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A novel integrated approach to heat transfer enhancement using baffles and inner fins in helical coil heat exchangers

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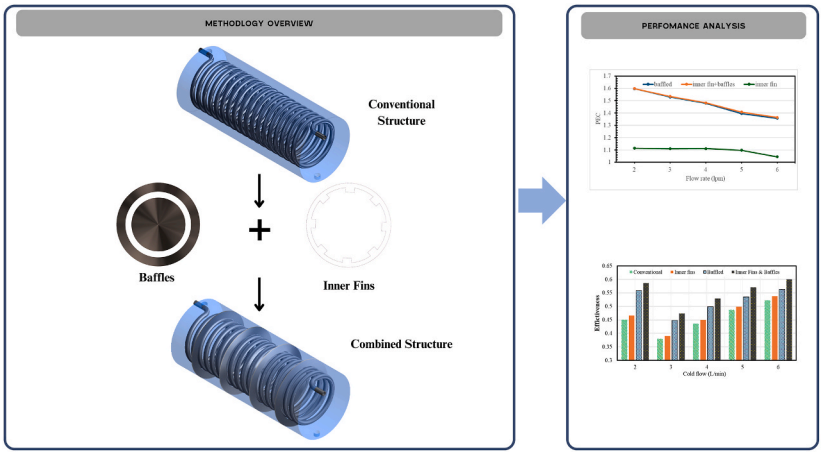
GRAPHICAL ABSTRACT



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ABSTRACT

The global rise in energy demand has intensified the need for improved efficiency in thermal systems, particularly in industrial and high-load applications. Heat exchangers play a critical role in energy recovery, and enhancing their performance is essential for maximizing overall system

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efficiency. This study presents a numerical investigation of a shell-and-helical coil heat exchanger enhanced by the integration of shell-side baffles and tube-side internal fins. A three-dimensional model was developed to simulate turbulent flow and heat transfer across four structural configurations: a conventional design, a baffled configuration, an internally finned tube design, and a combined baffle–finned configuration. The simulation results indicate that the integrated configuration achieves the highest performance improvement, with up to a 33 percent increase in effectiveness compared to the conventional design, reaching a maximum effectiveness of 0.60. The same configuration also demonstrated a peak thermal-hydraulic performance value of approximately 1.60 at low flow rates, reflecting an effective balance between heat transfer enhancement and pressure loss. The numerical model was benchmarked against experimental data with a maximum deviation of about 2 percent, supporting its reliability. The study introduces a novel enhancement strategy that combines two geometric improvements into a single configuration, offering a compact and efficient solution for advanced thermal system applications.

Nomenclature

T	Temperature, K
$\dot{m}$	Mass flow rate, kg/s
Q	Rate of Heat transfer, W
ε	Effectiveness
C_p	Specific heat capacity, J/kg.K
t	Thickness, mm
Abbreviations	
HE	Heat Exchanger
HT	Heat Transfer
HCHE	Helical Coil tube Heat Exchanger
CFD	Computational Fluid Dynamics
LMTD	Logarithmic mean temperature difference
PEC	Performance Evaluation Criteria
TKE	turbulent kinetic energy
GCI	Grid Convergence Index

1. Introduction

The escalating global energy consumption, coupled with mounting concerns regarding greenhouse gas emissions, has exerted significant pressure on various industries to adopt energy-efficient innovations. The worldwide CO_2 emissions from fossil fuels and industry have consistently risen over the past fifty years, surpassing 35 billion tons per year [1,2]. This worrisome trend underscores the necessity of mitigating ecological impacts while fulfilling energy requirements. Concurrently, worldwide energy consumption has experienced a significant surge, predominantly fueled by fossil fuels, including coal, oil, and natural gas, as depicted in Fig. 1. This overreliance on non-renewable energy sources has been shown to intensify greenhouse gas emissions and impede the realization of sustainable energy systems.

Heat exchangers (HEs) are essential components in industrial and commercial systems for effective energy transfer. Their extensive application in energy production, chemical processing, climate control systems, and the transportation industry renders them a crucial

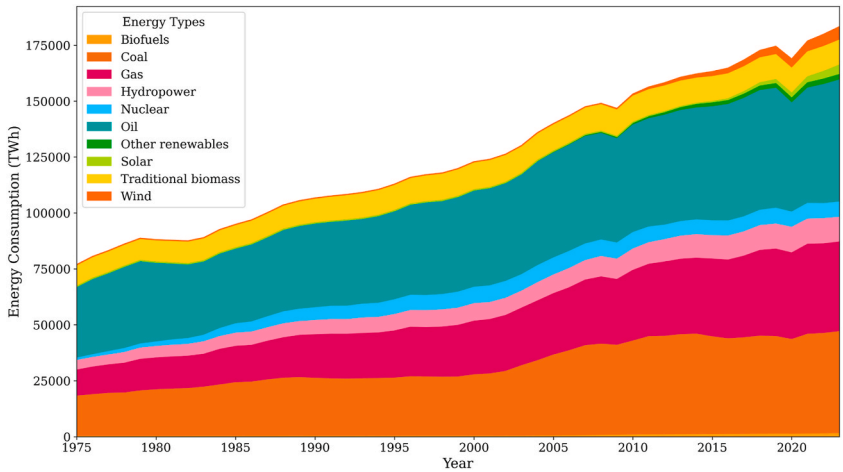

Fig. 1. Global primary energy consumption by source (1975–2023) [3].

focal point for optimizing energy use [4,5]. Improving the efficiency of heat exchangers is a viable approach to decreasing energy usage and minimizing ecological impacts in various applications [6,7]. The shell and helical coil heat exchanger has a remarkable impact on the performance of the refrigeration system compared with a conventional heat exchanger, as extending the length of the heat exchanger leads to a significant increment in the subcooling process. However, the pressure drop increases with the increase in refrigerant velocity [8]. An investigation was conducted to investigate the conservation of energy potential of utilizing wasted heat from a cooling system (R410A) through a helical coil tube-shell heat exchanger. The study found that this approach resulted in a 12.5 %–40 % improvement in the coefficient of performance (COP) [9]. Helical coil heat exchangers have enhanced performance owing to the generation of secondary flow patterns (Dean vortices), which improve thermal energy efficiency. Their small size and capacity to manage varied working conditions make them a favored option in industrial and commercial applications [10]. There are different ways to enhance heat transfer (HT) inside the heat exchanger; most of these techniques are used to increase the turbulence intensity of the fluid flow [11,12]. Structural enhancement is the main key to enhancing turbulence intensity. Changing the traditional pass of the fluid flow can increase the turbulence intensity which can be happened by either extending the contact surface area like adding fins or adding different barrier structure in the path of the fluid flow such as the commonly used enhancement that called baffles.

The integration of baffles in HEs can improve HT efficiency by augmenting the Nusselt number by as much as 1.54 times relative to plain tubes, albeit with a considerably greater pressure drop [13]. Numerical investigations on helical coil heat exchangers have shown that introducing flow-guiding structures such as twisted tubes can significantly enhance thermal-hydraulic performance, similar to the role of baffles in promoting secondary flow and fluid mixing. The study reported up to a 35 % improvement in heat transfer and a 10 % increase in the Performance Evaluation Criterion (PEC), emphasizing the effectiveness of flow disturbance mechanisms like baffles in improving heat exchanger efficiency [14]. The installation of drilled spiral baffles in coiled elastic copper tube heat exchangers can markedly improve heat flow efficiency, achieving enhancements of the JF-factor (overall heat transfer performance factor) of up to 4.28 % and overall HT performance increases of up to 4.24 %, underscoring their applicability in engineering contexts [15]. A recent numerical study on shell-and-tube heat exchangers with non-continuous helical baffles demonstrated that optimizing helix angle and hybrid nanofluid concentration can significantly enhance heat transfer performance and thermal efficiency, achieving up to a 6 % improvement over previous configurations [16]. To capitalize on The advantages offered by the compact design and high efficiency of spiral elastic tube HEs, reverse baffle spiral tube heat exchangers have demonstrated potential, attaining a utmost enhancement in the overall heat transfer coefficient (HTC) of 14 % with a single spiral baffle, while also emphasizing the influence of fluid-induced vibration on augmenting turbulence and heat transfer efficacy [17]. Unique baffle layouts, especially non-equal-shaped baffles, have shown a substantial thermal increase, elevating the thermal enhancement factor by 44 % relative to a basic channel absent of baffles, thereby improving thermal transfer and augmenting system effectiveness [18]. The integration of louver-punched triangle baffle vortex creators within the heat exchanger has demonstrated a significant improvement in thermal performance, with the Nusselt number increasing by as much as 5.1 times and achieving the highest thermal enhancement factor of 2.5 under optimized conditions, underscoring the efficacy of the louver-punched triangle baffle in facilitating fluid mixing and HT [19]. The X-type baffle configuration in shell-and-tube HEs exhibits enhanced mixing and HT efficiency compared to conventional shell-and-tube HEs, while also offering improved distribution mixing and a more uniform residence time distribution, though it incurs a higher pressure drop [20]. The implementation of a cross baffle markedly improves the thermal performance of nanofluids by facilitating vortex formation and enhancing thermal layer diffusion, resulting in augmented heat transfer efficiency [21]. The inclusion of a movable baffle structure markedly elevates the distribution of heat under laminar flow conditions, with optimal efficacy noted when the heat source is positioned at the bottom near the baffle, especially while employing a nanofluid with elevated nanoparticle weight fractions, leading to enhanced convective HT [22]. The installation of the fins is known as his ability to boost the rate of HT and somehow escalate the turbulence intensity.

Fins are generally engineered to improve heat transmission by enlarging the contact surface area, with their thermal efficacy affected by several factors, including fin height, width, pitch, and configuration. The incorporation of high thermal conductivity fins markedly improves heat transfer [23]. Optimum fin structures, including suitable length and spacing, significantly boost heat and mass transfer performance, resulting in significant increases in total system effectiveness [24]. Recent studies show that using nanofluids with optimized fin geometries in double-pipe heat exchangers can enhance thermal performance by up to 85 % [25,26]. A research investigation for the thermal behavior of a finned shell-and-tube system demonstrates that augmenting the number and height of fins markedly improves charging and discharging efficiencies, with an optimal configuration yielding efficiencies of 91.49 % and 86.4 %, correspondingly [27]. Pin fins markedly improve heat transfer by facilitating fluid mixing and vortex generation. At Re = 500, pin-finned microchannels featuring superhydrophobic sidewalls attain a base temperature reduction of 9.4 °C and enhance the Nusselt number by 6.6 %, demonstrating their efficacy in thermal management systems [28]. The integration of interrupted fins in pipes markedly improves the ability to transfer heat by elevating the heat transfer coefficient, especially when optimizing fin height, the number of fin rows, and interruption length, achieving enhancements of up to 25 % compared to conventional tubes under customized flow parameters [29]. A scientific investigation tested the effect of copper conical fins on the efficacy of conical solar distillers. The findings indicate that copper conical fins enhanced productivity by 33.33 %, 17.71 %, and 10.41 % at 0 cm, 1 cm, and 2 cm spacing, respectively, in comparison to the conventional distiller. The data underscore the substantial enhancement in distiller yield achieved by employing copper conical fins and emphasize the critical role of fin spacing in reducing shading [30]. Micro-finned surfaces have demonstrated efficacy in improving flow boiling ability by substantially augmenting the HT coefficient and diminishing thermal resistance, attaining a maximum enhancement of 59.3 % relative to smooth surfaces with ideal fin arrangements [31]. Recent studies quantitatively assessed the HT performance of asymmetric elliptical-cylindrical pin fin heat sinks in turbulent flow, revealing that improved fin geometries and perforation structures markedly improve thermal performance, with fin effectiveness rising by up to 2.25 relative to cylindrical pin fin arrangements [32]. Plate-fin heat sinks are affected by Reynolds number, fin quantity, and breadth, with

increased Reynolds number enhancing heat transmission and diminishing friction. Advanced models such as GA-BP neural networks effectively forecast their abilities under various scenarios [33]. Curved blade-like fins featuring NACA airfoil cross-sections have greater thermal performance and diminished fluid resistance relative to cylindrical fins, resulting in improved energy transmission via secondary flow generation and streamlined designs [34]. The thermal performance of a shell-and-helically coiled finned tube heat exchanger was examined, with conventional annular fins being compared to four novel fin geometries to evaluate improvements in HT efficiency. The stepped fin configuration attained an 80.79 % greater Nusselt number on the shell side relative to the simple annular fin, while an increase in fin pitch yielded a decrease in the shell side's Nusselt number. The Reynolds number exerted a negligible influence on the HT on the opposite side [35]. A study examined the effect of several fin geometries on the thermal efficiency of a shell-and-tube HE, with an emphasis on segmented and helical fins. Both fin forms augment the efficiency of the HE, with helical fins enhancing efficacy by 17 % relative to plain tubes. Segmented fins enhance efficiency by 6 %. The findings indicate that augmenting fin height enhances efficiency, whilst elevating fin pitch diminishes it. The ideal arrangement for enhanced thermal performance integrates minimal surface roughness with helical fins that possess a reduced pitch and increased height [36]. Internally finned helically coiled tubes enhance heat transfer by approximately 30 % compared to smooth tubes, though at the cost of increased pressure drop and heat load [37].

Previous studies indicate that baffles and fins are essential for optimizing HE performance by improving heat transfer rates and flow distribution. Baffles have been shown to increase flow turbulence and heat transfer on the shell side, while fins have been demonstrated to significantly expand the heat transfer surface area and enhance the efficiency of the HE. However, there has been no research conducted on the synergistic or hybrid impacts of integrating these two advancements within a single HE. Hybrid enhancement techniques have shown promising results in recent studies. For instance, a comparative investigation between circular and elliptical finned tube HEs demonstrated the superior performance of elliptical finned tubes [38]. This study investigates the synergistic effects of integrating baffles with an inner-finned helical tube in a shell-and-helical tube HE, offering a thorough assessment of their collective impact on thermal and hydraulic performance.

To the best of the authors' knowledge, no prior study has comprehensively investigated the combined effects of shell-side baffles and tube-side internal fins within a single shell-and-helical coil heat exchanger configuration. Previous works have primarily focused on these enhancement techniques individually, demonstrating that baffles improve shell-side turbulence and fluid mixing, while internal fins enhance tube-side surface area and localized convection. However, their synergistic interaction, which could potentially yield superior thermal-hydraulic performance, remains unexplored. The present study introduces a novel computational fluid dynamics (CFD) analysis that integrates both enhancement strategies into one design and systematically evaluates their individual and

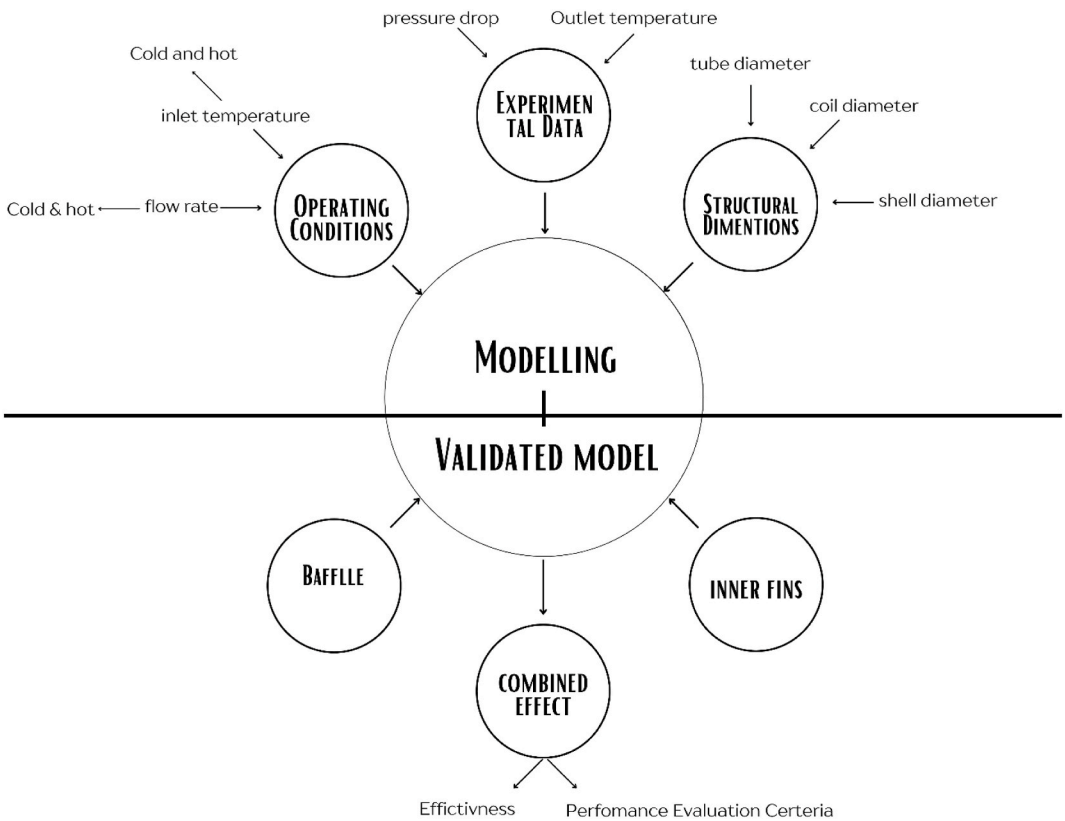

Fig. 2. Diagram for methodology procedure.

combined influences on heat transfer rate, effectiveness, pressure drop, and the Performance Evaluation Criterion (PEC). Four configurations are analyzed, conventional, baffled-only, finned-only, and hybrid (baffles + fins), under a range of flow conditions to provide a comprehensive comparative assessment. The findings reveal the synergistic mechanisms between shell-side turbulence generation and tube-side surface augmentation, offering new insights into the optimization of compact, high-efficiency heat exchangers. This study thus contributes a distinct and original perspective on the design and performance enhancement of shell-and-helical coil heat exchangers, bridging the gap between existing single-enhancement approaches and hybrid structural designs for advanced thermal systems.

2. Material and methods

The present research employs a simulation-based approach to assess the thermal-hydraulic efficiency of a shell and helically coiled tube heat exchanger (HCHE) fitted with baffles and internal fins. The simulation procedure is structured into the main essential phases:

1. **Geometry Creation:** A three-dimensional computational model of the HE is constructed by ANSYS Fluent, integrating the geometric characteristics of the shell, helical coil, baffles, and internal fins.
2. **Mesh Generation and Grid Independence:** A structured mesh is created to precisely represent the flow and temperature gradients. Grid independence research is performed to ascertain the mesh density that guarantees numerical precision while reducing computational expense.
3. **Model Setup:** The k-epsilon turbulence model is utilized for its reliability in forecasting turbulent flow and heat transfer in complicated structures. Fluid properties and boundary conditions are utilized to depict diverse operational scenarios.
4. **Model Validation:** The simulation model is validated by examining simulation outcomes with experimental data and an earlier published numerical model [39,40]. Validation relies on many performance measures to guarantee the dependability of the simulation framework.
5. **Parametric Study:** Following validation, a parametric analysis is performed to evaluate the effects of various fin and baffle configurations on thermal efficiency and pressure loss. This entails modifying the internal structure and flow rates to assess performance under various operating conditions.
6. **Performance Analysis:** The collected data are analyzed to determine the influence of individual and combined enhancements on HT, effectiveness, and the Performance Evaluation Criterion (PEC).

This systematic strategy provides a comprehensive understanding of the performance benefits of employing baffles and internal fins in helically coiled HEs. The comprehensive simulation process, encompassing geometry generation and performance assessment, is systematically represented in Fig. 2, which offers a visual overview of the employed computational methodology. This graphic elucidates the workflow and emphasizes the logical sequence of the modeling, validation, and analytic phases conducted in this study.

3. Model description

The HCHE examined in this study possesses a cylindrical shell with an overall length of 340 mm and a nominal inlet and outlet diameter of 12 mm. The helical tube, constructed from tubing with a nominal diameter of ¾", possesses an overall coil diameter of 100 mm and a coil length of 300 mm. The design ensures optimal thermal efficiency by facilitating the effective exchange of heat between the working fluids circulating through the shell and the helical coil. The dimensions were presented as shown in Fig. 3.

The baffles in the HCHE are engineered to improve HT and are affixed to the inside wall of the shell. Each baffle possesses an exterior diameter of 140 mm, an inner diameter of 110 mm, and a thickness of 1.5 mm, guaranteeing a secure fit against the shell wall, as shown in Fig. 4. The internal fins, incorporated within the helical coil, possess a thickness (t) of 12 mm and a length of 3 mm, thereby

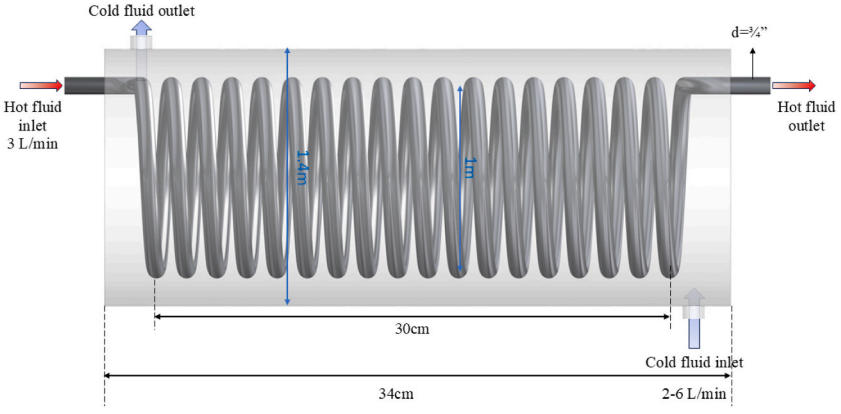

Fig. 3. HCHE structure.

enhancing the heat transfer surface area and facilitating turbulence in the flow. The integration of baffles and internal fins enhances thermal efficiency by optimizing fluid distribution and augmenting convective heat transfer.

3.1. Numerical model

The present investigation utilized ANSYS Fluent 19.0 software to conduct three-dimensional computational simulations of HCHE to assess and compare the thermohydraulic behavior of different structural designs. The modeled configurations consist of: (1) a conventional HCHE, (2) a baffled HCHE, (3) an internally finned HCHE, and (4) a hybrid design that integrates both baffles and internal fins. Table 1 shows the cell number of each structure, its skewness, and aspect ratio, and a sample of mesh structure is shown in Fig. 5. These improvements are intended to enhance the convective heat transmission mechanism within the shell side and the helical tube.

These adjustments are implemented to examine their solo and synergistic impacts on heat transmission. In all simulations, the working fluid is water, represented as an incompressible fluid with invariant thermophysical parameters. The governing equations for mass, momentum, and energy were discretized via the finite volume method.

The numerical configuration comprised the subsequent essential modeling components:

- The k-epsilon (k-ε) turbulence model was utilized for its shown effectiveness in accurately representing intricate turbulent flows, especially in coiled configurations [41–43].
- The fluid motion and heat transmission processes were represented by the Navier-Stokes equations, which encompass [14,44]:

○ **Continuity Equation (Mass Conservation):**

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

○**Momentum Equation (Navier–Stokes):**

$$\nabla \cdot (\rho \cdot \vec{v} \cdot \vec{v}) = -\nabla p + \nabla \cdot \left(\mu \left[(\nabla \vec{v} + \nabla \vec{v}^{T}) - \frac{2}{3} \nabla . \vec{v} I \right] \right) \tag{2}$$

○**Energy Equation:**

$$\nabla \cdot \left(\vec{V} (\rho E + p) \right) = \nabla \cdot k_{eff} \nabla T - h \vec{J} + \left(\mu \left[(\nabla \vec{v} + \nabla \vec{v}^{T}) - \frac{2}{3} \nabla . \vec{v} I \right] \cdot \vec{v} \right) \tag{3}$$

○**Turbulence equations:**

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \epsilon + Y_M + S_k \tag{4}$$

$$\frac{\partial}{\partial t}(\rho \epsilon) + \frac{\partial}{\partial x_i}(\rho \epsilon u_i) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_j} \right] + C_{1\epsilon} \frac{\epsilon}{k} (G_k + C_{3\epsilon} G_b) + C_{2\epsilon} \rho \frac{\epsilon^2}{k} + S_\epsilon \tag{5}$$

- Near-wall treatment: Enhanced wall functions were utilized to appropriately resolve boundary layer behavior [45–47].
- Pressure-velocity coupling: The pressure velocity coupling was resolved using the SIMPLEC (Semi-Implicit Method for Pressure Linked Equations Consistent) algorithm, which facilitates stable and accurate convergence while maintaining mass and momentum

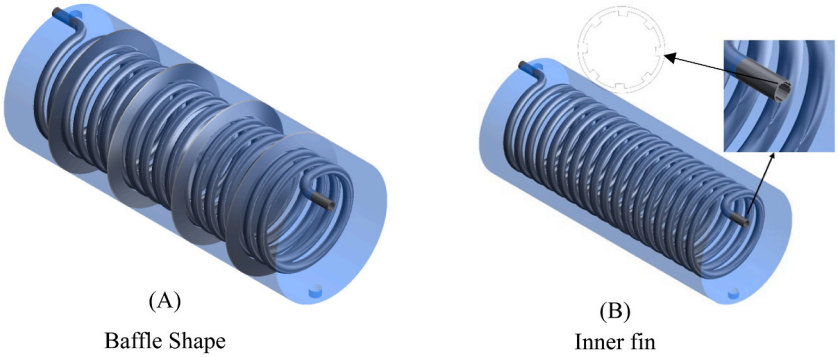

Fig. 4. Modification structures; (A) Baffle shape, (B) Inner fins.

Table 1
Statistical mesh data.

Structural Design	Element Number	Average Aspect Ratio	Average Skewness
Conventional	7,832,277	1.7567	0.23263
Baffled	8,912,603	1.9168	0.26821
Inner finned tube	8,679,066	1.9787	0.29125
Hybrid Design (Baffled + Inner fins)	9,420,568	1.9678	0.28695

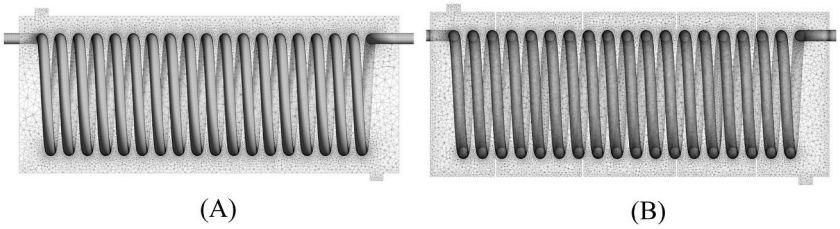

Fig. 5. Mesh structure; (A) Conventional, (B) Baffled cases.

conservation. A second-order upwind scheme was employed for the discretization of momentum, energy, and turbulence transport equations (k and ε), minimizing numerical diffusion and improving overall solution accuracy [44]. Pressure discretization was carried out using the second-order scheme, and gradients were calculated using the least-squares cell-based method, offering robust interpolation accuracy particularly in unstructured meshes. This combination of algorithms and discretization techniques ensures both numerical stability and high-resolution capture of flow and thermal phenomena within the simulation domain.

The boundary requirements for all configurations were as follows:

- The cold fluid entered the shell side from the bottom intake at 18.65 °C, with flow rates of 2, 3, 4, 5, and 6 lpm.
- The heated fluid entered the helical tube by a lateral entrance at 60.15 °C, maintaining a constant flow rate of 3 L per minute.

Furthermore:

- A counter-flow arrangement was employed in all simulation cases, where the liquids on the shell side and tube side flow in opposing directions across the length of the helical coil heat exchanger. As the heated fluid enters from the left side of the helical tube and the cold flow enters from the bottom right of the shell tube. The mesh was independently validated (not depicted here) to confirm solution independence.
- The convergence criterion for the continuity and velocity was established at 10^{-3}, and energy equations were established at 10^{-5} for all simulated configurations.

This comprehensive numerical approach facilitated the consistent assessment of the thermal and hydraulic performance of each HCHE configuration, establishing a basis for assessing the efficacy of internal fins and baffles, both individually and collectively, as



Fig. 6. Tele view for the test rig.

thermal enhancement measures.

4. Validation

A two-stage validation method was established to ascertain the correctness and dependability of the created numerical model, utilizing both experimental and numerical benchmarks [39,40].

Initially, the model was validated using experimental data from the authors' prior study [39], which examined the thermal performance of a conventional HCHE. The validation employs the experimental test setup depicted in Fig. 6. This arrangement was chosen as a baseline reference. The numerical predictions are compared with experimental data and demonstrate substantial concordance, with the absolute errors remaining within acceptable engineering limits between 2 % and 4 %. This validates the model's precision in representing the essential thermal-hydraulic characteristics of the standard setup.

In the second stage, additional validation was conducted by contrasting the current model's results with those from a published numerical work by Gungor et al. [40], which examined improved helical coil designs under analogous boundary conditions.

This dual validation method, grounded on experimental data and numerical benchmarking, exhibits the model's robustness and reliability for parametric studies and performance optimization. The main parameter for comparison procedure is the outlet temperatures for both fluids, cold and hot fluid.

The accuracy of the computational model used in this study was previously validated in earlier work by comparing simulated and experimental outlet temperatures of the hot and cold fluids for a conventional HCHE. As shown in Fig. 7, for a fixed hot water flow rate of 3 kg/min, the maximum deviation between simulation and experiment was 2.1 °C on the hot side and 2.25 °C on the cold side, both occurring at intermediate cold flow rates. Further validation was performed for the baffled HCHE configuration by benchmarking against the numerical and experimental results published by Güngör et al. [40]. As illustrated in Fig. 8, the simulation results differed by no more than 0.85 °C from the experimental data and by less than 0.5 °C from the published numerical model. These findings confirm the reliability of the present simulation methodology in accurately predicting the thermal performance of both conventional and modified HCHE designs.

4.1. Grid Independence

A grid convergence examination was conducted for the peak hot fluid temperature, utilizing a sequence of constantly modified grids. The simulations encompassed mesh densities between roughly 3 million and 8 million cells. The peak hot fluid temperature data are represented in Fig. 9, depicting temperature as a function of the number of mesh elements.

In accordance with the instructions established by Roache [48], the Richardson Extrapolation technique was utilized to approximate the asymptotic solution on a refined grid. The apparent order of accuracy P was determined using:

$$P = \frac{\ln\left(\frac{\varnothing_1 - \varnothing_2}{\varnothing_2 - \varnothing_3}\right)}{\ln(r)} \tag{6}$$

where.

- $\varnothing_1$ is the solution on the coarse grid,
- $\varnothing_2$ is the solution on the medium grid,
- $\varnothing_3$ is the solution on the finest grid,
- and r is the grid refinement ratio.

The extrapolated solution $\varnothing_{ext}$ was then computed using Eq. (7), to estimate the grid-independent result.

$$\varnothing_{ext} = \varnothing_3 + \frac{\varnothing_3 - \varnothing_2}{r^p - 1} \tag{7}$$

The Grid Convergence Index (GCI) was calculated to quantify the numerical uncertainty due to discretization:

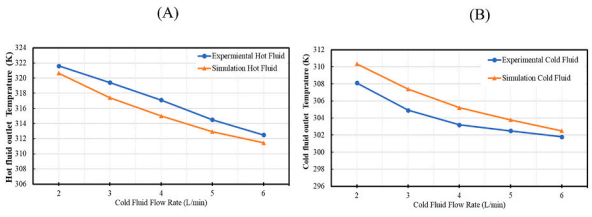

Fig. 7. Analysis of outlet temperatures between simulation and experimental studies for Conventional HCHE: (A) Hot fluid and (B) Cold fluid [39].

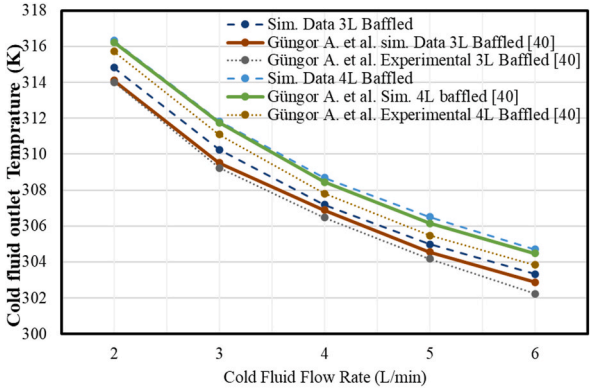

Fig. 8. Evaluation of hot fluid outlet temperatures among simulation, numerical analysis, and experimental results for baffled heat exchanger systems [40].

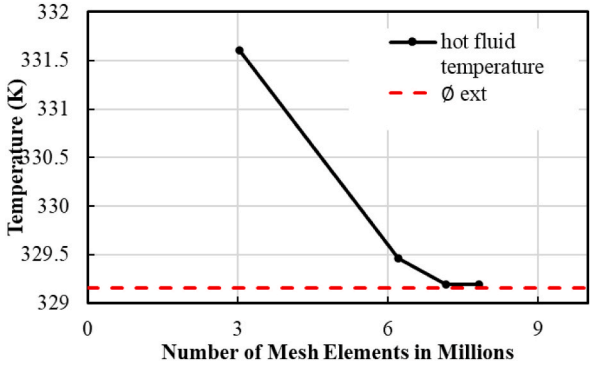

Fig. 9. Independence study curve.

$$GCI_{fine} = \frac{1.25|\varnothing_3 - \varnothing_2|}{\varnothing_3(r^p - 1)} \times 100\% \tag{8}$$

The red dashed line in Fig. 9 indicates the extrapolated temperature, which signifies the projected grid-independent solution. The extrapolated peak hot fluid temperature was roughly 329.0 K, which is lower than the peak temperature recorded at the coarsest grid (~3 million elements, ~331.5 K). This trend illustrates that smaller meshes diminish numerical mistakes and more accurately represent the underlying solution behavior.

The Grid Convergence Index (GCI) was computed utilizing overlapping grid triplets with a safety factor of 1.25, as instructed by Roache [48]. The GCI measures the numerical uncertainty arising from discretization error and is represented as a percentage of the fine grid solution. At the optimal grid level, the GCI was calculated to be 0.0139 %, indicating that the solution resides comfortably within the asymptotic convergence range and that the discretization error is sufficiently minimal.

This comprehensive study validates that the numerical solution has achieved a state of near grid-independence, exhibiting minimal discretization uncertainty. This finding serves to substantiate the reliability of the results obtained. This method aligns with established procedures in computational fluid dynamics, ensuring that numerical simulations adhere to recognized criteria for verification.

5. Post processing calculation

This section delineates the mathematical formulations utilized for the theoretical assessment of the computational simulation outcomes. The HT on the hot and cold fluid sides of the HCHE is calculated using Eq. (9), which incorporates mean specific heat capacity values to ensure precision in the evaluation of thermal performance. To further assess the exchanger's efficiency, critical performance indicators such as effectiveness and PEC are analyzed based on the numerically derived data. These characteristics provide a thorough understanding of the heat exchanger's performance by considering both thermal enhancement and related flow resistance [49,50].

$$\dot{Q}_{av} = \frac{\left(\left(\dot{m}_{hot} C_p \times \left(T_{hot,in} - T_{hot,out}\right)\right) + \left(\dot{m}_{cold} C_p \times \left(T_{cold,in} - T_{cold,out}\right)\right)\right)}{2} \tag{9}$$

A crucial element in the assessment of HEs is the evaluation of their thermal behavior. The effectiveness of the HE can be assessed

using Equation (10).

$$\varepsilon = \frac{Q}{Q_{max}} = \frac{C_{\substack{hot \\ Cold}} \left(T_{\substack{hot,in \\ Cold,out}} - T_{\substack{hot,out \\ Cold,in}} \right)}{C_{min} \times \left(T_{hot,in} - T_{cold,in} \right)} \tag{10}$$

The PEC is a methodology for evaluating the improvement of convective heat transfer performance. In numerous methods designed to promote fluid flow and HT, an augmentation in convective HT frequently correlates with an increase in flow resistance, resulting in elevated power consumption and an adverse element in the improvement of HT. Usually, the impact of flow resistance is more significant. Accordingly, the PEC, predicated on uniform pump power, serves as an all-encompassing metric that incorporates both augmented HT and the associated flow resistance. It is characterized as [51,52]:

$$PEC = \left(\frac{Nu}{Nu_0} \right) \tag{11}$$

6. Results

The numerical results of the shell and helical coil heat exchanger with baffles and inner fins, as simulated, are presented and analyzed in this section. Essential thermal performance metrics, such as effectiveness, heat transfer rate, and the Performance Evaluation Criterion (PEC), are assessed to comprehend the impact of geometric alterations. Furthermore, multiple contour plots of temperature, velocity, and pressure distributions are analyzed to elucidate the flow and heat transfer characteristics within the heat exchanger. These results underscore the influence of design improvements on thermal performance and hydrodynamic properties.

6.1. The rate of heat flow

The rate of heat flow is a fundamental parameter in evaluating the thermal performance of heat exchangers, as it directly reflects the system's ability to transfer thermal energy between fluids under specific operating conditions. Fig. 10 displays the fluctuation in the mean heat transfer rate and turbulent kinetic energy (TKE) in relation to the cold fluid flow rate across several configurations of the shell and helical coil heat exchanger. All configurations exhibit a positive relationship between flow rate and heat transfer rate, attributed to enhanced convective heat transfer at higher Reynolds numbers.

The baffled configuration with an inner fin design consistently attains the highest heat transfer rates, surpassing 5300 W at the maximum flow rate evaluated at 6 lpm. The exceptional performance results from the synergistic effects of augmented turbulence from the baffles and the increased internal surface area from the fins, which improves energy exchange on the tube side. The turbulence facilitates better mixing, while the fins enhance conductive and convective transfer, particularly on the hot fluid side.

The baffled-only configuration closely follows, suggesting that disruptions in shell-side flow significantly enhance heat transfer, indicating that shell-side turbulence plays a more dominant role in heat transfer enhancement than surface area alone. The inner fin configuration demonstrates a modest enhancement compared to the traditional design, although it falls short of the baffled designs, especially at elevated flow rates.

The TKE patterns corroborate these conclusions. Configurations using baffles and/or internal fins demonstrate increased TKE relative to the standard arrangement, signifying enhanced turbulent mixing. The baffled arrangement with inner fins again results in the highest TKE, reaching roughly 0.0335 m^2/s^2, while the baffled-only case likewise exhibits greater TKE than other configurations. The inner fin-only configuration exhibits reduced TKE values, reinforcing the assertion that baffles are the primary contributors to turbulence on the shell side. In summary, the combined use of baffles and inner fins leverages both shell-side turbulence and increased

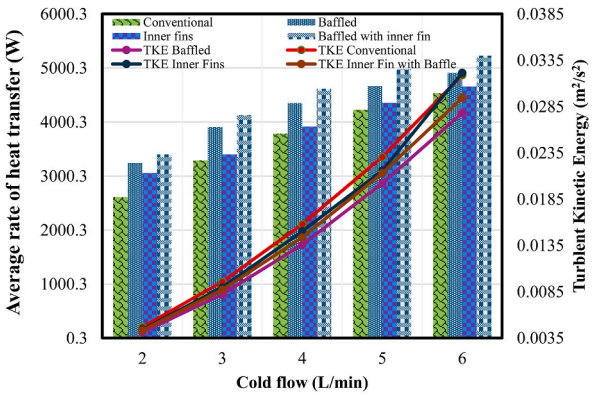

Fig. 10. The rate of heat transfer for different structural arrangements.

surface area to maximize heat transfer performance, as evidenced by the consistent improvement in both heat transfer rate and TKE across all flow rates tested. These findings highlight the importance of geometric enhancements in optimizing the thermal performance of shell and helical coil heat exchangers.

The results confirm that the integration of geometric adjustments baffles for shell-side turbulence and fins for surface enhancement offers a dual approach to improving thermal behavior. This dual methodology is particularly efficacious at elevated flow rates, when convective phenomena predominate. The findings highlight the physical importance of flow field modulation in improving energy transfer in small HE designs.

Fig. 11 illustrates that the variation of the surface Nusselt number with flow rate demonstrates substantial variations among the four analyzed configurations of the helical coil heat exchanger (HCHE). A steady increase in the Nusselt number is noted with rising flow rates across all scenarios, indicating the impact of elevated Reynolds numbers on the enhancement of convective heat transfer. The rate of enhancement fluctuates based on the interior geometry and the existence of flow-augmenting elements like fins and baffles.

The conventional arrangement has the lowest Nusselt numbers across the examined range, partly because it lacks flow interference features that could enhance mixing or destabilise the boundary layer. The addition of inner fins leads to a moderate enhancement, due to the augmented heat transfer surface area and the localised swirl created along the tube wall. Nonetheless, the improvement is constrained as the produced turbulence is restricted to the tube side.

The baffled arrangement exhibits a more significant improvement relative to both the conventional and finned scenarios. This enhancement results from the shell-side baffles, which modify the flow motion, generating cross-flow and localized recirculation zones that increase fluid mixing and thermal uniformity throughout the shell region.

The combined arrangement, incorporating both baffles and inner fins, produces the maximum Nusselt numbers at all flow rates, demonstrating a synergistic relationship between shell-side and tube-side benefits. The baffles facilitate extensive fluid mixing, while the internal fins enhance localised convection on the tube side, collectively reducing heat resistance. At elevated flow rates, the integrated system attains an enhancement of around 20–25 % in the Nusselt number relative to the conventional scenario, underscoring its better thermal-hydraulic effectiveness.

The results underscore that the concurrent use of internal fins and baffles optimally utilises the benefits of both enhancement schemes, resulting in a more thermally efficient heat exchanger design while little affecting hydrodynamic performance.

6.2. Hydrodynamic performance

Fig. 12 illustrates the associated pressure drop characteristics. A steady increase in pressure drop with rising flow rate is observed across all configurations, aligning with enhanced fluid momentum and viscous effects at elevated Reynolds numbers. The conventional and finned cases exhibit approximately equal pressure decreases, suggesting that the incorporation of fins adds negligible resistance. The perplexed and integrated designs demonstrate marginally elevated pressure losses, with the integrated scenario exhibiting the greatest increase (about 7–10 % compared to the conventional case at 6 lpm). This increase is due to the turbulence and flow redirection created by baffles; however it stays within an acceptable range considering the substantial boost in heat transfer obtained.

6.3. The thermal performance metrics

Thermal performance indicators, including effectiveness and the Performance Evaluation Criterion (PEC), offer significant insight into the efficiency of heat exchangers by reflecting the relationship between heat transfer improvement and the corresponding hydraulic performance. Effectiveness is defined as the heat exchanger's capacity to attain optimal thermal exchange, thereby serving as a direct metric for evaluating thermal behavior efficiency. Concurrently, PEC evaluates the net benefit of any heat transfer enhancement method by taking into account both the enhancement in heat transfer and the rise in flow resistance. This section undertakes a comprehensive analysis of these parameters across a range of configurations, encompassing conventional, baffled, finned, and mixed designs, over a spectrum of cold fluid flow rates. The results of the study provide a comparative analysis of the impact of geometric adjustments on the thermal-hydraulic performance of the helical coil heat exchanger.

As illustrated in Fig. 13, the effectiveness of the heat exchanger exhibits fluctuations across a range of cold flow rates for four distinct configurations: the conventional design, inner fins configuration, baffled configuration, and an integrated design combining

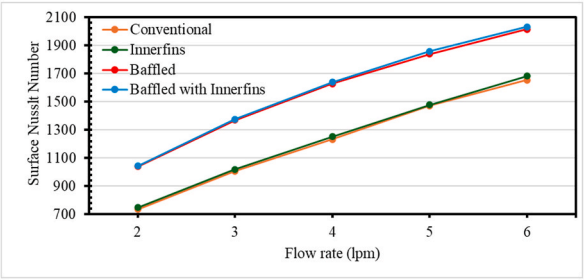

Fig. 11. Variation of surface Nusselt number with flow rate for different configurations.

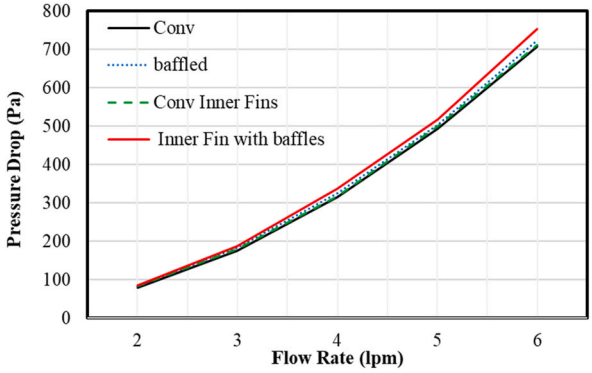

Fig. 12. Variation of Pressure drop with different structure.

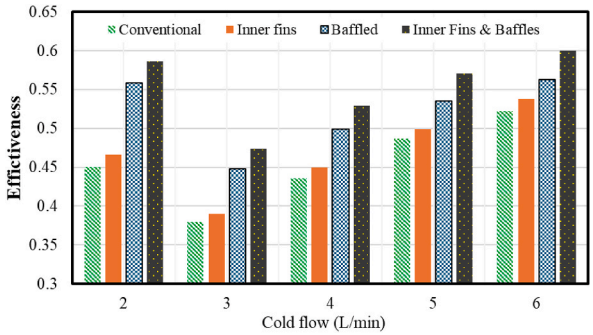

Fig. 13. Effectiveness for different structural arrangements.

inner fins and baffles. The combined layout (inner fins and baffles) consistently attains the highest effectiveness across all flow rates, achieving about 0.60 at 6 L/min and 0.58 at 2 L/min with maximum enhancement around 33 % compared to conventional setup, signifying a significant enhancement over the conventional arrangement and previous studies for different modification [53,54]. This outcome highlights the multiple benefits of incorporating shell-side turbulence (through baffles) and augmenting surface area (via internal fins), which collectively improve convective heat transfer and fluid-wall thermal interaction. At reduced flow rates, the prolonged residence time facilitates more efficient thermal exchange, but at elevated flow rates, the enhanced mixing maintains the temperature gradient throughout the exchanger.

The baffled structure solely provides a substantial enhancement compared to the conventional case. At a flow rate of 2 L/min, the baffled arrangement attains an efficacy of 0.56, in contrast to 0.45 for the traditional setup, indicating a 24.4 % enhancement which is a notable effect compared with the previously studied baffles [15,17]. At a flow rate of 6 L/min, the baffled design exhibits robust performance with an efficacy of 0.56, underscoring the essential function of baffles in disturbing shell-side flow, creating vortices, and rejuvenating the thermal boundary layer.

The internal fin arrangement demonstrates a minor improvement, with effectiveness values increasing from 0.47 at 2 L/min to 0.54 at 6 L/min. This indicates around a 15 % enhancement compared to the conventional setup at elevated flow rates, while its effect

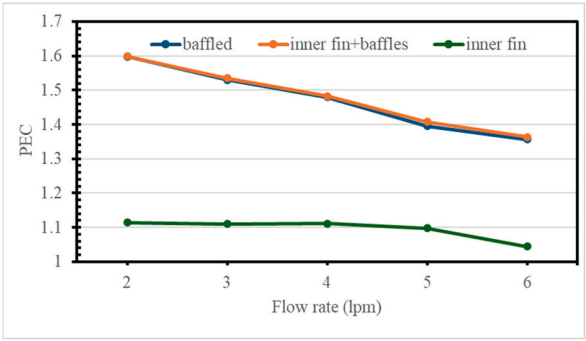

Fig. 14. The PEC for different structural arrangements.

diminishes at reduced flow rates owing to insufficient shell-side turbulence. The improvement is mostly due to the augmented heat transfer surface area on the hot fluid side, which becomes more efficient as the convective heat transfer coefficient rises with velocity.

These findings indicate that baffles substantially improve shell-side thermal performance, particularly at reduced flow rates, whereas fins augment tube-side heat transfer, notably at elevated velocities. The integrated configuration leverages both systems, delivering the most efficient and consistent thermal performance throughout the entire flow spectrum.

The Performance Evaluation Criterion (PEC) was assessed for the baffled, inner fin, and combination configurations to evaluate overall performance in terms of heat transfer enhancement and flow resistance across a flow rate range of 2–6 lpm Fig. 14 demonstrates that the baffled arrangement with inner fins consistently yields the greatest PEC values.

The combined arrangement of internal fins and baffles attains a maximum PEC value of 1.60 at 2 L/min, signifying a 60 % enhancement compared to the baseline reference. As the flow rate rises, the PEC progressively diminishes to 1.36 at 6 L/min, indicating the increasing impact of pressure losses at elevated velocities. This pattern indicates that the integrated design is most advantageous at low to moderate flow rates, where the pressure drop is controllable and the heat transfer benefits are optimized.

The baffled-only structure closely resembles the combined case, exhibiting PEC values between 1.58 at 2 L/min and 1.35 at 6 L/min. The close similarity between the two situations indicates that baffles are the principal factor in enhancing PEC, mostly due to the considerable turbulence and flow mixing they generate on the shell side. The small disparity between the two scenarios indicates that the inner fins positioned on the tube side have a lesser impact on the PEC, which is primarily influenced by the shell-side Nusselt number and pressure drop.

The inner fin-only arrangement exhibits the least fortunate performance, with PEC values varying from 1.14 at 2 L/min to 1.06 at 6 L/min. The marginal improvements suggest that although internal fins augment surface area and boost local heat transfer on the hot

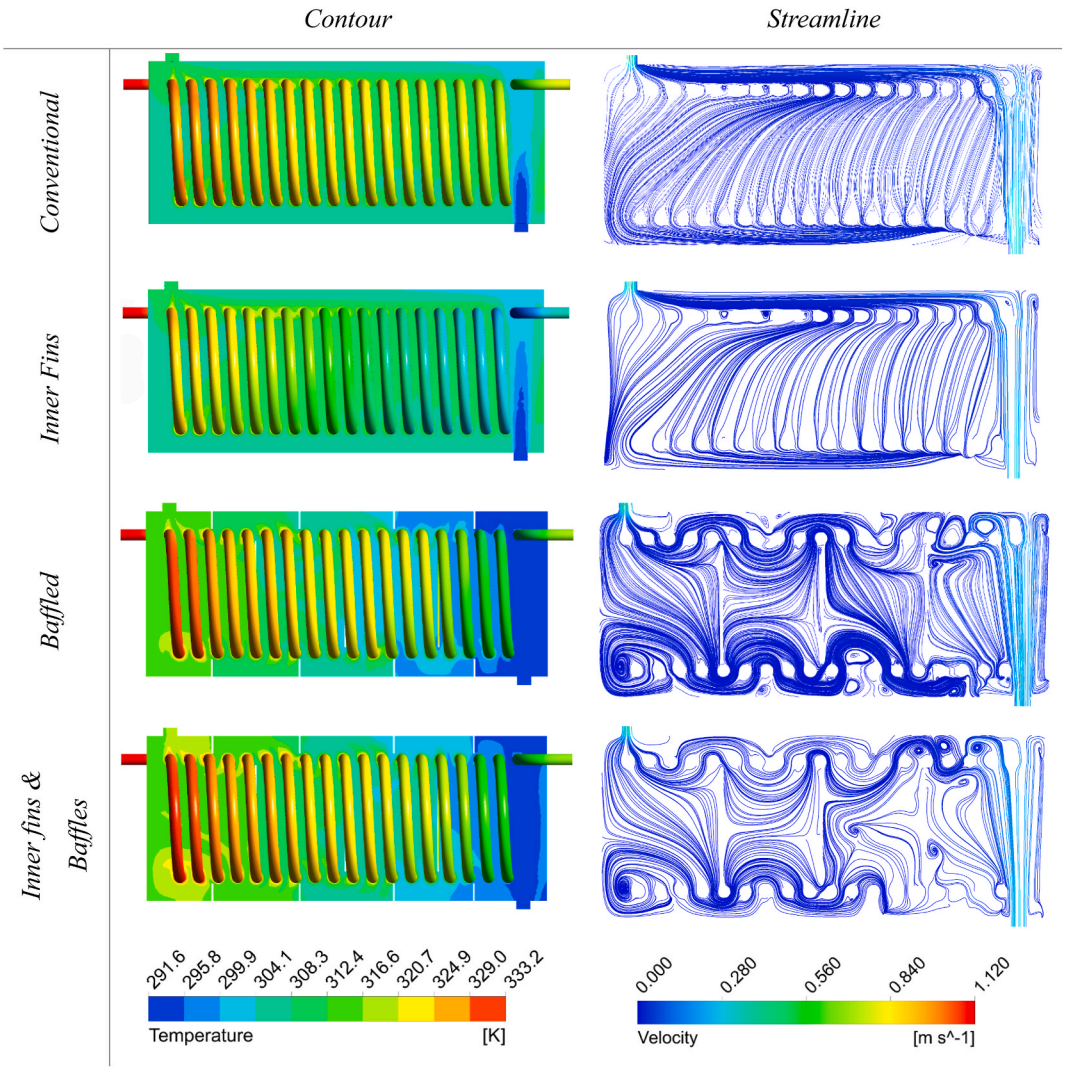

Fig. 15. Temperature contour and velocity streamlines for different modifications.

fluid side, they do not adequately offset the increased flow resistance, particularly in the absence of turbulence enhancement on the shell side.

The general downward trend in PEC across all configurations indicates the growing influence of pressure drop at elevated Reynolds numbers. This highlights the significance of accounting for hydraulic losses when applying thermal improvement methods in tiny heat exchangers.

6.4. The visual indicator

Fig. 15 illustrates a comparative illustration of temperature distribution (left column) and velocity streamlines (right column) across four structural configurations: conventional, inner fins, baffles, and an integration of inner fins with baffles. The contour and streamline plots offer essential insights into the thermal and flow path transformation within the HCHE.

In the conventional configuration, the temperature field reveals limited heat penetration into the shell-side domain. High thermal gradients are concentrated near the helical tube, while outer shell regions remain underutilized thermally. The streamline plot shows largely parallel and unidirectional flow with negligible disruption or recirculation, indicating weak turbulence and minimal convective mixing. In this case, heat transfer is largely governed by conduction around the tube boundary, with limited shell-side convection due to insufficient fluid–surface interaction.

The addition of inner fins enhances heat transfer along the tube surface by increasing the effective surface area and promoting localized convective activity. The temperature contours show intensified gradients around the finned coil, especially on the hot fluid side, indicating improved internal heat flux. However, the velocity streamlines remain smooth and organized on the shell side, suggesting that the fins have little influence on large-scale shell-side turbulence. Thus, while inner fins strengthen the internal (tube-side) convective process, their impact on shell-side fluid dynamics remains limited.

In the baffled configuration, a noticeable transformation occurs in both the thermal and flow fields. The streamline patterns display prominent vortex formation, recirculation loops, and cross-flow disruptions induced by the baffles. These features promote continuous thermal boundary layer renewal and increase shell-side turbulence intensity. As a result, the temperature contours become more uniformly distributed, especially in regions that were previously stagnant in the conventional design. This highlights the effectiveness of baffles in enhancing shell-side convection through active flow redirection and mixing.

The combined configuration featuring both baffles and inner fins exhibits the most favorable thermal and hydrodynamic behavior. The temperature field becomes more uniformly distributed throughout the shell volume, with reduced hot and cold zones. Simultaneously, the streamline plot reveals highly turbulent and chaotic flow patterns characterized by overlapping vortices and complex secondary flows. This configuration benefits from a synergistic interaction: baffles intensify shell-side turbulence and promote flow recirculation, while inner fins increase the heat transfer surface area and enhance the thermal gradient on the tube side. Together, they create a fully engaged convective environment that maximizes thermal contact and elevates overall heat transfer performance.

In summary, Fig. 15 visually confirms that while inner fins enhance heat transfer on the tube side, the baffles play a dominant role in promoting shell-side turbulence and mixing. When used in combination, they synergistically produce the most thermally efficient configuration, supporting the quantitative improvements observed in heat transfer rate, effectiveness, and PEC metrics.

The numerical analysis indicates that the incorporation of baffles and internal fins markedly enhances the thermal efficiency of the shell and helical coil heat exchanger. The combination of baffles and inner fins consistently shows optimal performance for efficacy, heat transfer rate, and flow field augmentation among all configurations. Baffles significantly influenced shell-side mixing and heat transfer, whilst inner fins predominantly improved the hot fluid side by augmenting surface area. The PEC 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 design optimization of compact and efficient heat exchangers for improved thermal systems.

7. Conclusion

This study presented a comprehensive numerical investigation of a shell-and-helical coil heat exchanger modified with shell-side baffles and tube-side inner fins, both individually and in combination. The key findings and insights are summarized below:

- **Thermal Performance Improvement:**

The integrated design achieved superior thermal performance across all tested flow conditions. At 6 L/min, the combined configuration produced an average heat transfer rate exceeding 5300 W, compared to approximately 4700 W for the conventional setup an increase of nearly 13 %. Effectiveness improved to 0.60, representing a 33 % enhancement over the unmodified design, demonstrating the synergistic effect of baffles and inner fins.

- **Enhancement of Flow Field:**

The use of baffles generated strong recirculation zones and intensified turbulence on the shell side, improving fluid mixing and boundary layer disruption. Inner fins, located on the hot fluid side, extended the heat transfer surface area and promoted localized enhancement. Together, these features significantly elevated convective performance on both sides of the exchanger.

- **Performance Evaluation Criteria:**

The Performance Evaluation Criterion analysis showed that the combined configuration achieved the most favorable balance between heat transfer and pressure drop. At a cold flow rate of 2 L/min, the PEC reached 1.60, indicating a 60 % improvement compared to the conventional configuration.

- **Visual Review:**

Contour plots of temperature and streamlines illustrated enhanced thermal distribution and mixing intensity in the modified configurations, especially in the combined design. These visual indicators confirm the role of shell-side turbulence and tube-side surface augmentation in maximizing exchanger efficiency.

7.1. Limitations of the study

This work offers meaningful insight into the thermal and hydraulic performance of a shell-and-helical coil heat exchanger enhanced with both baffles and internal fins. While the numerical approach provides a robust and efficient means to investigate complex design variations, several limitations should be acknowledged.

The simulations were conducted under steady-state conditions, assuming constant thermophysical properties. These simplifications, though commonly employed in similar CFD studies, neglect transient effects and temperature-dependent material behavior that may arise under real operating conditions. However, they significantly reduce computational complexity and enable efficient evaluation of structural enhancements across multiple configurations and flow scenarios.

Furthermore, the proposed hybrid configuration, integrating shell-side baffles with tube-side internal fins, has not yet been fabricated or experimentally validated. While the numerical results offer a reliable proof-of-concept, the practical implementation of such a design introduces engineering and economic challenges. The fabrication of helically coiled tubes with integrated internal fins requires high-precision manufacturing techniques, and the inclusion of shell-side baffles necessitates the use of accurate machinery to ensure proper assembly and disassembly, particularly for maintenance and operational adjustments. These complexities may affect the overall cost, scalability, and long-term maintainability of the system. As such, future work should focus on the experimental realization of the proposed configuration, supported by detailed techno-economic evaluations to assess its feasibility in real-world applications.

Despite these limitations, the study presents a novel and practical approach to enhancing compact heat exchanger's performance and contributes valuable guidance for both academic research and industrial application.

7.2. Future work and practical implications

The findings of this study demonstrate that integrating shell-side baffles and tube-side internal fins within a helical coil heat exchanger significantly enhances thermal performance and flow behavior. To further advance this research, future work may explore the physical realization of the proposed configuration using precision manufacturing techniques, enabling its performance to be examined under real operating conditions. Additional studies could focus on optimizing geometric parameters such as fin height, baffle spacing, and coil pitch, as well as investigating transient and temperature-dependent effects. The integration of artificial intelligence (AI)-based optimization models, such as machine learning or genetic algorithms, can also play a critical role in identifying optimal design configurations efficiently, reducing simulation time, and guiding experimental efforts. A comprehensive techno-economic assessment is recommended to evaluate fabrication feasibility, operational efficiency, and long-term maintainability. The demonstrated improvements in heat transfer effectiveness and performance evaluation criterion suggest strong potential for adopting this hybrid enhancement approach in compact heat exchangers used in energy-intensive sectors such as power generation, chemical processing, and HVAC systems.

CRediT authorship contribution statement

Mohamed A. Hamied: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Mina A. Saad:** Writing – review & editing, Supervision, Software, Methodology, Formal analysis. **Pedro García-Regodeseves:** Writing – review & editing, Supervision, Investigation, Conceptualization. **Juan Carlos Ríos-Fernández:** Writing – review & editing, Visualization, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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