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Experimental investigation and machine learning prediction of thermo-hydraulic performance in a double-pipe heat exchanger using wire coil inserts

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ABSTRACT

The increasing demand for compact and energy-efficient heat exchangers has accelerated the development of passive heat transfer enhancement techniques and intelligent predictive tools for improved thermal system design. In the present study, an experimental and machine learning-based investigation was conducted to evaluate the thermo-hydraulic performance of a counter-flow double-pipe heat exchanger equipped with helical wire coil (WC) inserts under turbulent flow conditions. The novelty of this work lies in the systematic assessment of fifteen insert configurations by combining three wire diameters (1.0, 1.5, and 2.0 mm) with five pitch ratios (P/Dc = 0.625, 1.25, 1.875, 2.5, and 3.125). Experiments were performed over a Reynolds number range of 5500-15000, and the experimental setup was validated against established Nusselt number and friction factor correlations. The thermo-hydraulic performance was evaluated using the heat transfer coefficient, Nusselt number, friction factor, pressure drop, and thermal performance factor. The results showed that the wire coil inserts generated strong swirl flow and secondary vortices, which enhanced fluid mixing and suppressed thermal boundary layer development, resulting in a maximum Nusselt number enhancement of 126.7% compared with the plain tube. The highest Nusselt number (180.24) was achieved using a 2 mm wire diameter with a P/Dc of 0.625. Although the friction factor increased by 156.5-410.8% due to greater flow resistance, the thermal performance factor remained above unity (1.01-1.35) for all configurations, confirming the overall thermo-hydraulic effectiveness of the inserts. Furthermore, Linear Regression, Ridge Regression, Random Forest, and Gradient Boosting models were developed to predict the heat transfer and flow characteristics. Among them, the Gradient Boosting model demonstrated the highest prediction accuracy, achieving R^2 values of 0.9984 and 0.9971 for the Nusselt number and friction factor, respectively, highlighting the potential of machine learning for the rapid design and optimization of advanced heat exchanger systems.

Nomenclature

d_i	Inner pipe inner diameter (m)	Re	Reynolds number (dimensionless)
d_o	Inner pipe outer diameter (m)	u	Velocity in the inner pipe (m/s)
d	Wire coil diameter	**Greek symbol**	
e	Thickness (m)	ρ	Mass density (kg/m^3)

(*continued on next column*)

(*continued*)

Dc	Coil diameter (m)	η	Thermal performance factor (dimensionless)
D_i	Outer pipe inner diameter (m)	**Subscripts**	
D_o	Outer pipe outer diameter (m)	t	Cases with helical coil inserts
D_h	Hydraulic diameter (m)	o	Cases without helical coil inserts

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(*continued*)

f_t	Friction factor of the inner pipe with wire coil inserts (dimensionless)	**Abbreviations**	
f_o	Friction factor of the plain pipe (dimensionless)	ΔP	Difference in pressure between inlet and outlet of hot water (Pa)
h	Convective heat transfer coefficient (W/m^2 K)	CPVC	Chlorinated polyvinyl chloride
k	Thermal conductivity (W/m K)	DPHE	Double pipe heat exchanger
L_i	Length of inner pipe (m)	TT	Twisted tape
L_o	Length of outer pipe (m)	TPF	Thermal performance factor
Nu	Average Nusselt number (dimensionless)	HT	Heat transfer
P	Pitch of the wire coil inserts	PR	Pitch ratio
Pr	Prandtl number	WC	Wire coil

1. Introduction

The continuous rise in energy demand and the escalating cost of raw materials have intensified need for the development of highly efficient and economically viable heat transfer (HT) systems [1]. In this context, considerable research efforts have been directed toward improving convective heat transfer characteristics within heat exchanger tubes, as these systems are integral to a broad spectrum of industrial applications [2]. Heat exchangers serve as the backbone of thermal management by facilitating effective energy exchange between fluids, thereby enhancing overall system performance and energy utilization [3]. To achieve higher efficiency without significantly increasing operational complexity or cost, passive enhancement techniques have gained substantial attention. Twisted tape inserts are considered one of most effective and commonly adopted methods among these [4]. These inserts induce swirl flow and disrupt thermal boundary layer, thereby promoting better fluid mixing and elevated heat transfer performance [5,6]. On account of their uncomplicated nature, low cost, and practical feasibility, twisted tape inserts are extensively utilized across various sectors, including Heating ventilation and air conditioning (HVAC) applications, waste heat recovery systems, food processing industries, and chemical manufacturing plants [7,8]. Consequently, the integration of such passive techniques offers a promising pathway toward achieving superior thermal performance while maintaining economic feasibility [9]. A main challenge in the design of heat exchangers lies in achieving an optimal balance between enhanced thermal performance and minimized operational penalties. While increasing heat transfer rates is desirable, it must not come at the expense of excessive fluid flow resistance, higher pumping power, or increased system size and weight [10]. Therefore, modern heat exchanger design demands innovative approaches that can simultaneously improve thermal efficiency while maintaining low pressure drop and compactness of the equipment. With rapid advancements in heat transfer technologies, considerable focus has recently been placed on designing high-performance systems that cater to a wide spectrum of engineering applications [11]. Rising costs of energy and raw materials have further accelerated the need for heat exchangers that are not only thermally efficient but also economically sustainable over long-term operation. In this regard, optimizing design parameters and incorporating advanced enhancement techniques have become crucial areas of research. The importance of such developments becomes even more pronounced in critical applications, particularly in aerospace and space missions, where thermal management plays a decisive role in system reliability [12]. Under extreme environmental conditions, heat exchangers must efficiently dissipate or regulate heat to maintain thermal equilibrium and ensure the proper functioning of onboard systems [13]. Consequently, enhancing heat transfer performance in such applications is not merely beneficial but essential for mission success and operational safety. These challenges become particularly pronounced in heat exchangers operating under harsh conditions, such as marine environments and chemical processing industries, where corrosion, fouling, and complex fluid behavior further complicate thermal management [14,15]. Among the most efficient techniques for augmenting heat transfer is the disruption of thermal and viscous boundary layers, coupled with the promotion of flow turbulence within the fluid. Such modifications intensify fluid mixing and improve energy transport between fluid and the heat transfer surface. Development of heat transfer remains a central objective across a wide range of engineering applications [16,17]. Although numerous studies have reported significant improvements in thermal performance using various augmentation techniques, these gains are often accompanied by a substantial rise in flow resistance, which in turn increases pumping power requirements. This trade-off highlights the need for carefully optimized solutions that balance heat transfer enhancement with hydraulic performance [18,19]. In this context, the use of helical coil inserts has gained considerable attention as an effective passive technique. By systematically adjusting parameters including pitch ratio and wire diameter, these inserts generate strong swirling flows and secondary motion within fluid, thereby significantly improving the HT rate [20,21]. Such design flexibility allows for tailored performance enhancements, making helical coil inserts a promising approach for achieving higher efficiency in modern heat exchanger (HE) systems. The design of efficient HEs requires a careful balance between minimizing geometric intricacy, diminished flow resistance, and regulated surface temperature maintenance, all while achieving high thermal performance [22,23]. To address these requirements, various heat transfer improvement methods have been developed, generally categorized into active, passive, and compound techniques. Among these, passive techniques was broadly preferred resulting from their simple configuration, reliability, and lack of exterior energy requirements, with twisted tape inserts being one of the most effective and commonly used solutions [24,25]. These inserts promote swirl flow and improved fluid mixing, thereby enhancing convective heat transfer; however, they also introduce increased frictional losses, making it essential to optimize stability between HT rate and pressure drop, as both significantly influence the size, efficiency, and complete cost of the scheme [26,27]. Further improvement in thermal performance can be enhanced by augmenting effective HT area via incorporation of secondary surfaces onto primary surface, while simultaneously maintaining structural integrity and ensuring efficient heat conduction. Extended surfaces such as fins play a vital role in this enhancement, while key mechanical components including tubes, baffles, gaskets, and support structures contribute to the overall functionality and durability of the system [28,29]. Heat exchangers incorporating twisted tape inserts within circular tubes are particularly advantageous due to their rapid superior thermal responsiveness and efficient heat recovery, even at low temperature differences, thereby making them well-suited for a broad spectrum of engineering and industrial uses [30,31].

The integration of machine learning (ML) into double pipe heat exchanger (DPHE) furnished through helical coil inserts offers a promising approach for enhancing thermal performance and operational efficiency. ML techniques can be employed to predict heat transfer characteristics, friction factor, and overall system behavior under varying operating conditions and geometric configurations such as pitch ratio and wire diameter. By analyzing large datasets generated from experiments or simulations, ML models enable accurate optimization of design and performance parameters, reducing the need for extensive trial-and-error studies. This data-driven approach not only improves heat transfer efficiency but also helps in minimizing pressure drop and energy consumption. Consequently, the application of ML in DPHE systems with helical coil inserts facilitates development of intelligent, optimized, and cost-effective thermal systems for advanced engineering applications.

Numerous experimental and numerical investigations have been undertaken over years to evaluate wire coil (WC) performance, with a particular focus on their influence on HT rates and thermophysical performance of fluid flow. Singh et al. [32] investigated thermal performance of a DPHE incorporating wire-wound helical inserts was

evaluated experimentally across different pitch lengths, revealing heat transfer enhancements up to 105.93% related to twisted tape. The highest performance evaluation criterion was attained at the ideal pitch length of 35 mm, while shorter pitch increased friction losses. In addition, machine learning models predicted the Nu, friction factor, and performance with an accuracy of about 98%, highlighting their effectiveness for design optimization. Raj et al. [33] conducted experiment to investigate performance evaluation of a HE tube fitted with hyperbolic-cut twisted tape (TT) and graphene oxide nanofluid (NF), conducted for turbulent flow regimes, covering Re from 10,000 to 22,000. It reported enhancements of 40.42% in Nu, 56.27% in friction factor, and 25.90% in thermal performance, with a supreme performance factor of 1.26 at higher cut ratio and nanoparticle concentration. Additionally, an adaptive neuro-fuzzy inference system (ANFIS) based artificial intelligence (AI) model was employed to accurately Forecast and improve heat exchanger's thermal efficiency. Zhang et al. [34] investigated HT and pressure drop features of HE tubes incorporating rotating TTs in turbulent flow regimes, and compared their performance with stationary TTs. It revealed that lower twist ratios enhance thermal performance, the Nu and friction factor were correlated using developed expressions showed excellent conformity with the measured results. Wijayanta et al. [35] examined thermal and hydraulic characteristics of a DPHE fitted with double-sided delta-wing tape inserts, covering Re from 5300 to 14,500. The conclusions indicated a 177% peak enhancement in Nu and a thermal performance factor (TPF) of 1.15 at a wing-width ratio of 0.63, though accompanied by a considerable friction factor penalty. Moreover, empirical correlations were formulated from experimental data to predict Nusselt number (Nu) and friction factor. Rajan et al. [36] experimentally determined HT, friction factor, and thermo-hydraulic performance of a HE tube containing a twisted tape with double-sided hyperbolic cut patterns, examined across Reynolds numbers from 10,000 to 22,000 and cut ratios of 0.2–0.65. The findings revealed Nusselt number enhancements of 5.74–25.22%, friction factor increases of 31.28–61.08%, and thermo-hydraulic performance improvements of 0.33–11.63% relative to conventional twisted tape. Additionally, correlations were proposed with deviations within ±8%, ±9%, and ±5%, respectively. Bahuguna et al. [37] experimentally examined the heat transfer, friction factor, thermal performance, and entropy generation attributes of a tube heat exchanger incorporating multiple helical tape inserts, with Reynolds numbers spanning 5000–29000. Maximum heat transfer augmentation of 3.95 times and a thermal performance factor of 1.23 were recorded, with the lowest entropy generation (0.27) occurring at a twist ratio of 2 and a tape count of three. In addition, the correlations derived in this study showed favorable correspondence with the measured data. Nagaraju et al. [38] conducted experiment to analyze HT behavior of both water and NFs (CuO, ZnO, and TiO_2 at 0.2% volume concentration) in a plain tube fitted with a rotating TT turbulator ($y = 2.88$). The results displayed that increasing flow rate (1–6 LPM) and rotational speed (0–300 RPM) significantly enhances the heat transfer coefficient (HTC) for convection, through maximum improvement observed at 300 RPM and 6 LPM. The study also highlighted the limited research on rotating TT configurations employing NFs to enhance HT. Singh et al. [39] analyzed thermal and hydraulic characteristics of a tube furnished with a triangular perforated nail-head TT insert underneath laminar flow conditions ($300 \leq Re \leq 1800$). The study reported enhancements of up to 123.62% in Nu and 495.30% in friction factor, achieving the highest thermal performance factor (TPF) of 2.98 at Re = 1700. Additionally, empirical relationships were formulated for estimating the Nu and f over studied operating conditions. Hong et al. [40] numerically examined thermal–hydraulic behavior of a spiral corrugated tube fitted with multiple TTs. for waste heat recovery applications. The findings indicated that a rise in TT count led to higher Nu and friction factors, while perforated tapes improved overall thermal performance, achieving a maximum performance index of 1.23 with an additional enhancement of about 7.9%. The study demonstrated that optimized geometric parameters such as S/D and L/D significantly influence heat transfer and stream performance. Nakhchi et al. [41] numerically investigated turbulent flow and thermal performance of HEs fitted with perforated louvered strip inserts using RNG k–ε model for Re from 5000 to 14,000. A study revealed that perforations significantly enhance fluid mixing and HT, with Nu improvements of 30.1% and 45.84% for double inserts at slant angles of 15° and 25°, respectively. A peak TPF of 1.84 was noted at Re = 14,000 for double perforated configuration. Keklikcioglu et al. [42] conducted experimental investigations on thermal-hydraulic behavior of a circular tube containing coiled-wire inserts of triangular cross-section for Re from 3429 to 26,663. It demonstrated significant enhancement in HT and friction factor, with an extreme thermal performance of 1.82 observed for P/D = 1- and 1-mm clearance. Results confirmed that boundary layer disturbance induced by coiled-wire inserts effectively improves HT performance. El-Sebaey et al. [43] conducted a numerical investigation of internally hollow longitudinal finned tubes to enhance heat transfer while minimizing pressure losses. The effects of fin angle, inscribed diameter, and fin thickness on thermo-hydraulic performance were systematically evaluated, demonstrating significant improvements over smooth tubes. The optimized fin configuration achieved up to 75% higher heat transfer while maintaining acceptable friction losses, providing valuable design guidelines for compact and energy-efficient heat exchangers. Diwaker et al. [44] conducted an experimental investigation into the thermo-hydraulic behavior of a DPHE equipped with twisted tape featuring combined triangular and semicircular cuts (TSCTT) under turbulent flow regimes, with Reynolds numbers ranging from 4000 to 18,000. The study reported significant enhancement in HT, with a maximum TPF of 1.57 observed for x/b = 4.5, φ = 8 mm, and B/Y = 1.1. Additionally, an IoT-based measurement approach was employed to improve data accuracy and reliability. Alfaro-López et al. [45] achieved investigational to analyze HT and hydrodynamic performance of 3D-printed TT inserts made from various thermoplastic materials under laminar flow conditions (Re = 100–700). The results showed/that materials such as polylactic acid and nylon enhanced heat transfer by up to 20% related to steel, although pressure drop increased, with nylon exhibiting highest resistance. Among the tested materials, acrylonitrile butadiene styrene (ABS) and polyethylene terephthalate glycol (PETG) were identified as the most suitable due to their balanced thermal performance and mechanical stability. Singh et al. [46] carried out an experimental study to evaluate thermal-hydraulic characteristics of a DPHE incorporating triangular perforated nail head TT inserts, across Re = 10,000–22,000. As compared to standard twisted tape, the results demonstrated enhancements of 122.69% for HT, 543.96% for friction factor, and 11.53% for thermal characteristics, with maximum TPF recorded as 1.18 at W = 20 mm. The study also confirmed superior performance, particularly at lower Reynolds numbers (Re < 16,000). Wang et al. [47] Conducted combined numerical and experimental investigations on planar and punched vortex generators (VGs) with a novel arrangement in a heated tube under turbulent flow conditions (Re = 6060–21,210). The study demonstrated that vortex strength varied periodically along the flow direction, influencing both heat transfer and pressure loss. The thermo-hydraulic performance was found to depend strongly on the perforation index (PI) and pitch ratio (PR), with the optimum configuration (PI = 7.8%, PR = 3.27) achieving a maximum thermal enhancement factor (TEF) of 1.44 at Re = 6060. Wu et al. [48] conducted a numerical investigation of a multi-V-winglet vortex generator with perforated winglets to improve heat transfer and thermo-hydraulic performance in a heated tube. The introduction of punched holes generated jet flows that reduced recirculation zones and friction losses while enhancing local heat transfer. The optimized configuration, comprising eight winglets with an outer-surface perforation and a 25 mm pitch, achieved a maximum performance evaluation factor (PEF) of 2.83. Promvonge et al. [49] conducted combined experimental and numerical investigations on louvered baffle vortex generators (LBVGs) to improve the thermo-hydraulic performance of heated tubes under turbulent flow conditions. The study demonstrated

that louver-punched holes effectively reduced friction losses while maintaining high heat transfer through jet-induced mixing. An optimized configuration (RP = 0.75, LR = 0.4, θ = 20°) achieved a maximum thermal effectiveness factor (TEF) of approximately 2.64, with holes positioned near the baffle ends providing the best overall performance. Although traditional optimization techniques such as analysis of variance (ANOVA) and response surface methodology (RSM) have been extensively utilized in heat exchanger analysis, their effectiveness is often constrained when dealing with highly nonlinear and complex interactions among design and operating parameters [50]. To overcome these limitations, present study incorporates machine learning–based approaches, offering a more advanced, flexible, and data-driven framework for performance prediction and optimization [51]. Machine learning has quickly risen to prominence as a game-changing methodology in thermal engineering, with the capability to distill actionable intelligence from extensive data repositories and generate remarkably accurate predictions [52]. ML algorithms, including linear regression, ridge regression, and gradient boosting, have demonstrated exceptional effectiveness in forecasting critical performance metrics such as heat transfer coefficient (HTC) and pressure drop. This enhanced predictive capability not only improves the reliability of thermal analysis but also facilitates the development of optimized and cost-effective heat exchanger designs [53,54]. Recent investigations have underscored increasing efficacy of sophisticated machine learning methods in accurately predicting thermo-hydraulic performance parameters in heat exchanger systems [55]. Approaches such as Bayesian regression and K-nearest neighbor (KNN) have demonstrated strong capability in capturing complex, nonlinear relationships between operating conditions and system responses. These approaches have been successfully applied to estimate critical parameters, including HTC and pressure drops, by high precision. Their ability to generalize from data and provide reliable predictions makes them valuable tools for improving design efficiency and supporting data-driven optimization of thermal systems [56,57]. These data-driven approaches significantly reduce computational effort while enabling rapid, near real-time analysis, thus expanding the scope of machine learning in thermal system design and assessment., this research ensures reliable validation of results but also establishes a robust and efficient framework for performance prediction and optimization. Overall, this work addresses an important gap in heat exchanger research through a systematic examination of the effects of varying pitch ratio with different wire diameter of helical coil inserts, a research gap that has received minimal attention in prior studies. By combining detailed experimental analysis with advanced machine learning models, the study provides deeper insight into heat transfer enhancement mechanisms and supports the development of optimized, high-performance heat exchanger designs.

Despite the extensive research conducted on passive heat transfer enhancement techniques, previous studies on wire coil inserts have primarily focused on evaluating the influence of a single geometric parameter, such as pitch ratio or wire diameter, with limited attention given to their combined effects on the thermo-hydraulic performance of double-pipe heat exchangers. Furthermore, most investigations have concentrated on conventional experimental or numerical analyses, while the application of data-driven approaches for accurately predicting heat transfer and flow characteristics remains relatively unexplored. Consequently, there is a lack of comprehensive studies integrating experimental investigation with machine learning techniques to optimize wire coil insert geometry and predict system performance under varying operating conditions. To address these research gaps, the present study systematically investigates the combined influence of three wire diameters and five pitch ratios, resulting in fifteen different wire coil configurations tested over a wide Reynolds number range (5500-15000). In addition to experimental evaluation, several machine learning models are developed and validated to predict the Nusselt number and friction factor with high accuracy. The integration of detailed experimental analysis and intelligent predictive modeling represents the primary novelty of this work and contributes new insights into the design, optimization, and performance prediction of compact double-pipe heat exchangers employing helical wire coil inserts.

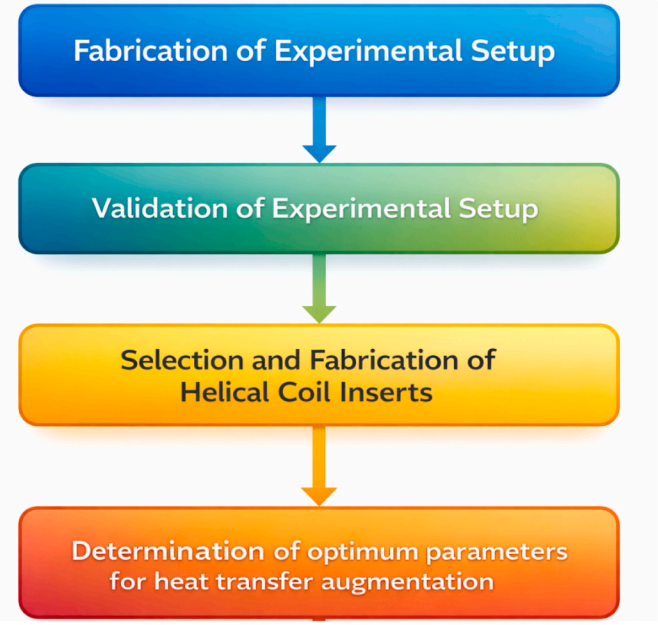


Fig. 1. Methodology of the present work.

2. Methodology

The approach followed in the present research followed a structured experimental and analytical framework to systematically study heat transfer enhancement using helical coil inserts and to identify optimum process conditions. Initially, a test rig was designed, built, and fitted with the necessary components, including the test section, heating system, measuring instruments, and data acquisition system ensured accurate tracking of both thermal and hydraulic variables. The reliability of the setup was established through a validation process in which baseline experimental results were compared with well-established theoretical correlations and published data. After successful validation, helical coil inserts with different geometrical configurations were selected and fabricated. These inserts were introduced into the test section to induce swirl flow, enhance fluid mixing, and improve convective heat transfer performance. A comprehensive experimental campaign was then conducted under a range of flow conditions, during which restrictions such as fluid temperature, flow rate, pressure drop, and HT rate were recorded. The collected data were processed to extract critical performance metrics namely, the Nu, friction factor, and TPF thereby facilitating a thorough comparison among the different insert configurations. To further strengthen the analysis and facilitate optimization, machine learning techniques were integrated into the study.

The experimental dataset was utilized to develop predictive models capable of capturing the complex relationships between operating variables and thermal performance. Following model training and validation, the machine learning framework was employed to predict system behavior and identify the optimal combination of geometrical and operating parameters that maximized heat transfer enhancement while minimizing hydraulic losses. The combined experimental and machine learning methodology offered deep insight into the thermal-hydraulic characteristics of helical coil inserts and established an efficient methodology for performance prediction and optimization in advanced heat transfer systems. Fig. 1 illustrates the methodology adopted in present study.

Table 6
Performance comparison of machine learning algorithms for Nusselt number (Nu) prediction, assessed via MAE, MSE, RMSE, and R^2.

S. No	Model	MAE	MSE	RMSE	R^2
1	Linear Regression	5.698	49.216	7.015	0.976
2	Ridge Regression	5.686	48.769	6.983	0.976
3	Decision Tree	4.495	26.675	5.164	0.987
4	Random Forest	2.529	9.734	3.120	0.995
5	Gradient Boosting	1.309	3.221	1.795	0.998
6	XGBoost	1.774	4.794	2.189	0.997

Table 7
A qualified assessment of ML models for friction factor (f) calculation was conducted, with model performance quantified using MAE, MSE, RMSE, and R^2.

S. No	Model	MAE	MSE	RMSE	R^2
1	Linear Regression	0.005	0.000060	0.0077	0.992
2	Ridge Regression	0.006	0.000060	0.0078	0.992
3	Decision Tree	0.011	0.000157	0.0125	0.979
4	Random Forest	0.007	0.000074	0.0086	0.990
5	Gradient Boosting	0.003	0.000022	0.0047	0.997
6	XGBoost	0.004	0.000026	0.0051	0.996

Re value, while Nu gradually decreases as the pitch ratio increases from 0.625 to 3.125. Fig. 13 (ii) demonstrates the corresponding difference of friction factor (f) with Re for same pitch ratios. In all cases, f decreases with increasing Re, indicating a reduction in flow resistance at higher turbulent intensities. The figure also highlights how the pitch ratio influences the friction factor. The smallest pitch ratio (P/d = 0.625) results in the highest friction factor values across the entire Re range. Overall, the results suggest that increasing Re lowers the friction factor, while increasing the pitch ratio also reduces flow resistance, enhancing the system's hydraulic performance. To evaluate the performance of diverse machine learning approaches, a range of models were constructed and systematically compared. The predictive capability of each machine learning model was assessed using conventional statistical metrics, namely Mean Squared Error (MSE), Root Mean Squared Error (RMSE), Mean Absolute Error (MAE), and the coefficient of determination (R^2). These metrics collectively assess precision and robustness of the predictions. Across all tested models, Gradient Boosting emerged as the best performer, demonstrating the lowest prediction errors and the highest R^2 for both Nu and f. A detailed comparison of model performance for Nu prediction is presented in Table 6, which reports MAE, MSE, RMSE, and R^2 for each algorithm. Similarly, Table 7 provides the corresponding performance comparison for friction factor (f) prediction using the same evaluation metrics. Fig. 14 shows the prediction accuracy of the developed models for (i) the Nusselt number and (ii) the friction factor.

Overall, the results demonstrate that machine learning models, particularly ensemble methods, provide an effective approach for forecasting both heat transfer performance (Nu) and hydraulic performance (f). Fig. 14 (i) compares the actual Nu values from the dataset with those predicted by the GBR model. The predicted values closely track actual data, with most points falling along the reference line, confirming that model demonstrates a strong capability to capture intricate relationship between the input parameters and Nu with high fidelity. Fig.14 (ii) presents a similar comparison for friction factor (f). Here too, the model's output agrees well with the actual numbers across entire range, demonstrating that the Gradient Boosting model delivers equally accurate and reliable predictions for the friction factor.

Fig. 15 presents a 3D plot demonstrating relationship between the predicted Nu and Re as well as the pitch ratio (P/d), as generated by machine learning. The flowing transition across surface indicates that the model efficiently captures combined nonlinear influence of parameters on HT performance, offering a comprehensive visual representation of their interactive effects. Fig. 16 (i) and 16 (ii) compare the actual and forecast Nu distributions for training and testing datasets, respectively, using the GBR model. A density curves in both figures reveal that the predicted values exhibit a distribution that is highly consistent with the actual data, confirming that the model maintains the statistical properties inherent in the dataset across both training and testing phases. Overall, the ML approach was successfully applied to develop predictive models for two critical thermal-hydraulic parameters, specifically Nu and friction factor (f), utilizing provided dataset. The close agreement between predicted and actual values, as evidenced by comparison designs and distribution analyses, demonstrates that machine learning methods offer a reliable and efficient alternative to traditional experimental techniques for estimating HT and flow characteristics.

8. Conclusion

An applied research study was carried out to assess thermo-hydraulic performance of a DPHE equipped with wire coil (WC) inserts of varying pitch ratios (P/Dc = 0.625-3.125) and wire diameters (d = 1-2 mm).

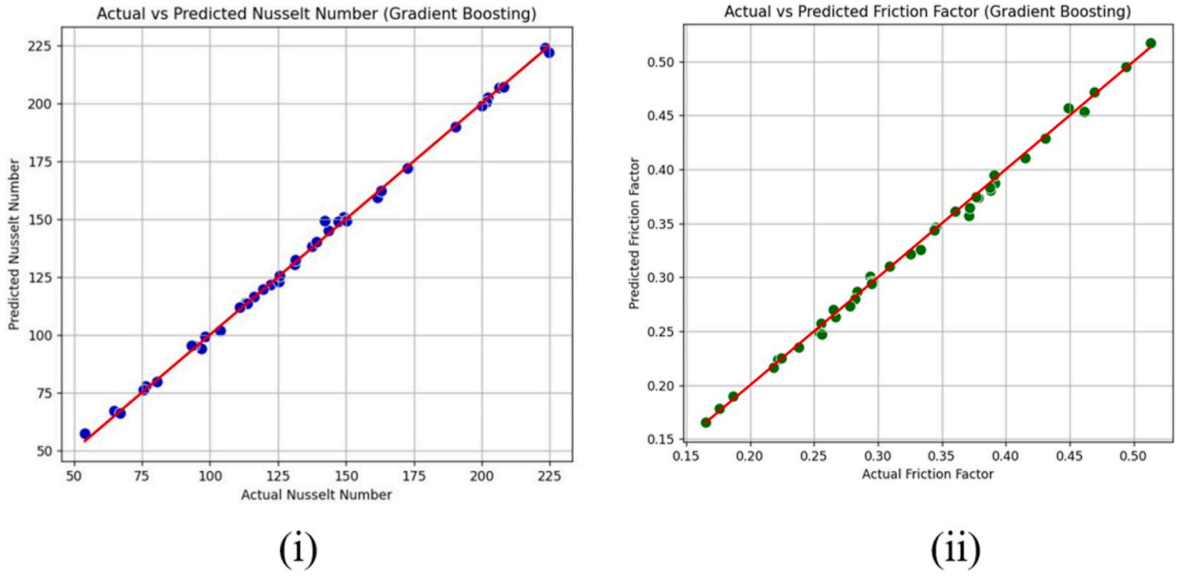


Fig. 14. (i) Model prediction accuracy for Nusselt number (ii) Model prediction accuracy for friction factor.

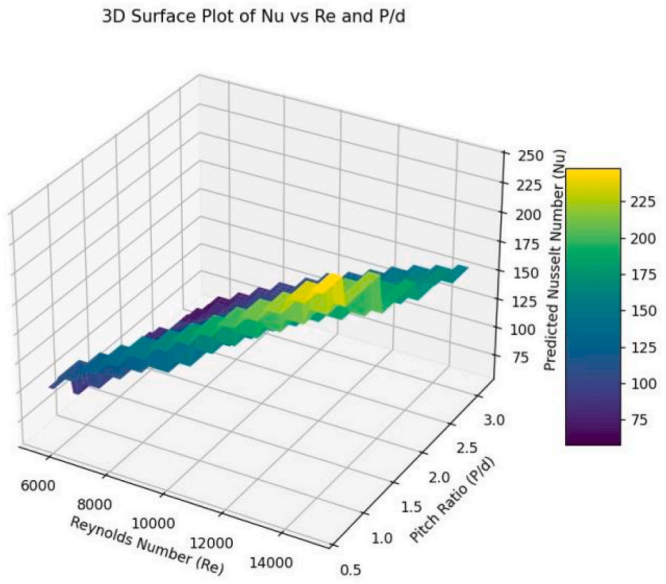


Fig. 15. 3D visualization of heat transfer variation.

Additionally, ML models were established to forecast both thermal and hydraulic behavior of system. The key findings of the present study are outlined below.

- For all wire coil configurations, the Nusselt number exhibited a continuous increase with Reynolds number, reflecting enhanced convective heat transfer driven by heightened turbulence and improved fluid mixing.
- The use of WC inserts improved the Nusselt number by 101.2-126.7% compared with the plain tube, demonstrating their strong heat transfer enhancement capability.
- The optimal heat transfer performance was attained at a pitch ratio of P/Dc = 0.625 and wire diameter of d = 2 mm, yielding a maximum Nusselt number of 180.24.
- Increasing the wire diameter from 1 mm to 2 mm enhanced Nusselt number by 13.57%, while an improvement of 6.58% was observed compared with d = 1.5 mm.
- While friction factor decreased with increasing Re, it stayed markedly higher than for plain tube, attributable to powerful swirl flow and secondary vortices generated by inserts.
- The friction factor of tubes equipped with WC inserts was found to be 156.5-410.8% greater than that of plain tube, through maximum value observed for P/Dc = 0.625 and d = 2 mm.
- Thermal performance factor (TPF) exceeded unity across all tested configurations, ranging from 1.01 to 1.35, thereby confirming the thermo-hydraulic viability of wire coil (WC) inserts below constant pumping power situations.
- The maximum TPF of 1.35 was achieved at a pitch ratio (P/Dc) of 0.625 with a wire diameter of 2 mm, which was approximately 8% and 3.9% higher than the values obtained for wire diameters of 1 and 1.5 mm.
- Furthermore, correlation analysis revealed a strong positive relationship among Reynolds number and Nusselt number (r = 0.84), while the friction factor revealed a strong negative correlation with P/Dc (r = −0.75).
- Among the machine learning models evaluated, the Gradient Boosting model established the highest prediction accuracy with R^2 = 0.9985 for Nusselt number prediction and R^2 = 0.9971 for friction factor prediction, indicating its excellent capability for thermo-hydraulic performance forecasting.
- Overall, wire coil inserts with a low pitch ratio and larger wire diameter significantly enhanced heat transfer performance while maintaining favorable thermal performance factors, creation them a hopeful passive technique for energy-efficient heat exchanger applications.

Future direction.

- Forward-thinking machine learning and deep learning architectures as well as Artificial Neural Networks (ANN), Long Short-Term Memory (LSTM), and Deep Neural Networks (DNN) can be effectively employed to enhance the prediction accuracy of thermo-hydraulic parameters across a broader operational range.
- Furthermore, the integration of these data-driven models with hybrid optimization techniques, for instance Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Grey Wolf Optimizer (GWO), and Differential Evolution (DE), offers a powerful strategy for identifying optimal wire diameter, pitch ratio, and operating conditions that maximize thermal performance.
- Looking ahead, future research may focus on developing intelligent digital twin frameworks capable of real-time monitoring, predictive analysis, and performance optimization of heat exchangers equipped with wire coil inserts, thereby facilitating their practical deployment in industrial applications.

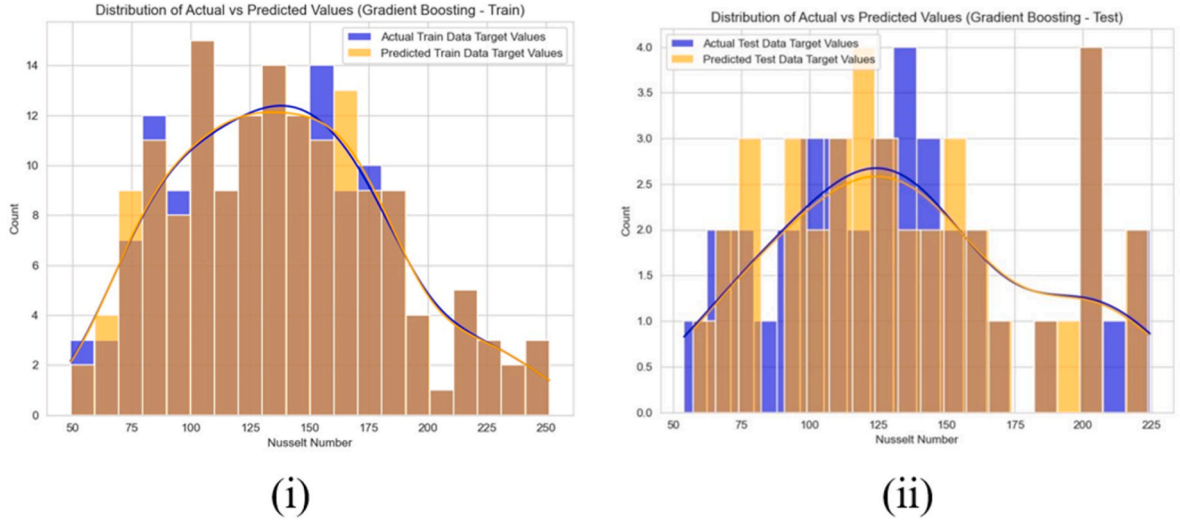


Fig. 16. (i) Training data distribution comparison (ii) Testing data distribution comparison.

- The integration of Computational Fluid Dynamics (CFD) data with ML models can be explored to create high-fidelity surrogate models capable of reducing computational time while maintaining prediction accuracy.
- Multi-objective optimization approaches can be employed to simultaneously maximize HT enhancement and minimize pressure drop, leading to more energy-efficient heat exchanger designs.
- Explainable Artificial Intelligence (XAI) techniques may be applied to identify the relative importance of operating parameters and provide a deeper understanding of physical mechanisms governing HT and fluid flow behavior.
- Future research can investigate the applicability of transfer learning and physics-informed neural networks (PINNs) for predicting thermo-hydraulic performance under conditions where experimental data are limited.
- The developed machine learning framework may be extended to heat exchangers operating with nanofluids, hybrid nanofluids, phase change materials, and renewable energy systems, enabling intelligent thermal system strategy and optimization.

CRediT authorship contribution statement

Brajesh Kumar Ahirwar: Writing – original draft. **S. Anitha:** Writing – review & editing. **Abdullah Alghafis:** Conceptualization. **Abdullah Alrashidi:** Visualization. **Mahmoud S. El-Sebaey:** Visualization.

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Declaration of competing interests

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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