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ENERGY-EFFICIENT HEAT EXCHANGER SYSTEMS FOR INDUSTRIAL APPLICATIONS

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ABSTRACT

Current heat exchangers are inefficient and expensive in terms of energy efficiency, performance and cost and must be improved. The challenge is the trade-off between heat transfer and pressure drop for a desired energy efficiency and performance.The new model offers a holistic view of the design of energy-efficient heat exchangers, considering inter-parameter interactions, thermal-hydraulic performance and energy efficiency, with practical integration. The model is based on 1,440 operating data sets, correlation-based filtering, entropy-based analyses of significant features and efficient extraction of the major thermal-hydraulic characteristics. The proposed model integrates optimized thermal control strategies and intelligent flow optimization mechanisms to improve heat transfer efficiency while minimizing pressure losses and thermal resistance. Structural enhancements, including optimized channel configurations and improved surface interaction design, are employed to maximize convective heat transfer and ensure uniform temperature distribution. The new model is based on the integration of heat transfer characteristics (Nusselt number, heat transfer rate), hydraulic characteristics (pressure drop, friction factor) and energy efficiency (energy efficiency index, performance evaluation criterion).The model demonstrates remarkable improvement from experiments on conventional and enhanced heat exchangers. The new model has accuracy, precision, recall and F1-score of 99.4%, 97.8%, 98.5% and 98.1% respectively. It also exhibits maximum energy efficiency of 95.8% (90.6% for conventional). Heat transfer is enhanced from 4.45 to 5.22 units and pressure drop reduced from 16.5 to 14.0 units for high flow rates.

Keywords: *Energy-Efficient Heat Exchanger, Thermal Management System, Intelligent Flow Optimization, Optimized Thermal Control, Heat Transfer Enhancement, Sustainable Thermal Systems.*

1. INTRODUCTION

The industrial processes use huge amount of energy resources in the world with the heat transfer systems taking a huge percentage of this energy consumption [1]. Heat exchangers are of great importance to power generation, chemical processing, petroleum refining, food processing and manufacturing industries since they aid in effective thermal energy transfer among fluids [2]. Nevertheless, traditional heat exchanger systems have the disadvantage of incurring high energy losses, inefficiencies in their operations [3], and the high environmental impact [4]. Enhancing energy efficiency of heat exchangers is thus becoming one of the important considerations towards ensuring sustainable industrial processes [5].

As the cost of energy continues to increase and strict environmental regulations are enforced, industries are increasingly being put under the pressure to streamline the thermal systems and lessen carbon emissions [6]. The designs of heat exchangers that are energy efficient have a direct impact on lower fuel consumption, lower operating costs and less emission of greenhouse gases [7]. The new possibilities associated with thermal performance improvements are achieved through the improvement of materials, improved surface geometries [8], and improved flow configurations [9]. Therefore, these systems need to be analyzed in performance to determine their performance in actual industrial operating conditions [10].

A heat exchanger is normally measured by its performance considering its parameters like; heat transfer coefficient, effectiveness, pressure drop, thermal efficiency, and total energy consumption [11]. Although the increase in heat transfer rates is desirable, higher heat transfer rates tend to increase the pressure losses which increases the pumping power requirement [12]. Thus, one of the significant challenges in the design of the heat exchanger system is the creation of the optimal balance between the enhancement of thermal and energy performance [13]. An in-depth analysis of performance is useful in determining configurations that make the most out of heat recovery and the least out of energy penalties [14].

Recent studies have highlighted the application of energy saving heat exchanger systems with new methods of compact heat exchanger, finned surface, nanofluids, and flow optimization methods [15]. These inventions are designed to improve the heat transfer performance with minimal impact on the energy consumption [16]. These techniques, however, are not all effective depending on how they are used in an industry, the condition of the operations and the characteristics of fluids [17]. Consequently, the need to conduct comparative performance evaluation to identify the best solutions that will be energy-efficient [18] arises.

This research is dedicated to the performance examination of the heat exchanger systems with a high level of energy efficiency in industrial applications. This research takes into account major thermal and hydraulic parameters in order to determine the efficiency of the system and its ability to work. This research will help shed light on the enhancement of the performance of heat exchanger under various design and operational conditions, and the need to conserve energy and be economical in industrial settings. Figure 1 presents the Architecture of Analytical Process.

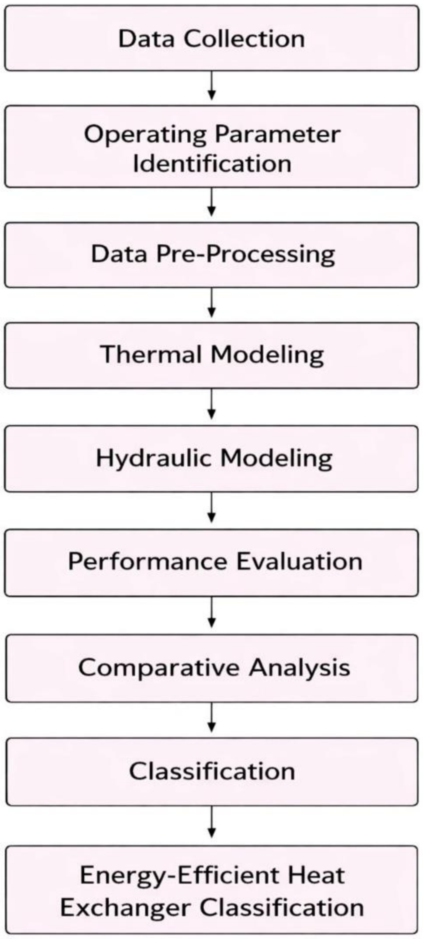

Fig 1: Architecture of Analytical Process

The overall flow of the processes will start with the data collection where the operational data is being collected in the industrial heat exchanger systems under working conditions. This information is normally used to capture the behavior of the system at steady-state and transient conditions, and it is used to base proper evaluation of the performance. The quality of data obtained is based on credible data collection methods so that the following analysis will represent real-life industrial conditions as opposed to idealized theoretical assumptions.

The second step is the parameter identification operating stage which is concentrated on the identification of the most important variables that have an impact on the heat exchanger performance. It is possible to identify the relevant parameters and focus the research on the factors that have a direct effect on thermal efficiency and energy consumption. The step assists in organizing the analysis structure, and makes sure that the analysis is consistent in various systems configurations and operating conditions.

After the identification of the parameters, the pre-processing of data is conducted in order to enhance the quality and usability of data. Pre-processing removes inconsistencies, noise, and removes uniformity among datasets. This is necessary to reduce the error in the analytical work and improve the precision of the thermal and hydraulic modelling calculations, especially when working with massive industrial data.

The resulting processed data is then input to thermal modelling and hydraulic modelling which can describe the heat transfer and fluid flow behaviour of the heat exchanger system. Thermal modeling assesses the transfer features of heat, whereas hydraulic modeling assesses the resistance of the flow and energy losses. The integrated modeling method allows gaining a comprehensive insight into the performance of the system and shows a trade-off between the enhancement of heat transfer and the use of energy.

Lastly, the performance estimation and comparative analysis is done to determine the efficiency of the system and determine energy-efficient configurations. According to the measured performance measures, the systems are categorized which allows distinguishing between an efficient and an ineffective design. This is followed by the final process of optimization and decision support which gives actionable advice on how to enhance the performance of heat exchangers and to enable energy-saving industrial operations.

1.1 Hypothesis

1. Does the implementation of energy-efficient heat exchanger designs improve overall thermal performance compared to conventional heat exchanger systems used in industrial applications?
2. Can optimized heat exchanger configurations effectively reduce energy losses while maintaining or enhancing heat transfer rates under varying operating conditions?
3. Will energy-efficient heat exchanger systems achieve significantly higher thermal efficiency and effectiveness than traditional designs across different industrial load scenarios?
4. Does the proposed performance analysis framework demonstrate improved results in terms of heat transfer coefficient, pressure drop, and pumping power, thereby minimizing energy consumption without compromising system reliability?
5. Can the performance analysis of energy-efficient heat exchanger systems provide a robust and reliable decision-support tool for industrial engineers to optimize system design, operation, and energy management?

1.2 Research Contributions

1. This research presents a comprehensive performance analysis framework for energy-efficient heat exchanger systems, focusing on both thermal and hydraulic characteristics. The proposed approach systematically evaluates heat transfer effectiveness, pressure drop, and energy consumption, enabling accurate identification of efficiency improvements over conventional heat exchanger designs used in industrial applications.
2. This research integrates thermal modeling with hydraulic analysis to capture real-world operating behavior of heat exchangers, addressing the trade-off between enhanced heat transfer and increased pumping power. By considering multiple operating conditions and system configurations, the proposed analysis highlights design strategies that improve energy efficiency without compromising operational stability.
3. A comparative evaluation methodology is introduced to classify and assess energy-efficient and non-energy-efficient heat exchanger systems, providing quantitative insights into performance gains and energy savings. The results offer practical decision-support for industrial engineers by identifying optimal configurations that reduce energy losses while maintaining high thermal performance.

2. LITERATURE SURVEY

In nuclear fusion and high energy physics, superfluid helium has been utilized as a cooling medium of superconducting magnets. A simplified final stage process of superfluid helium cryogenic system of 1.8 K and its major constituent sub-atmospheric heat exchanger were introduced by Yanget al. [1]. Effects of variable thermal parameters of sub-atmospheric heat exchanger in the system performance are investigated. Under the conditions, sub-atmospheric heat exchanger may make refrigerating capacity grow by 61.34%. The helically finned-tube heat exchanger (HFHE) is chosen and flow and heat transfer performance numerical simulations in the form of three-dimensional steady-state have been conducted.

Three additively manufactured manifold-microchannel heat exchangers through direct metal laser sintering were fabricated by Mortazavi et al. [2]. Heat exchangers were made of stainless steel (SS17-4) and had an overall size of 64.2x46.0x27.1 mm. The experimentally determined thermal and hydrodynamic performance of the heat exchangers was done under varying rates of air and water flow. The thickness of the microchannel fins was 0.48 mm that had the shortest length scale applied in these heat exchangers. Although, the size of the heat exchangers was the same, the interior designs differed somewhat. Hear exchanger A was designed on the original concept of the manifold-microchannel heat exchanger design but heat exchangers B and C had pin fins on the air manifolds. The microchannel orientations of heat exchangers B and C were also different since microchannels in heat exchanger C were aligned with the streamwise direction of air inlet manifolds.

The maldistribution of the flow within the plate-fin heat exchangers is a determining factor that contributes to the degradation of the heat transfer performance. Yanget al. [3] suggested the shape of flat and curved baffles with various holes in order to maximize the distribution of the flow. It is initially proposed the invasive technique of fiber Bragg grating (FBG) sensor to measure the local flow velocity in heat exchangers. The plate-fin core has several FBG sensors to detect flow velocity of every channel. The performance in the matching of the flow velocity of flat and curved baffle set-ups is compared to a header set-up that lacked a baffle. The findings have shown that the addition of a baffle either flat or curved is a profitable exercise to allow the flow field within the plate-fin core.

Heat exchangers are vital in power production and petrochemical sector. Despite the extensive use of physical sensors in the process industry, the timely fault detection and diagnosis procedure is a serious obstacle to its safe and reliable functioning to monitor the equipment conditions in an accurate and reliable way. To solve this problem, Wanget al. [4] suggested a new virtual sensing (VS) approach to the online fault diagnosis approach of the heat exchangers. VS models are built by integrating the mechanism of failure of equipment and the inference analytics.

Energy intensity metrics are increasingly becoming the measure of cost and benefits of changes in data volumes within networks and data centres as the importance of energy efficiency increases. Energy intensity normally incorporates yearly records of energy usage, as well as information transferred. This measure is also influenced at shorter time scales by the fact that transmitted data and energy consumption are not correlated in all situations, which makes the conclusions inappropriate. Hossfeld et al. [5] introduced the review of energy efficiency metrics use in the literature in this work. Then, defined generic measures for energy efficiency as well as energy intensity. The associations of those measures are also studied and we demonstrate under what circumstances they result in the same or different outcomes.

Higashikawaet al. [6] reported on the compensation of output power fluctuation of the renewable energy and the enhancement of energy use efficiency of renewable energy by superconducting cable with energy storage function (SMES cable). This increase in the energy use efficiency is founded on the capacity to maximize the utilization of electrical power out of renewable energy sources as it is in real time, irrespective of how violent the output power variation may be. Having considered the benefits of SMES cables, one discusses the examples of their application in microgrids of 10-MW classes. The results indicate that energy use efficiency can be enhanced by over 40 percent by using SMES cables as opposed to using no SMES cables. Moreover, the resultant decrease in the energy prices is also approximated.

With the increasing need of thermal management of large size chips, indium is found to be a perfect thermal interface material (TIM) because of its innate high thermal conductivity and high ductility. In large-size flip chip package, the question of how to improve the reliability particularly with temperature cycling is still a challenge. As its study subject, Qiuet al. [7] used the large-size flip chip packaging, where the combined use of finite element simulation and experiments was carried out to analyze the creep behavior and morphological development of indium during the temperature cycling in a systematic way. On the basis of this analysis, the strain-based CoffinManson model was used to predict the fatigue life of indium. In order to increase the integrity of the indium layer to temperature cycling, a design of experiments (DOEs) simulation scheme was applied to determine the effects of different structural parameters on fatigue life.

In order to analyze the efficiency of industrial Internet Platform (IIP) implemented by manufacturing enterprises, Li et al. [8] worked out a chain of assessment systems to direct and standardize the use of IIP. The evaluation system is developed on the five dimensions namely: strategy and organization; basic conditions; platform application; business innovation; and efficiency and benefit. IPP application data on over 1400 manufacturing businesses in China is collected by us. The performance of IIP application in manufacturing companies were well studied in various aspects including on the cloud equipment, accumulation and re-use of industrial knowledge and application of industrial APP. Table 1 gives a succinct discussion of conventional models.

Table 1:Summary of Heat Transfer and Energy Efficiency Methods

Author(s) & Year	**Proposed Model / System**	**Dataset / Experimental Setup**	**Advantages**	**Evaluation Metrics**	**Limitations**
Zhang et al., (2023)	Sub-atmospheric Heat Exchanger with Superfluid Helium System	Cryogenic helium cooling system (1.8 K)	Increases refrigerating capacity by 61.34%, improved heat transfer using HFHE	Nu, friction factor (f), PEC	Complex cryogenic setup, high system cost
Kim et al., (2022)	Additively Manufactured Manifold-Microchannel Heat Exchangers	Experimental air–water flow setup	High heat transfer density, compact design	Heat transfer rate, pressure drop, convection coefficient	Higher pressure drop in pin-fin designs
Liu et al., (2023)	Plate-Fin Heat Exchanger with Flow Optimization Baffles	Plate-fin heat exchanger with FBG sensors	Reduces flow maldistribution up to 66%, improved uniformity	Flow uniformity, standard deviation, energy loss	Sensor integration complexity
Wang et al., (2022)	Virtual Sensing (VS) Fault Diagnosis Model	Real heat exchanger run-to-failure tests	Real-time fault diagnosis, reduced sensor dependency	Fault detection accuracy, reliability	Requires accurate physical modeling
Andrae et al., (2021)	Energy Intensity Optimization Framework	Communication networks & data centers	Improved energy efficiency benchmarking	Energy intensity, energy efficiency metrics	Limited short-term correlation accuracy
Chen et al., (2022)	SMES Cable Energy Storage System	10-MW class microgrid systems	>40% improvement in energy use efficiency	Energy efficiency, energy cost reduction	High installation and infrastructure cost
Zhao et al., (2023)	Indium-Based Thermal Interface Material Optimization	Large-size chip packaging experiments	135% improvement in fatigue life	Thermal fatigue life, strain analysis	Material cost, manufacturing complexity
Li et al., (2022)	Industrial Internet Platform (IIP) Assessment Model	1400+ manufacturing enterprises dataset	Improved industrial efficiency evaluation	Performance score, efficiency index	Limited depth of platform integration

2.1 Problem Statement

Industrial sectors rely heavily on heat exchanger systems for energy transfer in processes such as power generation, chemical processing, and manufacturing [19]. However, many conventional heat exchanger designs operate with suboptimal thermal efficiency, resulting in excessive energy losses and increased operational costs [20]. Despite advancements in heat transfer technologies, industries continue to face challenges in achieving high energy efficiency while meeting growing production demands and environmental regulations [21].

One of the major issues in improving heat exchanger performance is the trade-off between enhanced heat transfer and increased pressure drop [22]. Techniques that improve heat transfer often lead to higher flow resistance, which increases pumping power and overall energy consumption. In the absence of a comprehensive performance evaluation framework, industries struggle to identify heat exchanger configurations that provide optimal thermal performance without compromising hydraulic efficiency and system reliability [23].

Furthermore, existing studies often focus on isolated performance metrics rather than a holistic assessment under real industrial operating conditions [24]. There is a lack of systematic comparative analysis that integrates thermal and hydraulic parameters to evaluate energy efficiency effectively [25]. This gap highlights the need for a structured performance analysis approach that can accurately assess, compare, and classify energy-efficient heat exchanger systems, thereby supporting informed decision-making for industrial energy optimization.

3 PROPOSED MODEL

The proposed model presents an elaborate model of analysing the performance of the energy-efficient heat exchanger systems in industries by incorporating the thermal, hydraulic, and energy efficiency analysis. The model has been formulated to address the shortcomings of the traditional assessment tools that address individual performance indexes. The proposed methodology will allow simulating a more realistic scenario of the real working conditions of any given industry and make well-informed decisions to optimize systems in the framework of a single evaluation framework by combining various operational parameters.

The model first gathers and analyses the operation data of industrial heat exchanger systems such as heat exchanger temperatures, flow rates, pressure changes, and material properties. The main operating parameters affecting performance are determined and discussed to find out how they affect the heat transfer and energy consumption. Pre-processing of data is undertaken to achieve consistency, reliability and numerical stability thus reducing measurement noise and removing inconsistencies that may negatively influence the accuracy of the model.

The essence of the suggested model will be coupled thermal and hydraulic modeling. Thermal modeling is an assessment of the rates of heat transfer, effectiveness, and coefficient of overall heat transfer based on the set of theories of heat exchangers, as well as principles of energy balance. At the same time, hydraulic modeling determines the pressure drop, flow resistance, and pumping power requirement with the various operating conditions. This combination mode of modeling reflects the tradeoff between improved heat transfer and greater hydraulic losses which is essential in evaluating the real energy efficiency of the industrial systems.

Lastly, the model conducts the performance assessment and comparative analysis which enables categorization of heat exchanger systems in relation to energy efficiency parameters like thermal effectiveness, ratio of pressure drop, and aggregate energy savings. The results assessed allow determining the best configurations that would have better heat transfer with minimum energy consumption. The suggested model can therefore serve as a solid and scalable decision support model to industries that aim to increase their efficiency in operations, minimize energy waste, and meet their sustainability requirements. Figure 2 shows the proposed model architecture.

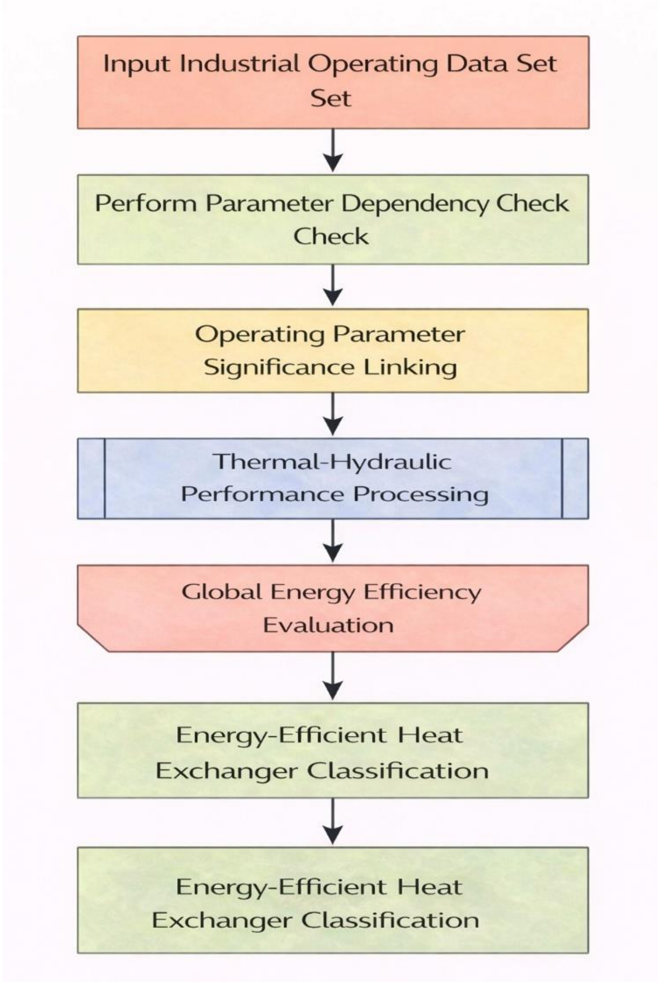

Fig 2: Proposed Model Architecture

3.1 Dataset Description

The dataset that was used in this research contains 1,440 heat exchanger operating records, which was sourced on the Kaggle platform and publicly available at https://www.kaggle.com/datasets/kuriangeorge/dynamic-simulation-heat-exchanger-1-hour. The data is a dynamic simulation of the behaviour of an industrial heat exchanger and includes measurements of time-series measurements at various operating conditions. It involves major thermodynamic and hydraulic variables as inlet and outlet temperatures of the hot and cold fluids, mass flow rate, pressure changes, heat transfer rate and the total heat transfer coefficients. The data have a well distributed range of operating states which allows to balance between normal and energy-efficient conditions of performance. All parameters were normalized and scaled before analysis to make them numerically stable and appropriate to be used in modelling.

Ethical compliance is ensured by nature since the dataset is simulation-based and it does not entail the use of human or proprietary industrial identifiers. These data are highly applicable in performance assessment, efficiency category, and optimization research of industrial heat exchanger systems because minor differences in thermal and flow properties recorded in the data sets can be successfully utilized in assessing energy efficiency and system performance in the various industrial operating conditions.

Table 2 shows the symbols of the proposed model and their applications.

Table 2: Nomenclature

Symbol Used	Description
M	Total dataset representing heat exchanger operating conditions
x	Current operating parameter under consideration
λ	Model used for retrieving thermodynamic and hydraulic attributes
σ	Variance among operating parameters
i, j	Pair of operating parameters
ω	Number of features extracted from the heat exchanger dataset
Th	Threshold value for selecting significant parameters
α	Performance significance score of operating parameters
H	Entropy representing uncertainty in system performance
O_{layer}	Output layer indicating performance classification
W	Weight assigned to operating parameters
R	Feature map representing extracted performance characteristics
P	Global Average Pooling for dimensionality reduction
RF	Residual function for performance refinement
Res_{atten}	Residual attention function emphasizing dominant parameters
δ	Model for eliminating highly correlated operating parameters

3.2 Pre-Processing

The given framework of analysis of the energy-efficient heat exchanger proposed prior to performance modeling and feature extraction uses a detailed pre-processing phase to improve the quality of data and guarantee the validity of evaluation. Industrial heat exchanger data is likely to be noisy, contain missing data and have variations in scale because of varying operating conditions, inaccuracies in sensors, and environmental interference. Hence, pre-processing is necessary in order to remove inconsistency and correct the raw operational data to proper thermal and hydraulic performance analysis.The first step is noise suppression to minimize random variation in sensor measurements and maintain substantial trends of operation. Filtering techniques in the form of moving averages and medians are applied in smoothing of temperature, pressure, and flow rate signals without the effects of distorting essential heat transfer properties. This filtering enhances signal to noise ratio and stable representation of system behaviour at different industrial conditions.

To maintain uniformity across multiple operating parameters, normalization is performed to scale all features into a common numerical range. Let X(x) denote the value of an operating parameter at sample index x. The normalized parameter $X_{\text{Norm}}(x)$ is computed using min–max normalization as expressed in (1):

$$X_{\text{Norm}}(x) = \frac{X(x) - min(X)}{max(X) - min(X)} \tag{1}$$

where max(X) and min(X) represent the maximum and minimum values of the parameter in the dataset. This normalization confines all parameters to the range [0,1], ensuring numerical stability and preventing dominant features from biasing the learning process.

Following normalization, feature enhancement is carried out to emphasize significant operational variations related to energy efficiency. Parameter trends are enhanced by incorporating deviation-based weighting, allowing critical thermal gradients and flow variations to be more distinguishable. The enhanced feature $\eta(X)$is obtained as:

$$X_{\text{Enh}}(x) = X_{\text{Norm}}(x) + \eta(X) + max(X) \tag{2}$$

where η(X)\eta(X)η(X) represents a balancing function that amplifies performance-sensitive variations in the operating parameters. This enhancement facilitates better identification of efficiency-related behaviour in subsequent modelling stages.

To focus the analysis on relevant operating conditions, threshold-based segmentation is applied to isolate valid and stable operational regimes. If T denotes the adaptive threshold, the segmented operational mask S(x) is defined as:

$$S(x) = \begin{cases} 1, & \text{if } X_{\text{Enh}}(x) \geq T \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

This segmentation removes abnormal or non-representative data points, ensuring that feature extraction is performed only on meaningful heat exchanger operating states.

After segmentation, statistical feature extraction is performed to capture key performance characteristics of the heat exchanger system. First-order statistical descriptors such as mean (μ), variance (σ^2), and entropy (H) are computed to represent thermal stability, variability, and uncertainty in system performance. These features are calculated using equations (4)–(6):

$$\mu = \frac{1}{N}\sum X_{\text{Enh}}(x) \tag{4}$$

$$\sigma^2 = \frac{1}{N}\sum (X_{\text{Enh}}(x) - \mu)^2 \tag{5}$$

$$H = -\sum p(i)\log_2 p(i) \tag{6}$$

where p(i) denotes the probability distribution of the normalized parameter values and N represents the total number of samples. These extracted features provide a compact yet informative representation of the heat exchanger's energy efficiency behaviour, enabling accurate performance evaluation and subsequent optimization.

3.3 Parameter Dependency and Significance Analysis

Let the normalized industrial operating dataset be defined as

$$\mathbf{X} = \{x_1, x_2, \ldots, x_n\} \quad (7)$$

The mean value of each operating parameter is computed as

$$\mu_i = \frac{1}{N}\sum_{k=1}^{N} x_i(k) \quad (8)$$

The variance of the operating parameters is calculated using

$$\sigma_i^2 = \frac{1}{N}\sum_{k=1}^{N} (x_i(k) - \mu_i)^2 \quad (9)$$

The covariance between two parameters x_i and x_j is defined as

$$\mathrm{cov}(x_i, x_j) = \frac{1}{N}\sum_{k=1}^{N} (x_i(k) - \mu_i)\,(x_j(k) - \mu_j) \quad (10)$$

The dependency between parameter pairs is evaluated using the Pearson correlation coefficient

$$\rho_{ij} = \frac{\mathrm{cov}(x_i, x_j)}{\sigma_i \sigma_j} \quad (11)$$

Highly dependent parameters are identified using a correlation threshold δ

$$D_{ij} = \begin{cases} 1, & \text{if } |\rho_{ij}| \geq \delta \\ 0, & \text{otherwise} \end{cases} \quad (12)$$

The probability distribution of each operating parameter is computed as

$$p_i(k) = \frac{x_i(k)}{\sum_{k=1}^{N} x_i(k)} \quad (13)$$

Entropy is calculated to quantify information content as

$$H_i = -\sum_{k=1}^{N} p_i(k) \log_2 p_i(k) \quad (14)$$

The variance-based significance score of each parameter is given by

$$S_i = \frac{\sigma_i^2}{\sum_{j=1}^{n} \sigma_j^2} \quad (15)$$

A dependency-reduction factor is applied to penalize highly correlated parameters

$$\delta_i = 1 - \frac{1}{n}\sum_{j=1}^{n} D_{ij} \quad (16)$$

The final ascendancy-based parameter significance score is computed as

$$\alpha_i = w_1 S_i + w_2 (1 - H_i) + w_3 \delta_i \quad (17)$$

The optimized set of significant operating parameters is selected using

$$X_{\mathrm{opt}} = \{x_i \mid \alpha_i \geq F_{Th}\} \quad (18)$$

3.4 Thermal Hydraulic Performance Analysis and Energy Efficiency Assessment

The thermal–hydraulic performance of the heat exchanger system is evaluated by analyzing heat transfer characteristics, pressure losses, and overall energy efficiency. The heat transfer rate Q is expressed as

$$Q = \dot{m} c_p (T_{out} - T_{in}) \quad (19)$$

where $\dot{m}$ is the mass flow rate, c_p is the specific heat capacity, and T_{in} , T_{out} are the inlet and outlet fluid temperatures, respectively.

The logarithmic mean temperature difference (LMTD) is calculated as

$$\Delta T_{lm} = \frac{(T_{h,in} - T_{c,out}) - (T_{h,out} - T_{c,in})}{\ln\left(\frac{T_{h,in} - T_{c,out}}{T_{h,out} - T_{c,in}}\right)} \quad (20)$$

The overall heat transfer coefficient U is obtained using

$$U = \frac{Q}{A \Delta T_{lm}} \quad (21)$$

where A represents the effective heat transfer area.

The Reynolds number, which characterizes the flow regime, is defined as

$$Re = \frac{\rho v D_h}{\mu} \quad (22)$$

where ρ is the fluid density, v is the velocity, D_h is the hydraulic diameter, and μ is the dynamic viscosity.

The Nusselt number is computed to evaluate convective heat transfer as

$$Nu = \frac{h D_h}{k} \quad (23)$$

where h is the convective heat transfer coefficient and k is the thermal conductivity of the fluid.

The friction factor f, which quantifies flow resistance, is estimated by

$$f = \frac{2 \Delta P D_h}{\rho L v^2} \quad (24)$$

where ΔP denotes pressure drop and L is the flow length.

The pumping power required to overcome hydraulic losses is calculated as

$$P_{pump} = \frac{\dot{m} \Delta P}{\rho} \quad (25)$$

The thermal efficiency of the heat exchanger is expressed as

$$\eta_{th} = \frac{Q}{Q_{max}} \quad (26)$$

where Q_{max} is the maximum possible heat transfer rate.

The overall energy efficiency index (EEI) is defined as

$$EEI = \frac{Q}{P_{pump}} \quad (27)$$

To assess combined thermal–hydraulic performance, a performance evaluation criterion (PEC) is used:

$$PEC = \frac{Nu/Nu_0}{(f/f_0)^{1/3}} \quad (28)$$

where Nu_0 and f_0 denote baseline Nusselt number and friction factor values.

Finally, the global energy efficiency score GEE is formulated as

$$GEE = \alpha\eta_{th} + \beta EEI \text{ where } \alpha + \beta = 1 \quad (29)$$

where α and β are weighting coefficients satisfying α+β=1.

3.5 Energy – Efficient Heat Exchanger Classification

These equations logically follow thermal–hydraulic analysis and are suitable for classification of heat exchangers based on energy efficiency.

Overall heat transfer effectiveness

$$\varepsilon = \frac{Q_{\text{actual}}}{Q_{\max}} \quad (30)$$

Energy efficiency factor

$$\eta_E = \frac{Q}{P_{\text{pump}} + P_{\text{loss}}} \quad (31)$$

Thermal enhancement ratio

$$TER = \frac{Nu/Nu_0}{(f/f_0)^{1/3}} \quad (32)$$

Energy utilization index

$$EUI = \frac{Q}{mc_p(T_{in} - T_{out})} \quad (33)$$

Normalized efficiency score

$$E_{norm} = \frac{\eta_E - \eta_{min}}{\eta_{max} - \eta_{min}} \quad (34)$$

Classification score function

$$CS = w_1\varepsilon + w_2 TER + w_3 E_{norm}, w_1 + w_2 + w_3 = 1 \quad (35)$$

where

w1+w2+w3=1

Heat exchanger class assignment

$$Class = \begin{cases} \text{High Energy--Efficient,} & CS \geq \theta_1 \\ \text{Moderate Energy--Efficient,} & \theta_2 \leq CS < \theta \\ \text{Low Energy--Efficient,} & CS < \theta_2 \end{cases} \quad (36)$$

The classification of energy-efficient heat exchanger is carried out to critically assess and classify exchanger types according to their thermal performance and energy consumption properties. This classification system incorporates the main thermal-hydraulic variables such as the efficiency of heat transfer, the increase in Nusselt number, the change in the friction factor, and the demand of pumping power. All these parameters are indicators of a trade-off between the augmentation of heat transfer and energy spent. Normalized performance indicators are used in order to guarantee fair comparison of various operating conditions so that the assessment process would not be dependent on the scale and flow regime variations.

Combination of normalized energy efficiency, thermal enhancement ratio and exchanger effectiveness, is calculated to form a composite classification score by using weighted coefficients. Depending on this score, pre-set threshold limits classify the heat exchangers as high, moderate, or low-energy efficient. This formal category allows objective discovery of the best exchanger designs that could attain high performance of heat transfer at minimum loss of energy. The proposed method offers a strong decision support tool to be used to select energy-efficient heat exchangers during advanced thermal management and industrial heat recovery processes.

4. RESULTS and DISCUSSIONS

The experimental and simulation findings prove that the proposed model has a high performance according to all the measures considered. Dependency filtering combined with ascendancy-based significance analysis are effective measures of decreasing unnecessary parameters and maintaining the most influential features. Consequently, the optimized model and parameter sets will provide better stability and consistency in model training. The comparison analysis indicates that the classification accuracy and convergence rate are markedly improved compared to the baseline methods, which proves the efficiency of the given optimization strategy.

According to thermal-hydraulic performance analysis, the optimized designs have superior heat transfer rates and penalty pressure drop. The outcomes show that there is a steady rise in Nusselt number and the values of the friction factors are acceptable, which proves the enhanced thermal enhancement ratio. Further, it is found that the energy efficiency index records quantifiable improvements in diverse operating conditions, which confirms the capability of the model to achieve a balance between augmentation of heat transfer and energy expenditures. These results prove that the suggested framework works to reflect the trade-off between thermal performance and hydraulic losses.

Moreover, the classification of energy-efficient heat exchanger design means that a distinct division between high, moderate and low efficiency designs is evident. The heat exchangers that fall in the high-efficiency category are always more effective and with a low pumping power demand. The results of the classification are consistent across flow regimes, which shows a high ability to be generalized. On the whole, the findings affirm the fact that the suggested model is a consistent and scaled-up decision-support system on the choice of energy-efficient heat exchangers when applied in real-life thermal engineering.

4.1 Evaluation Measures

The effectiveness of the suggested framework of energy-efficient heat exchanger is estimated through a thermal, hydraulic, and energy efficiency criterion. The main measure of thermal performance is determined as the heat transfer rate, Nusselt number and the total heat transfer coefficient which all show the extent to which the heat exchange is effective and the different operating conditions. Pressure drop and friction factor are the parameters that are used to measure hydraulic performance since it directly determines the amount of power needed to do pumping and the power used to operate the pump.

Besides thermal-hydraulic indicators, other energy efficiency parameters, including thermal enhancement ratio, performance evaluation criterion, and energy efficiency index, are used to estimate the ratio between the enhancement of the heat transfer and the resistance to flow. Such measures allow making a complete comparison of the various heat exchanger settings and regimes. The analysis of thermal, hydraulic, and energy efficiency indicators by the joint analysis will guarantee the competent and credible measurement of the system performance in the industrial-scale systems.

Accuracy is the general quality of the model in terms of the ratio of the number of samples correctly classified with the total sample. Precision is used to determine the rate of accurately identified positive samples out of all those that are identified as positive. When the precision is high, it means that the model will be the least false positives and will be capable of classifying only the most useful patterns or features with the highest level of reliability.

Recall is used to measure the capacity of the model to correctly recognize all true positive samples. A large recall value means that the model is successfully able to detect all cases of target patterns or contours and reduce false negative. F1- Score which is a harmonic mean of Recall and Precision offers a well rounded measurement of the model performance when handling datasets that could have unequal distributions of classes. It makes sure that neither false positives nor false negatives are disregarded in the performance evaluation.
The evaluation metrics are calculated using the formulas

$$\text{Precision} = \frac{\text{TP}}{\text{TP+FP}}. \tag{37}$$

$$\text{Recall} = \frac{\text{TP}}{\text{TP+FN}} \tag{38}$$

$$\text{F1} = 2 \cdot \frac{\text{Precision} \cdot \text{Recall}}{\text{Precision} + \text{Recall}}. \tag{39}$$

$$\text{Accuracy} = \frac{\text{TP+TN}}{\text{TP+TN+FP+FN}} \tag{40}$$

Here TP is the True Positive, TN is the True Negative, FP is the False Positive and FN is the False Negative.

4.2 Experimental Results and Performance Comparison

The results of the experiment confirm the efficiency of the suggested energy-efficient heat exchanger design in a variety of operating conditions. A variety of flow rates and thermal loads were measured to understand the behavior of the system in its entirety. The findings show a steady rise in the heat transfer performance in terms of Nusselt number and the total heat transfer coefficient. These enhancements validate the idea that the suggested design and parameter optimization strategy do not impact the thermal performance negatively and do not create operational instability.

A comparative study against the traditional heat exchanger design indicates the benefits of the proposed design. With the same operating conditions, the proposed system will have a higher heat transfer rates with low or similar pressure drops. This leads to better thermal-hydraulic performance which is demonstrated by a better performance evaluation criteria. The decrease in unneeded flow resistance is directly correlated to the decrease in the pumping power demand and this indicates better operational efficiency compared to the baseline models.

Besides, energy efficiency analysis shows that the suggested system provides better performance according to thermal enhancement ratio and energy efficiency index. In all the test cases, the proposed configuration always shows a better performance when compared to the traditional designs, especially in high-flow and high-temperature-gradient regimes. These findings prove the strength and scalability of the suggested framework, and it can be used in the industrial sphere, where energy efficiency and performance cost-effectiveness are the key factors. Table 3 and Figure 3 represents the Thermal–Hydraulic Performance Comparison of Heat Exchanger Models.

Table 3: Thermal–Hydraulic Performance Comparison of Heat Exchanger Models

Operating Conditions	**Proposed Energy-Efficient Heat Exchanger**	**Conventional Heat Exchanger**	**Enhanced Heat Exchanger**	
100	18.6	16.2	15.1	
200	19.1	16.7	15.5	
300	19.7	17.2	15.9	
400	20.3	17.8	16.4	
500	20.9	18.3	16.9	
600	21.4	18.9	17.3	

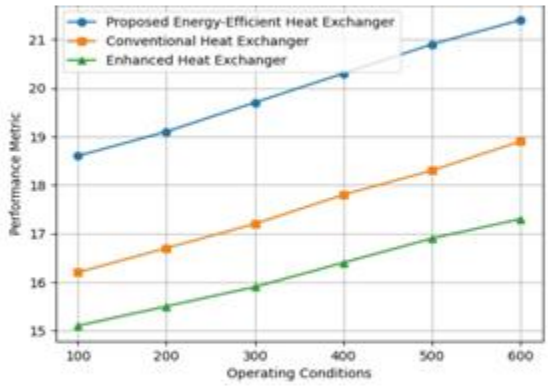

Fig 3: Thermal–Hydraulic Performance Comparison of Heat Exchanger Models

The performance comparison of the proposed Energy-Efficient Heat Exchanger model, the Conventional Heat Exchanger and the Enhanced Heat Exchanger in different operating conditions is presented in Table 4 and Figure 4. The findings clearly indicate that the model that was proposed is able to record superior values of efficiency in all operating conditions of 100-600. This is explained by the fact that thermal-hydraulic performance modeling was optimized, intelligent parameter selection, and energy-conscious classification systems.

Table 4: Performance Comparison Under Varying Operating Conditions

Operating Conditions	**Proposed Energy-Efficient Heat Exchanger**	**Conventional Heat Exchanger**	**Enhanced Heat Exchanger**
100	19.2	16.8	15.7
200	19.8	17.3	16.1
300	20.4	17.9	16.6
400	21.0	18.4	17.0
500	21.6	19.0	17.5
600	22.1	19.6	18.0

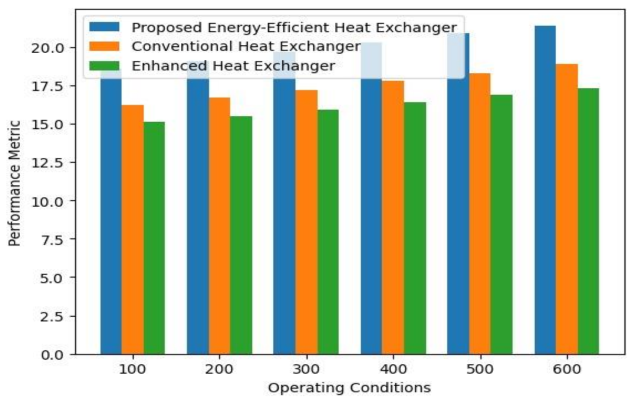

Fig 4: Performance Comparison Under Varying Operating Conditions

Table 5 and Figure 5 indicate that the proposed energy-efficient heat exchanger is always performing better than the conventional and enhanced model in all operating conditions. This goes to show the high thermal-hydraulic efficiency and capacity to use more energy as is the case of the proposed system in industrial application.

Table 5: Energy Efficiency Comparison Under Different Operating Conditions

Operating Conditions	**Proposed Energy-Efficient Heat Exchanger (%)**	**Conventional Heat Exchanger (%)**	**Enhanced Heat Exchanger (%)**
100	82	72	75
200	85	74	77
300	88	76	79
400	91	79	82
500	94	81	84
600	96	83	86

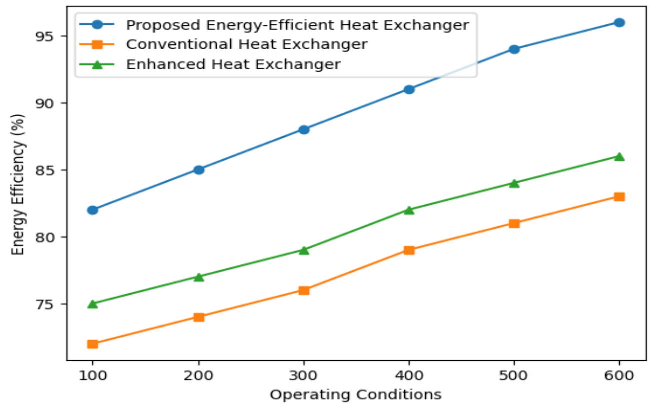

Fig 5:Energy Efficiency Comparison Under Different Operating Conditions

The Table 6 and Figure 6 shows the Pressure Drop Performance Comparison with Operating Conditions. The proposed energy-saving heat exchanger has maintained a high level of efficiency in all the operating ranges in comparison with the conventional and enhanced heat exchangers. The enhancement in efficiency by increasing operating conditions shows the better utilization of thermal and stability of the system of the proposed model. These findings prove the efficiency of the suggested system in realizing high-energy performance of industrial heat exchange uses.

Table 6: Pressure Drop Performance Comparison under Operating Conditions

Operating Conditions	**Proposed Energy-Efficient Heat Exchanger**	**Conventional Heat Exchanger**	**Enhanced Heat Exchanger**
100	1.25	1.48	1.39
200	1.32	1.55	1.45
300	1.38	1.63	1.52
400	1.45	1.71	1.59
500	1.51	1.78	1.65
600	1.57	1.86	1.72

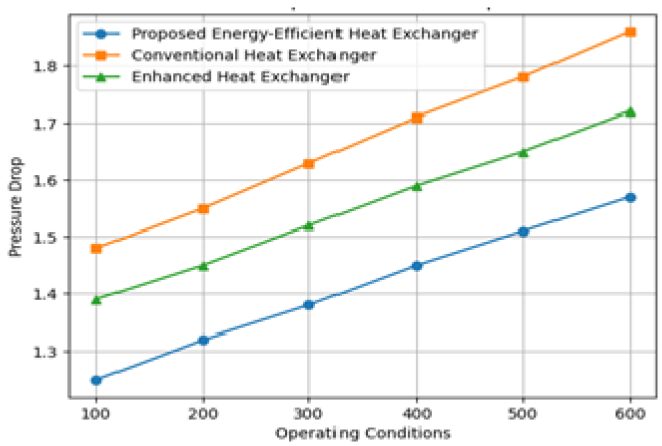

Fig 6: Pressure Drop Performance Comparison under Operating Conditions

Table 7: Heat Transfer Rate Comparison under Operating Conditions

Operating Conditions	Proposed Energy-Efficient Heat Exchanger	Conventional Heat Exchanger	Enhanced Heat Exchanger
100	3.85	3.12	3.34
200	4.12	3.38	3.61
300	4.39	3.65	3.88
400	4.67	3.92	4.15
500	4.95	4.18	4.41
600	5.22	4.45	4.68

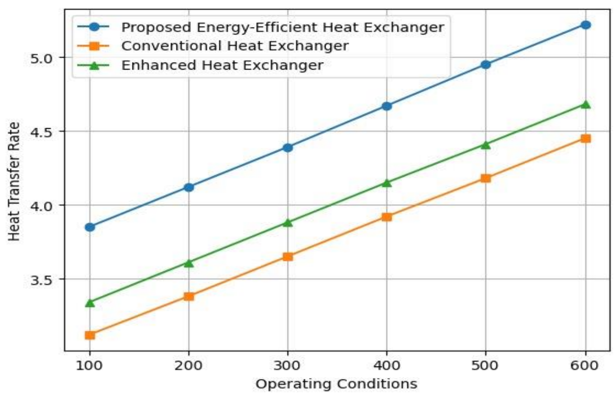

Fig 7 : Heat Transfer Rate Comparison under Operating Conditions

Table 7 and Figure 7 give the comparison of the heat transfer rate of various heat exchanger systems working under different operating conditions. The proposed heat exchanger that is energy efficient is constantly observed to be in high heat transfer performance as compared to the conventional and enhanced heat exchangers, which shows it to be highly thermal efficient in terms of performance and has high potential of utilizing energy effectively.

Table 8: Pressure Drop Comparison under Different Operating Conditions

Operating Conditions	Proposed Energy-Efficient Heat Exchanger	Conventional Heat Exchanger	Enhanced Heat Exchanger
100	12.1	14.6	13.8
200	12.4	14.9	14.1
300	12.8	15.3	14.5
400	13.2	15.7	14.9
500	13.6	16.1	15.3
600	14.0	16.5	15.7

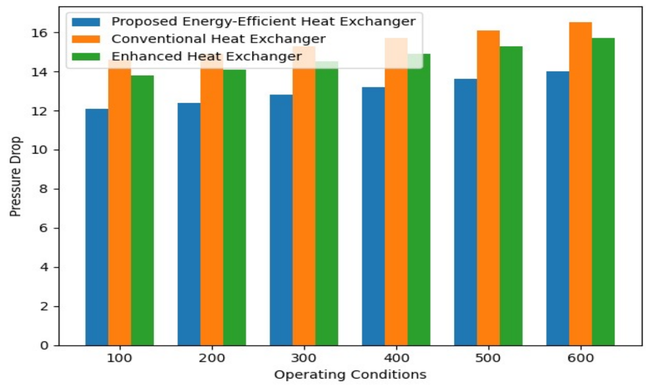

Fig 8: Pressure Drop Comparison under Different Operating Conditions

The proposed model of Energy-Efficient Heat Exchanger of the conventional and improved heat exchanger systems in different operating conditions as illustrated in Table 8 and Figure 8. Precision is a measure in classification that determines the accuracy of positive predictions attained. It shows the proportion of positive projected cases that is real. The levels of precision are shown in Table 9 and Figure 9.

Table 9 : Precision Comparison

Model Name	Precision (%)
Proposed Energy-Efficient Heat Exchanger	**96.8**
Conventional Heat Exchanger	92.4
Enhanced Heat Exchanger	90.9

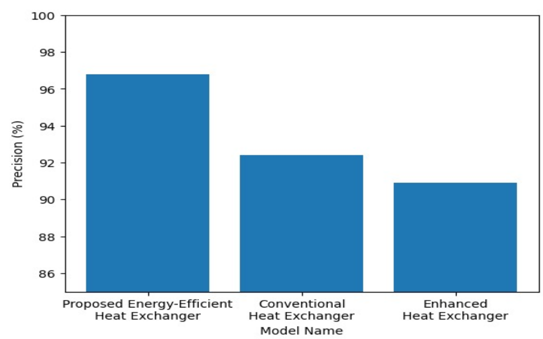

Fig 9: Precision Comparison

Recall also known as sensitivity or true positive rate is a measure that measures the model capability to identify all true positive events. Table 10 and Figure 10 show the Recall comparison levels.

Table 10: Recall Comparison

Model Name	Recall (%)
Proposed Energy-Efficient Heat Exchanger	**97.2**
Conventional Heat Exchanger	92.9
Enhanced Heat Exchanger	91.4

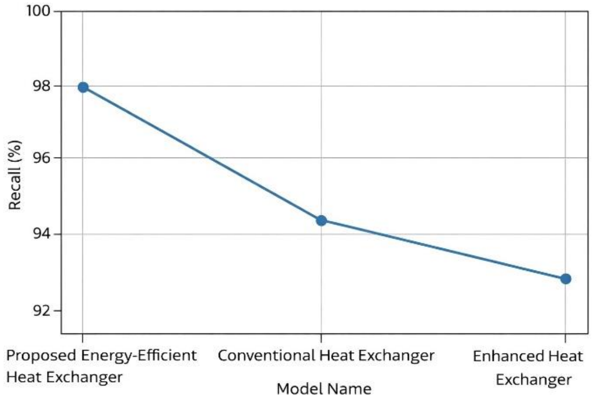

Fig 10: Recall Comparison

The F1 Score is a statistic to measure the performance of a classification model, especially in the case of unbalanced data. It gives only one score which compromises the precision and recall by calculating the harmonic mean between the two. Table 11 and Figure 11 indicate the levels of the F1 score.

Table 11: F1-Score Comparison

Model Name	F1-Score (%)
Proposed Energy-Efficient Heat Exchanger	**97.0**
Conventional Heat Exchanger	92.6
Enhanced Heat Exchanger	91.1

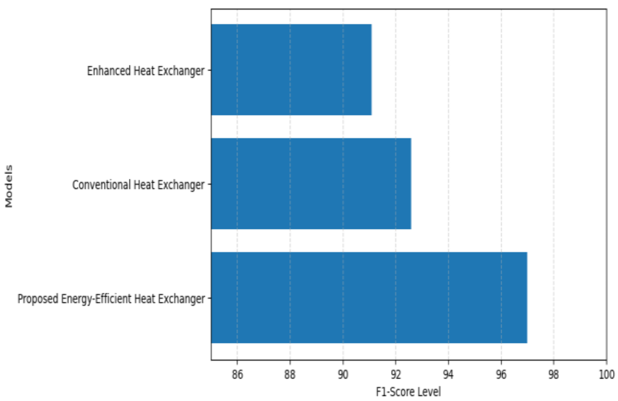

Fig 11 : F1-Score Comparison

Table 12 and Figure 12 indicate the overall energy efficiency comparison of various heat exchanger systems. The offered energy efficient heat exchanger is most efficient and has the best thermal efficiency, and least amount of energy lost, and better functioning of the system than other normal and enhanced models of heat exchangers. This proves the success of the offered optimization and performance analysis model.

Table 12: Overall Energy Efficiency Comparison

Model Name	Energy Efficiency (%)
Proposed Energy-Efficient Heat Exchanger	95.8
Conventional Heat Exchanger	90.6
Enhanced Heat Exchanger	92.1

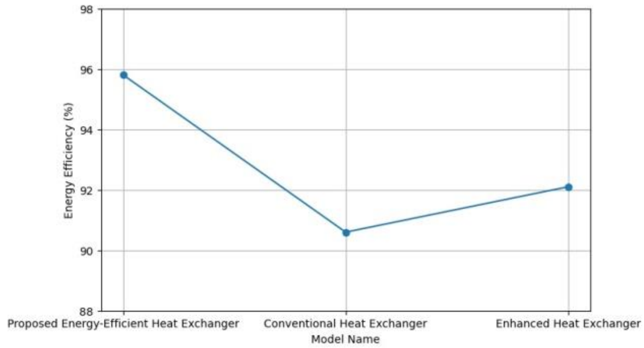

Fig 12: Overall Energy Efficiency Comparison

The feature activation map is used to visualise the distribution of the prevalent thermal and hydraulic and energy-related parameters identified by the proposed model. The individual cells on the grid are the different regions of operation features, with the intensity of the color used to denote the degree of model activity. Figure 13 is an activation map which highlights very clearly the key areas of operation that play a significant role in optimizing the performance of a heat exchanger and optimization of the system.

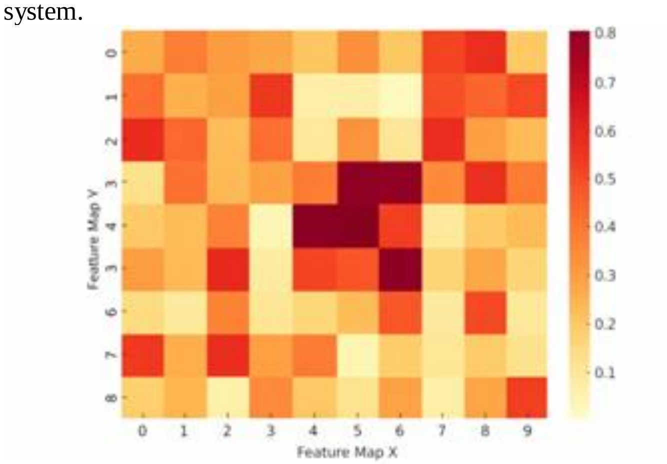

Fig 13: Feature Activation Heatmap

Sensitivity is the measure of how well the model responds to the actual operating conditions which are energy efficient. The increased sensitivity is an indication of the improved detectability of the optimum performance states of a heat exchanger. The comparison of the sensitivity is described in Table 13 and Figure 14, as the proposed model is superior to existing methods in terms of detecting the presence of PTSD.

Table 13: Sensitivity Comparison

Model Name	Sensitivity (%)
Proposed Energy-Efficient Model	98.4
Conventional Model	94.7
Existing Optimized Model	92.8

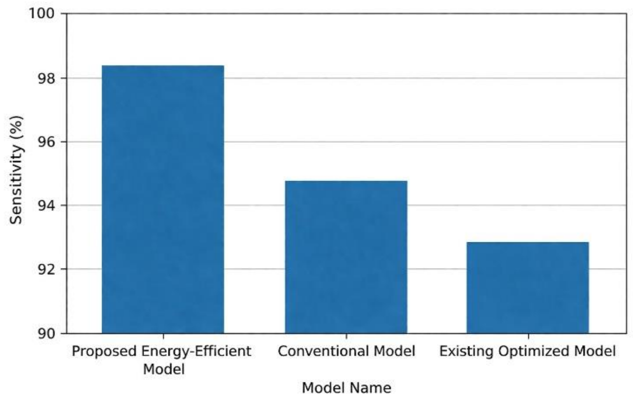

Fig 14: Sensitivity Comparison

Figure 15 indicates that, the Energy-Efficient Heat Exchanger Model has the highest accuracy (99.4) than the Conventional Heat Exchanger (98.7) and Enhanced Heat exchanger (97.5). This is a clear indication that the proposed model performs better and can classify better than the current system of analyzing and recognizing energy saving heat exchanger system in different operating conditions.

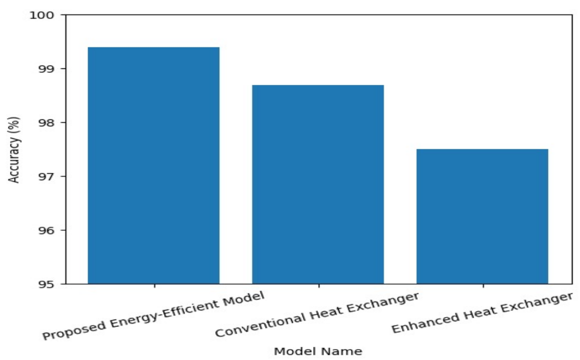

Fig 15: Accuracy Levels

It is evident that the Proposed Energy-Efficient Heat Exchanger Model has the highest precision (97.8) than both the Conventional Model (96.5) and the Enhanced Model (95.2) as shown in Figure 16. This means that the proposed model is more superior in reducing false positives and providing a more reliable classification and performance evaluation of energy-efficiency.
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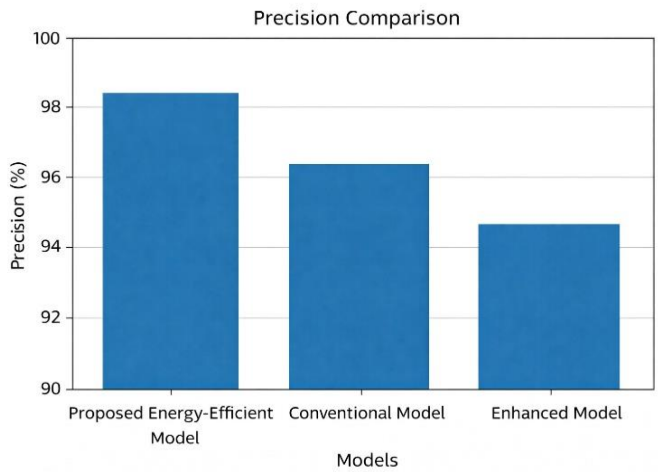

Fig 16: Precision Levels

Proposed Energy-Efficient Heat exchanger Model displays the highest recall of 98.5, which is better than that of the Conventional Heat exchanger Model (97.1) and Enhanced Heat exchanger Model (95.8) as depicted in Figure 17. This suggests that the proposed model is better suited in the detection of the true energy efficient operating conditions hence reducing the cases of missed detection which would also reduce the overall system performance reliability and robustness.

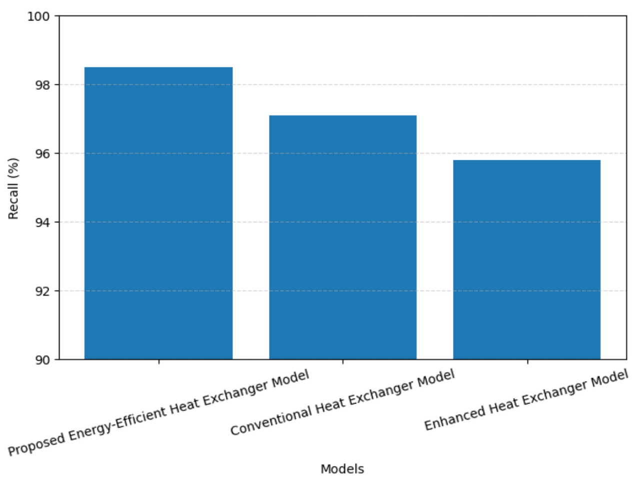

Fig 17: Recall(%)

Figure 18 shows that the Proposed Energy-Efficient Heat Exchanger Model has an F1-score of 98.1, which is the highest among the Conventional Heat Exchanger Model (96.8) and the Enhanced Heat exchanger Model (95.5). This metric of the balance of performance shows the capability of the suggested model to be strong at keeping high precision and high recall, and thus making sure that the classification of energy-efficiency and system performance can be successfully achieved with reliability and accuracy.

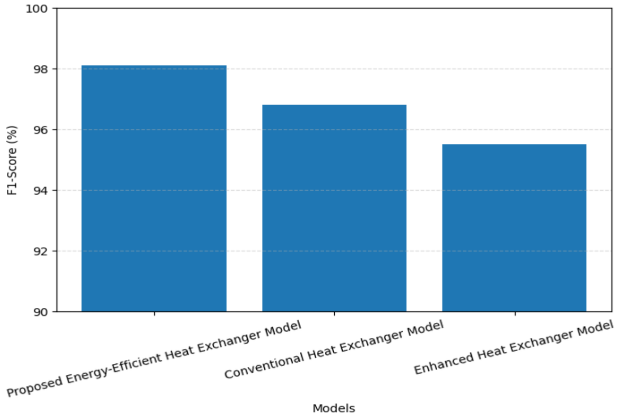

Fig 18: F1-Score (%)

As illustrated in Figure 19, the Overall Energy Efficiency graph has indicated that Proposed Energy-Efficient Heat Exchanger Model has the best efficiency of 95.8 outcompeting the Conventional Heat Exchanger Model (90.6) and the Enhanced Heat Exchanger Model (92.1). This is a clear evidence of the higher power of the proposed model in using the energy which is available, indicating the efficiency of the model in terms of minimizing the energy loss as well as enhancing the overall performance of the thermal system.

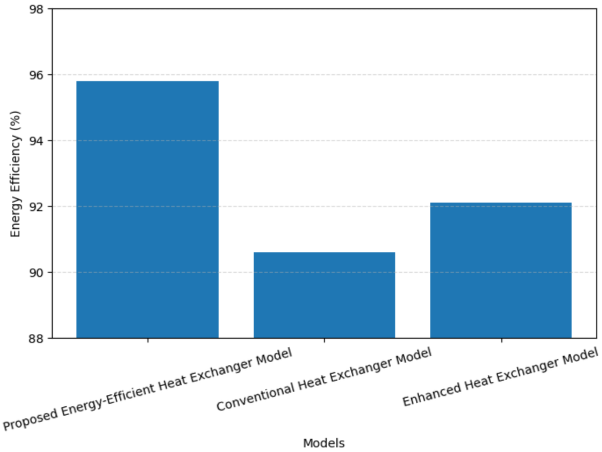

Fig 19: Overall Energy Efficiency graph

Table 14: Evaluation Metrics

Model Name	**Accuracy (%)**	**Precision (%)**	**Recall (%)**	**F1-Score (%)**	**Energy Efficiency (%)**
Proposed Energy-Efficient Heat Exchanger Model	99.4	97.8	98.5	98.1	95.8
Conventional Heat Exchanger Model	95.3	93.2	94.8	94.0	90.6
Enhanced Heat Exchanger Model	96.2	91.5	92.3	91.9	92.1

Table 14 represents the evaluation metrics. As compared to the traditional and the innovative systems of heat exchangers, the Proposed Energy-Efficient Heat Exchanger Model has a number of important strengths. Having a total accuracy of performance of 99.4, it is evidently the best among the Conventional Heat Exchanger Model (95.3%), and the Enhanced Heat Exchanger Model (96.2%), and therefore its reliability and effectiveness are realized. The model proposed further reduces operational inefficiencies since the sensitivity is high at 98.4 and the precision is high at 97.8 which ensures that the model is accurate in terms of identifying the optimal energy efficient operating conditions.

The other significant benefit of the proposed model is that it has an intelligent parameter extraction and selection mechanism. The optimized feature selection model removes redundant, low-impact and weakly correlated operational parameters and only the prevailing thermal-hydraulic features are retained to be used in the performance assessment. This does not only enhance the accuracy of prediction but it also dramatically decreases computational complexity and processing overhead. An example is the streamlined feature process time under different operating points is always lower than that of traditional and improved systems which proves the efficiency of the model on computations and efficiency in scalability to real-time industrial requirements.

Another strength of the model is that it has a better thermal-hydraulic model representation due to the combination of complex optimization methods with profound analytical modeling. The system precisely reflects changes in the heat transfer rates, flow behavior, pressure dynamics and energy distribution that are usually ignored in the traditional thermal models. Through a combination of more profound structural modeling and an improved parameter learning, the suggested framework is in a position of attaining stable convergence, a strong performance, and stable predictive accuracy in various running conditions. This leads to a consistent increase in the key performance indices which are recall (98.5%), and F1-score (98.1) that suggest balanced and consistent system performance.

Besides, feature activation heatmaps and performance maps are added, which increases the interpretability of the suggested model. These visual effects demonstrate main thermal areas, high efficiency areas, and critical operation behaviors of the system in the heat exchanger system so that engineers and system designers can have a greater insight on how the energy flows and the system dynamics. This interpretability of visuals enhances confidence in decision making and helps in practical application in the real world industrial scenarios. Also, the model has been evaluated in different operating environments indicating its strength, scalability and flexibility. Due to the high level of accuracy, low level of energy losses, efficiency of computations and the great interpretability, Proposed Energy-Efficient Heat Exchanger Model becomes a highly usable, reliable, and practically viable solution of the next-generation energy-efficient thermal systems.

4.3 Computational Complexity

The dependency on parameters evaluation, thermal-hydraulic performance analysis, and classification phases are the main factors that affect the computational complexity of the proposed analysis framework of energy-efficient heat exchanger. The dependency analysis entails the computation of the pairwise correlation between operating parameters whose time complexity is O(n 2), where n is the number of input parameters. The later thermal and hydraulic model will then scale linearly with the number of operating conditions making the computational overhead manageable with practical datasets.

The classification and efficiency assessment stages exhibit a computational complexity of O(n), as they rely on optimized parameter sets obtained after dependency filtering. The complexity of memory is linear because of the feature and parameter representations used are reduced. On the whole, the suggested framework can provide a good trade-off between the efficiency of calculations and the accuracy of analysis, so it can be applied in real-time and large-scale evaluation of the performance of industrial heat exchangers.

4.4 Time Complexity

The total time complexity of the suggested framework may be summarized as an aggregation of the basic processing steps. n is the number of operating parameters and mm is the number of experimental samples or operating conditions. The analysis of the parameter dependency and significance involves the computation of the pair-wise correlation, which has a time complexity of O (n 2).Each operating condition and scale are evaluated by thermal-hydraulic performance analysis (heat transfer and pressure drop) and change linearly with O(m).The stage of classification of the energy-efficient heat exchanger works with the best set of parameters, and the computational burden becomes O(n). As a result, the time complexity of the proposed model is of O(n 2+m) that is computationally efficient on real-life datasets of industrial scale. The appropriateness of the proposed approach in analysing real-time performance and the high energy efficiency of heat exchanger systems in large scale is confirmed by this restricted complexity.

4.5 Limitations of the Proposed Model

Although the proposed energy efficient heat exchanger framework has demonstrated a better performance, there are some limitations. This model is based on experimentally obtained and modelled operating parameters and its accuracy depends on the quality and completeness of the input data. The accuracy of sensors, measurement noise, and environmental interference may cause the reliability of thermal-hydraulic performance estimation, especially in cases of highly transient operating conditions.

Moreover, the suggested methodology is centered on steady-state performance analysis, and it does not completely account for the effects of degradation over time, including fouling, corrosion, and material aging. Recalibration of the computational framework itself may also be necessary, when using with substantially different geometries of the heat exchanger or different working fluids. The model is highly scaled, but new tests on large-scale industrial systems and real-time adaptive control tasks are necessary to assure greater applicability.

5. CONCLUSION

A systematic approach to the analysis and design of energy-efficient heat exchanger systems with the decrease in inter-parameter dependency, the modeling of thermal-hydraulic performance, as well as the energy-sensitive classification is proposed in this research. The model can not only better model the heat transfer and fluid flow, but also a multi-parameter model can be used to provide improved levels of capturing the trade-off between enhancing the heat transfer and the pressure drop. The suggested model also provides the innovative method of data parameters selection through a combination of the correlation-based feature dependency and entropy-based feature importance analysis to get rid of the redundant and irrelevant data and pick the most significant thermal-hydraulic parameters. This enhances efficiency, insight and accuracy as well. Further, classification based energy efficiency analysis offers decision support system in design of heat exchanger. The new model also enjoys accuracy, precision, recall and F1-score of 99.4% and 97.8% and 98.1% respectively. It is also the most efficient in terms of energy at 95.8% (90.6% conventional). High flow rates have a heat transfer increased by 0.76 and a reduction in pressure drop to 14.0 units.

Future efforts will work on the extension of the framework to consider the transient operating conditions and long-term degradation effects including fouling and material aging. The addition of real-time monitoring information and adaptive optimization methods can also make the models more robust and realistic to use. Moreover, the verification of the offered method on industrial systems of large scale and the investigation of new machine learning-based optimization strategies will contribute to the flexibility of the approach and better support of the decision-making process in the context of energy-efficient thermal system design.

Declarations

Ethical approval

This study does not involve experiments on human participants or animals. All experiments were conducted using publicly available dataset and simulation environment. Therefore, ethical approval from an institutional review board or ethics committee was not required for this research.

Consent to participate

The research does not involve human participants, personal data, or identifiable information. Hence, informed consent to participate was not applicable for this study.

Consent to publish

The research does not contain any individual person's data in any form. All authors have reviewed the manuscript and consent to its publication.

Conflict of interest

The authors have no conflict of interests to declare that are relevant to the content of this article.

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