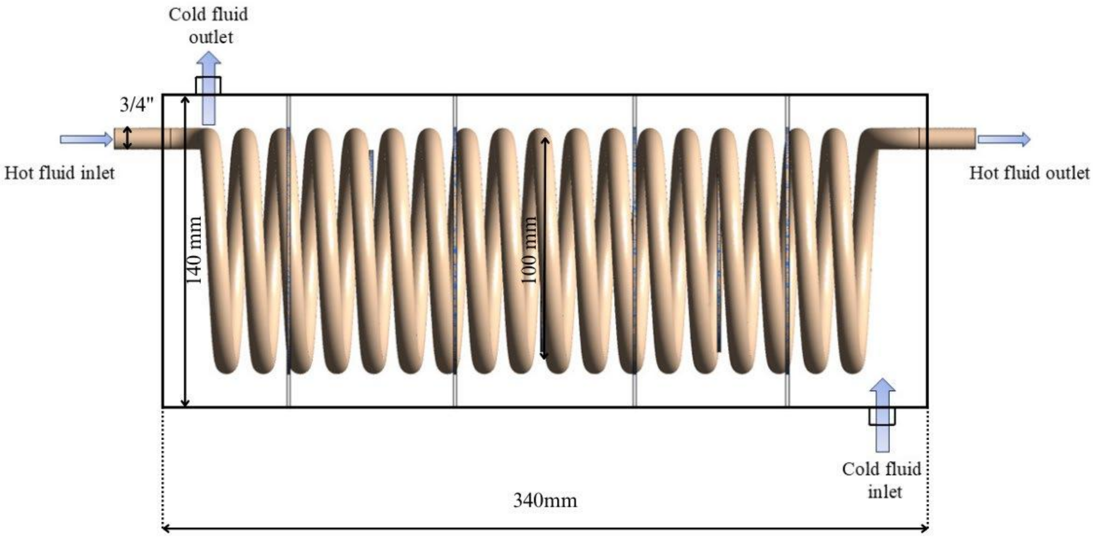

Figure 1: HCHE Structure

3.2. Meshing

A structured hexahedral mesh was created for the complete 3D geometry of the shell-and-helical coil heat exchanger utilising ANSYS Meshing tools. Particular emphasis was placed on enhancing the mesh next to the tube walls, baffle edges, and fluid-solid interfaces to precisely identify boundary layers and record velocity and temperature gradients. A grid independence test was conducted by progressively refining the mesh and observing variations in output temperature and heat transfer rate. Following this research, a final mesh including about 8 million components was selected, as more refinement resulted in minimal changes to the simulation outcomes.

3.3. Validation and Verification

To guarantee dependability and precision of the numerical model, a dual validation approach was employed. This process consisted of two stages: (1) comparison with experimental data obtained from a controlled test rig, and (2) benchmarking against an established numerical and experimental model from literature.

In the first stage, the CFD results were directly compared with data measured from a custom-built experimental setup replicating the same shell-and-helical coil heat exchanger geometry and boundary conditions shown in Figure 2. Key performance indicators—including outlet temperatures, Nusselt number, and pressure drop were recorded and compared with simulation outputs. The simulation results demonstrated significant concordance with the experimental measurements, with deviations maintaining within an acceptable error range, so affirming the model's capacity to accurately represent the structure's physical behavior within scenarios from the real world [18].

The second stage included an evaluation using a previously developed model that incorporated both numerical and experimental results for a corresponding HE structure. This stage facilitated the cross-validation of the simulation framework across various geometric and flow parameters. The evaluation of performance parameters, including the average Nusselt number and U-factor, revealed consistent patterns with the mentioned study, so validating the robustness of the numerical methodology [19].

The success of this two-tiered validation process confirms the model's credibility and its suitability for conducting parametric studies focused on shell diameter optimization and thermal-hydraulic performance assessment.

Figure 3 illustrates the difference of the computed and experimental outlet temperatures of the hot fluid over an interval of cold fluid flow rates (2–6 L/min) for the conventional shell-and-helical coil heat exchanger. The results reveal a constant correlation between the two datasets, with the simulation accurately mirroring the experimental response. The measured greatest absolute variation is roughly 2 °C, while the average inaccuracy across all tested flow rates is consistently below 1.5 °C. This robust agreement validates the dependability and predictive precision of the numerical model in depicting the thermal performance of the heat exchanger under steady-state conditions.

Figure 2: Experimental Setup layout

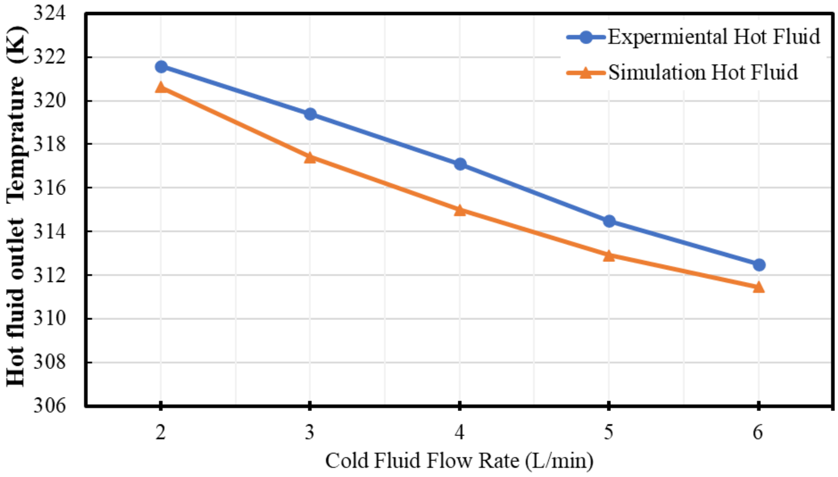

Figure 3: Comparison between the experimental and numerical hot fluid temperature

This model was previously going through a mesh independence study which Published in a prior article as shown in Figure 4 [18].

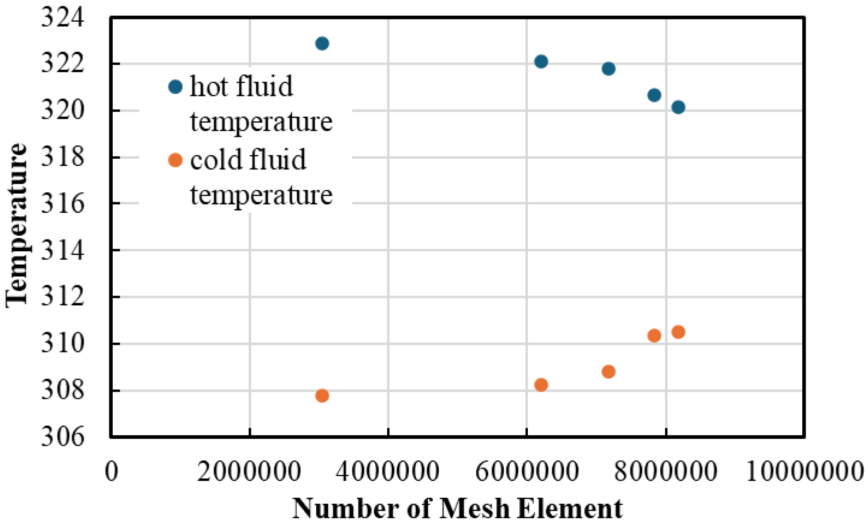

Figure 4: Mesh Independence Study

4. POST PROCCING CALCULATION

The theoretical evaluation of the numerical results is carried out using fundamental heat transfer relations. The rate of heat transfer on both the hot and cold fluid sides of the HCHE is determined using Eq. (1). This equation incorporates the average specific heat capacity of the fluid to accurately reflect temperature-dependent thermal behavior. By applying this approach, the thermal performance of the exchanger can be quantitatively assessed under various operating conditions [20].

$$Q_{av} = \frac{\left(\dot{m}_{hot} c_p \times \left(T_{hot,in} - T_{hot,out}\right)\right) + \left(\dot{m}_{cold} c_p \times \left(T_{cold,in} - T_{cold,out}\right)\right)}{2} \qquad (1)$$

The rate of heat transfer, Q̇, is calculated using Eq. (1), where ṁ is the mass flow rate (kg/s), Cp is the specific heat capacity (J/kg·K), and Tin, Tout are the fluid inlet and outlet temperatures (K), respectively.

Evaluating the energy performance of a HE is essential for understanding its operational efficiency. One key metric used for this purpose is effectiveness, which quantifies the exchanger's ability to transfer heat relative to its maximum potential. The effectiveness is calculated using Eq. (2).

$$\varepsilon = \frac{Q}{Q_{max}} = \frac{C_{\substack{hot\\cold}} \left(T_{\substack{hot,in\\cold,out}} - T_{\substack{hot,out\\cold,in}}\right)}{C_{min} \times \left(T_{hot,in} - T_{cold,in}\right)} \qquad (2)$$

5. RESULTS

This section presents and analyzes computational results concerning the thermophysical behavior of the baffled HCHE. Key performance indicators, including the heat transfer rate and thermal effectiveness, are assessed to examine the impact of shell diameter variation on the system's thermal efficiency. Furthermore, temperature contour plots are analyzed to depict the distribution and gradient of thermal fields within the exchanger, providing insights into the efficacy of heat exchange between the shell-side and coil-side fluids. These findings underscore the influence of geometric variations on total thermal capability.

Figure 5 illustrate the temperature contours for three shell diameters—120 mm, 140 mm, and 160 mm—within a baffled HCHE. Among the configurations, Shell 120 mm distinctly exhibits enhanced heat transfer efficiency, as evidenced by the elevated temperature distribution (yellow to red regions) concentrated around the helical coil. The compact shell design compels the shell-side fluid to stay near the coil surface, hence improving convective heat transfer through heightened flow turbulence and intensified temperature gradients. The heightened interaction between the hot and cold fluids enhances energy exchange and increases overall efficacy, which aligns with the goal of optimizing heat transfer.

The Shell 140 mm and Shell 160 mm casings exhibit increasingly colder temperature zones, especially adjacent to the outside shell wall. As the shell diameter enlarges, the flow on the shell side becomes less restricted and more stratified, diminishing contact with the coil surface and impairing heat mixing. The Shell 160 mm configuration has extensive areas of unused low-temperature fluid, leading to markedly diminished heat transmission rates. The increased distance between the coil and the shell wall results in reduced fluid velocity and decreased turbulence, both of which adversely affect convective heat transfer. Moreover, the augmentation of shell volume results in irregular flow distribution and the emergence of stagnant zones, which impede the exchanger's capacity to sustain a uniform temperature gradient. This decline in thermal performance diminishes the efficacy of the heat exchanger and leads to an inefficient utilization of shell space and material.

From an engineering and economic standpoint, an excessively large shell diameter may incur increased material expenses and need more installation area without providing equivalent thermal advantages. Consequently, Shell 120 mm exemplifies superior thermal efficiency while also embodying a more compact and economic design solution. The temperature contours indicate that a more compact shell design improves contact between the shell-side fluid and the helical coil, facilitating more uniform and enhanced heat transmission across the exchanger. These findings highlight the essential importance of optimizing shell diameter, which enhances heat transfer and improves overall design efficiency and cost-performance balance in compact heat exchanger applications.

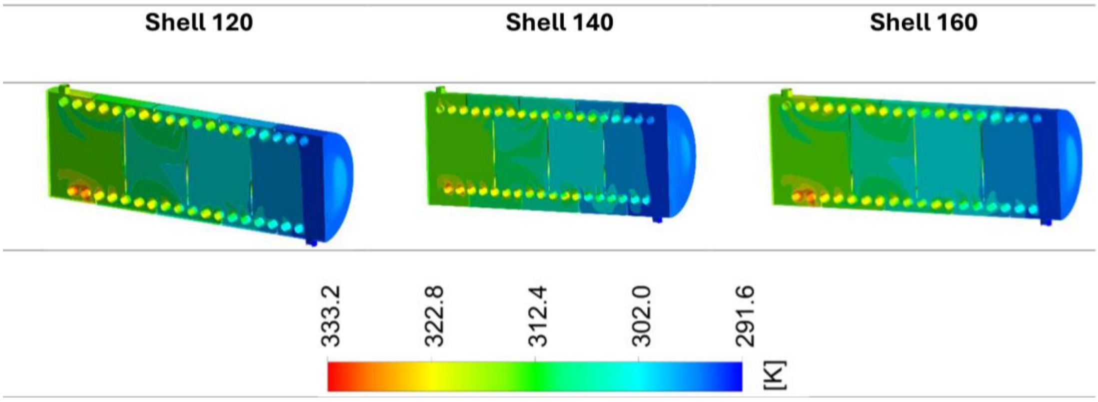

Figure 5: Temperature contour for different modifications

Figure 6 shows the velocity streamline profiles for three shell sizes: 120 mm, 140 mm, and 160 mm, in the baffled HCHE. The streamlines clearly exhibit the fluid flow dynamics within the shell side, revealing the impact of shell diameter on mixing, flow dispersion, circulation, and convective transmission.

In the Shell 120 mm configuration, the flow demonstrates greater recirculation quantity and more compact, closely spaced vortices between baffles. The streamline density and orientation suggest that the fluid is interacting with the coil surface because of the narrow shell space, which amplifies turbulence and interaction. This improved contact promotes efficient heat transfer, as the fluid is compelled to flow closely over the heated coil surfaces with minimal stagnant areas.

According to the Shell 140 mm design, the streamlines widen and exhibit a marginal decrease in the capacity of recirculating flows. While certain robust vortex regions persist, especially adjacent to the baffles, the flow seems more dispersed, indicating a moderate reduction in turbulence and mixing efficiency relative to the denser arrangement. This may result in diminished heat transmission efficiency, particularly in areas furthest from the coil surface.

In the Shell 160 mm layout, the flow exhibits markedly increased separation, characterized by wider and smoother recirculating loops and a noticeable reduction in high-velocity zones. The streamlines reveal the presence of stationary flow zones, particularly adjacent to the shell edges, where fluid velocity is minimal (as illustrated in the blue sections). These regions denote ineffective thermal zones, as diminished fluid actively participates in convective heat transfer. The diminished turbulence and the extended flow separation distance from the coil surface result in the noted decrease in heat transfer efficiency for this scenario.

The streamline plots indicate that reduced shell diameters provide superior flow confinement and mixing, hence augmenting turbulence and enhancing thermal endurance. As the shell diameter increases, flow uniformity and energy decrease, hence decreasing the performance of the HE, particularly at lower Reynolds numbers.

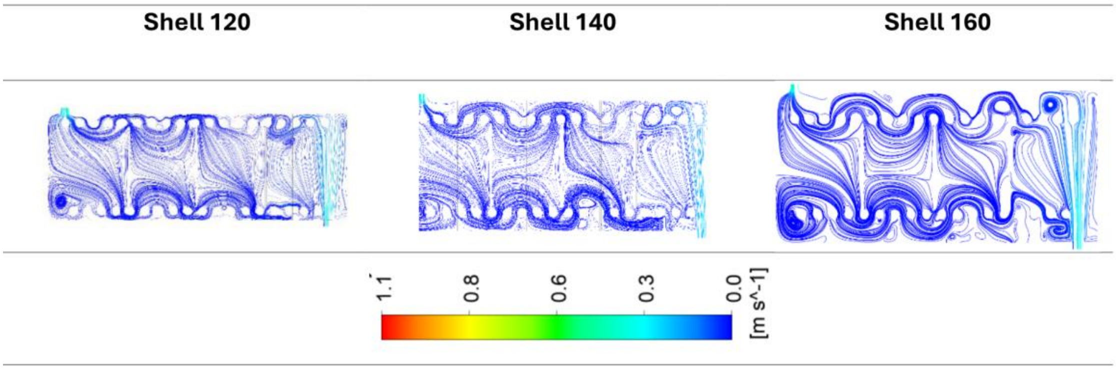

Figure 6: Streamline for different diameters

Figure 7 illustrates the fluctuation in heat exchanger efficacy concerning cold-side flow rates (2–6 L/min) for three distinct baffled shell diameters: 120 mm, 140 mm, and 160 mm. The findings indicate that the 120 mm shell consistently exhibits the maximum efficacy across all flow rates, reflecting greater thermal performance attributable to the closer fluid contact to the helical coil and improved convective interaction. This arrangement demonstrates a significant advantage at lower flow rates, achieving an effectiveness of around 0.575 at 2 L/min, in contrast to 0.555 and 0.545 for the 140 mm and 160 mm shells, respectively. With an increase in cold flow rate, efficacy improves across all configurations owing to superior mixing and elevated convective heat transfer rates. Nonetheless, the 120 mm shell exhibits a marginal performance advantage consistently, suggesting that the advantages of a more compact design endure even at elevated flow conditions. At a flow rate of 6 L/min, the effectiveness values of all three configurations start to converge, indicating a reduced impact of shell diameter as turbulence prevails. Nevertheless, the consistently superior performance of the smaller shell underscores its efficacy in optimizing heat exchange under limited flow conditions. These findings highlight the significance of optimizing shell diameter for thermal enhancement, compact design, material efficiency, and increased system responsiveness under various operational loads.

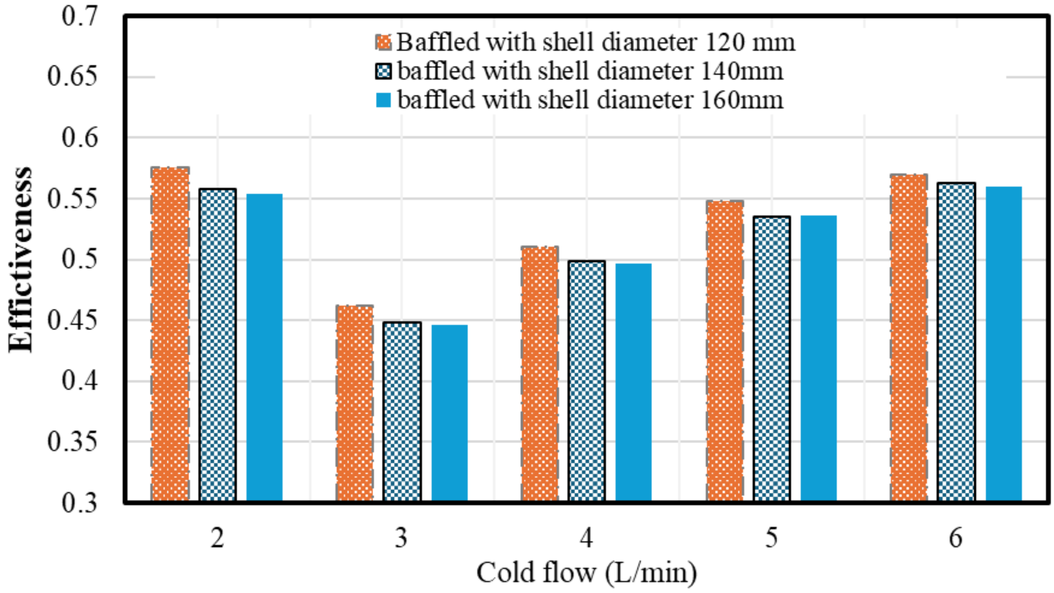

Figure 7: Effectiveness for different structural arrangements

The impact of shell diameter variation on the mean heat transfer rate was examined throughout cold flow rates between 2 and 6 L/min. Figure 8 reveals that all configurations exhibit a distinct upward trend in heat transfer rate as flow rate increases, showing the influence of elevated Reynolds numbers and enhanced convective activity. At a flow rate of 2 L/min, the HE with a 120 mm shell diameter attains a heat transfer rate of roughly 3450 W, surpassing the 140 mm and 160 mm shell configurations, which achieve around 3300 W and 3250 W, respectively. This indicates a thermal enhancement of approximately 5% to 6% favoring the more compact shell.

With elevating in the cold flow rate to 6 L/min, the performance disparity diminishes, as the 120 mm shell achieves an average heat transfer rate near 5100 W, while the 140 mm and 160 mm shells reach approximately 5000 W and 4950 W, respectively. Although the extent of benefit diminishes at elevated flow rates due to intensified convective mixing in all instances, the 120 mm shell consistently retains a thermal superiority. The results highlight that a reduction in shell diameter enhances heat transfer, especially at lower flow rates, by facilitating closer fluid interaction with the helical coil and improving the overall efficacy of the exchanger design.

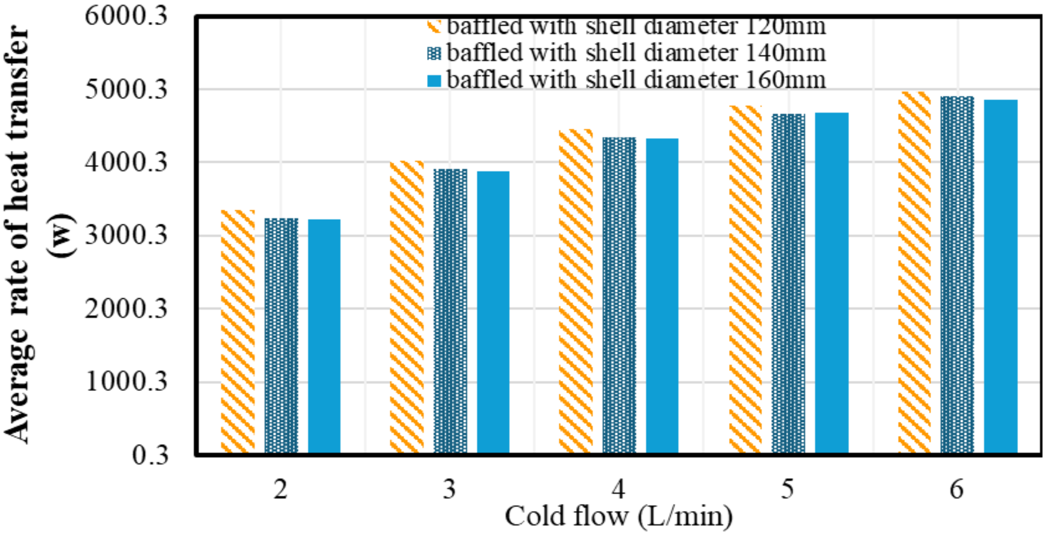

Figure 8: The rate of heat transfer for different structural arrangements

The numerical analysis indicates that the incorporation of baffles and internal fins markedly enhances the energy efficiency of the HCHE. The combination of baffles and the smallest diameter consistently shown optimal performance for efficacy, heat transfer rate, and flow field augmentation among all configurations. Baffles significantly influenced shell-side mixing and heat transfer, whilst the smaller diameter increases the contact time between fluid and the coil surface. The study further validated that the combined configuration provides the optimal balance between thermal enhancement and flow resistance, especially at reduced flow rates. Contour and streamline plots visually corroborated these findings, emphasizing the enhanced mixing and optimized temperature distribution due to geometric alterations. These findings offer significant insights into the model optimization of compact and efficient HEs for improved thermal systems.

In summary, the numerical results clearly demonstrate that shell diameter plays a critical role in shaping the energy efficiency of baffled HCHEs. Among the tested configurations, the 120 mm shell consistently achieved higher effectiveness and greater heat transfer rates within the margin of flow conditions, particularly at lower flow rates where fluid confinement enhances thermal interaction. As shell diameter increased, both effectiveness and heat transfer performance declined due to reduced turbulence and weaker contact between the shell-side fluid and the coil surface. These findings highlight the importance of geometric optimization specifically shell sizing as a key design consideration for improving exchanger efficiency, reducing energy losses, and maximizing heat recovery in compact thermal systems.

6. CONCLUSION

This study comprehensively investigated the effect of shell diameter on the thermal performance of baffled HCHEs. Through validated numerical simulations, several key observations were made regarding how shell geometry influences heat transfer behavior, fluid dynamics, and overall system efficiency. The main conclusions are summarized as follows:

- The shell diameter plays a critical role in determining the HE's thermal effectiveness and heat transfer rate.
- The 120 mm shell diameter consistently exhibited the best performance across all tested flow rates, demonstrating superior thermal behavior due to enhanced fluid proximity and stronger convective interaction with the coil.
- Larger shell diameters (140 mm and 160 mm) led to more stratified flow, reduced turbulence, and the formation of underutilized cold zones, resulting in lower heat transfer performance.
- The performance gap narrowed at higher cold flow rates (up to 6 L/min), but the compact 120 mm shell maintained a consistent thermal advantage throughout.
- A smaller shell diameter facilitated better flow confinement and turbulence generation, which are essential for efficient heat exchange, especially under lower Reynolds number conditions.
- From a practical standpoint, optimizing shell diameter not only improves thermal efficiency but also offers economic advantages by reducing material usage and system footprint.
- These findings highlight that geometric optimization, particularly in terms of shell sizing, is crucial for enhancing both performance and cost-effectiveness in compact heat exchanger applications.

- The research highlights the significance of geometrically influenced design in facilitating high-performance, compact heat exchangers, especially advantageous for offshore and marine applications where decreasing footprint, reducing weight, and enhancing thermal performance are essential.

6.1. Limitations and Future Work

This research examined the impact of shell diameter under steady-state conditions, utilizing constant fluid characteristics and simplified assumptions, including the disregard of wall conduction and fouling effects. These limits may restrict the applicability of the results to real-life operating situations.

Future studies should aim to expand the model to incorporate transient simulations, dynamic fluid properties, and a broader spectrum of geometric configurations to enhance the generalizability of the results. Ultimately, examining the complex relationship between shell geometry and other passive improvement methods (such as twisted tubes or vortex generators) may uncover further avenues for enhancing heat exchanger efficiency in small and space-restricted settings.

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