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REVIEW OF PASSIVE METHODS OF HEAT TRANSFER ENHANCEMENT IN HELICAL TUBE HEAT EXCHANGER

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ABSTRACT. In contemporary times, Helical tube heat exchangers (HTHXs) have gained significant prominence in energy-related sectors, frequently finding application in industrial and technical settings. Their impact on overall system efficiency and size is substantial. A comprehensive review addressing passive methods of heat transfer enhancement in HTHXs is notably absent. This paper justifies its significance by providing a recent and systematic review of available passive methods. The passive approach offers advantages such as the absence of external power requirements and lower operational costs compared to active methods. Studies collectively indicate a noteworthy progression in heat transfer enhancement in HTHXs. The paper meticulously evaluates passive methods like fins, inserts, geometry modifications, and baffles, which collectively represent 18.7%, 22.3%, 42.2%, and 16.8% of research efforts, respectively. Both experimental and numerical studies focus on improving heat transfer in HTHXs. However, further exploration is necessary to understand the negative effects of pressure drop in tube-side flow. Future research should also prioritize the development of geometric designs for HTHX surfaces, potentially incorporating materials coatings to further enhance heat transfer. The authors present insightful issues and ideas that they estimate deserving of additional investigation in subsequent research endeavors.

KEYWORDS: Helical tube heat exchanger; Passive methods; Inserts; Baffles; Heat transfer enhancement.

NOMENCLATURE

A	Area, m^2
Re	Reynolds number
$\dot{m}$	Mass flow rate, *kg/s*
V	Volume, m^3
U	Overall heat transfer coefficient, W/m^2.K
T	Temperature, $^\circ$C
h	Enthalpy, *J/kg*
E	Exergy loss
Nu	Nusselt number
g	Gravity acceleration. m/s^2
f	Friction factor
ΔP	Pressure drop
C_p	Specific heat, *J/kg.K*
u	Velocity, *m/s*.
Greek Symbols	
η	Efficiency, %

ε	Effectiveness
ψ	Availability, *J/kg*
Subscripts	
ave	Average
in	In
out	Out
ex	Exergy
c	Cold
Abbreviation	
CFD	Computational fluid dynamics
PT	Plain tube
HTHX	Helical tube heat exchanger
HCTT	Helically coiled trilobal tube
HX	Heat exchanger
HT	Heat transfer

LMTD	Logarithmic mean temperature difference
TT	Twisted tape
THP	Thermal and hydraulic performance

NTU	Number of transfer units
SB	Segmental baffle
PEF	Performance evaluation factor

1. INTRODUCTION

A helical tube heat exchanger (HTHX) is a specialized thermal device designed for efficient heat transfer in various industrial applications. Its distinctive feature lies in the arrangement of tubes, which are helically coiled to form a continuous and compact structure. This helical configuration enhances *HT* efficiency by inducing turbulence in the fluid flow, promoting effective mixing, and maximizing the surface area available for heat exchange. The helical tube design offers versatility, making it suitable for applications in chemical processing, refrigeration, air conditioning, and renewable energy systems. These heat exchangers can be configured for either parallel flow or counterflow, accommodating different thermal requirements. The choice of materials, often copper or stainless steel, ensures good thermal conductivity and corrosion resistance. The compact and continuous flow path, along with the increased surface area, contributes to the overall efficiency of the HX. The HTHX's adaptability to space constraints makes it an ideal solution where compact design and efficient *HT* are paramount. Some designs may even integrate phase change materials for thermal storage applications, further enhancing their energy efficiency and versatility in addressing diverse industrial needs [1-9].

1.1 HEAT EXCHANGERS

A heat exchanger is a device employed to convey heat from one fluid to another, ensuring that the fluids do not directly interact. These devices are extensively utilized across industrial, commercial, and residential contexts, spanning various applications such as nuclear power, food industries, oil and gas industries, and renewable energy systems. In terms of construction, heat exchangers are broadly categorized as shell-and-tube, plate, finned-tube, and others. Shell-and-tube heat exchangers consist of tubes housed within a shell, facilitating efficient heat transfer. Plate heat exchangers use thin plates to separate fluid streams, promoting heat exchange. Finned-tube heat exchangers enhance heat transfer surfaces using fins attached to tubes. Flow arrangement classifies heat exchangers as parallel flow, counterflow, or crossflow. In parallel flow, both fluids move in the same direction, while in counterflow, they move in opposite directions, optimizing temperature differences. Crossflow involves perpendicular fluid movements, often seen in compact designs. Heat exchangers are also classified based on heat transfer mechanisms as convective or radiative. Convective heat exchangers rely on fluid movement, while radiative heat exchangers use electromagnetic waves for energy transfer. These classifications aid in selecting the appropriate heat exchanger for specific applications, ranging from HVAC systems and refrigeration units to industrial processes such as chemical production and power generation. Each type offers advantages and trade-offs, influencing the efficiency and performance of the heat exchange process.

1.1.1 Structure and geometry of HTHX

A HTHX is a type of HX that incorporates helically coiled tubes as a key component. The structure and geometry of a HTHX are designed to enhance *HT* efficiency. Here are the key aspects of the HTHX structures and geometry [10]:

- Tube Configuration:

The primary feature is the helically coiled arrangement of tubes. Tubes are wound in a spiral or helical shape, creating a continuous and compact structure. the tubes are typically made of metals like copper or stainless steel, chosen for their good thermal conductivity and corrosion resistance.

- Coil Diameter and Pitch:

The diameter of the coil refers to the size of the circular cross-section formed by the helical tubes. It influences the compactness of the HX. The pitch is the axial distance between successive turns of the helix. It determines the spacing between the coils and affects the flow pattern of the fluid.

- Flow Path:

The helical arrangement allows for either parallel or counterflow configurations. In parallel flow, both the hot and cold fluids travel in the same direction, while in counterflow, they move in opposite directions, enhancing *HT* efficiency.

- Tube Orientation:

HTHXs can be designed with either vertical or horizontal orientations, depending on the application and space constraints.

- Enclosure and Casing:

The helical coil is enclosed within a casing or shell to contain the fluids and facilitate efficient heat exchange. The casing includes ports for the inlet and outlet of the hot and cold fluids, allowing for controlled flow through the helical tubes.

- Support Structures:

Depending on the size and application, the helical tube bundle may be supported by frames or structural elements to ensure stability and proper alignment.

- Enhancements for Turbulence:

To enhance *HT*, fins or inserts may be incorporated inside the helical tubes, creating turbulence in the fluid flow, and improving overall efficiency.

- Materials and Thermal Insulation:

The casing may be equipped with thermal insulation to minimize heat losses and maintain efficiency. Materials are chosen based on the compatibility with the fluids involved and the desired thermal properties.

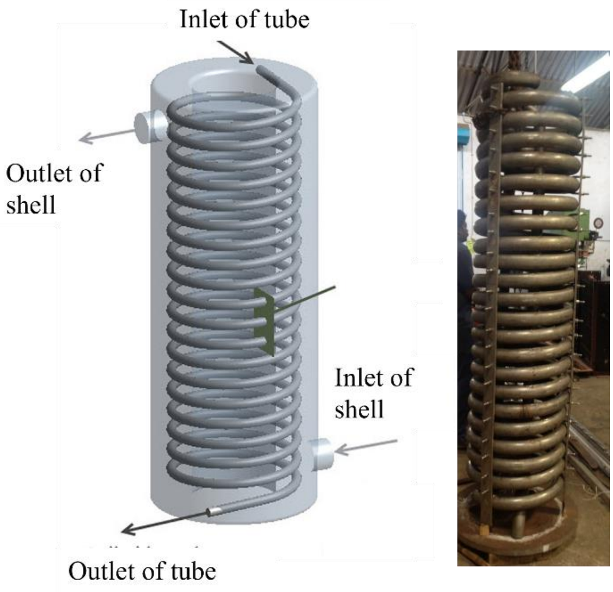


Fig. 1. The structure of the HTHX.

1.1.2 Limiting requirements for HTHX

When designing a HTHX, several critical factors must be carefully considered to ensure both efficient and safe operation. The success of the design hinges on meticulous attention to limiting requirements, encompassing considerations such as pressures, temperatures, flow rates, fouling, and materials limitations. Each of these aspects plays a pivotal role in determining the overall effectiveness and reliability of the HTHX. Consequently, the design process involves addressing these specific points to meet performance objectives and ensure the system's longevity and safety. [11]:

- The HTHX must operate within specified pressure limits to ensure structural integrity and safety. The materials used should be compatible with the temperature range of the fluids involved, avoiding potential issues such as overheating or thermal degradation.
- The materials selected for the helical tubes and casing must be resistant to corrosion, especially when dealing with corrosive fluids. Materials should be chosen based on compatibility with the properties of the fluids circulating in the HX.
- Adequate fluid velocities within the helical tubes are crucial to ensure efficient HT. Maintaining a suitable *Re* helps in determining whether the flow is laminar or turbulent, impacting *HT* efficiency.
- The design parameters, such as the diameter and pitch of the helix, should be optimized for the specific application to achieve desired HT characteristics. Considerations related to available space may limit the size and geometry of the HTHX, especially in constrained environments.
- The thermal conductivity of the materials used in the helical tubes affects the overall HT efficiency. Materials with high thermal conductivity are preferred.
- The design should allow for effective cleaning of the tubes to prevent fouling and maintain optimal performance. Considerations for ease of maintenance, such as accessibility for inspection and tube replacement, are essential.
- The HTHX should be designed to accommodate variations in fluid viscosity and density to maintain efficient HT. If phase changes (e.g., boiling or condensation) are involved, the design must account for these transitions.
- The HX should remain stable and operate effectively under varying conditions, including changes in flow rates and temperatures [12].

1.2 OVERALL VIEW OF METHODS OF HEAT TRANSFER ENHANCEMENT

In HTHXs, *HT* enhancement methods are pivotal for optimizing efficiency. These methods, designed to improve thermal performance, encompass a range of strategies. Incorporating helical fins or inserts inside tubes induces turbulence, augmenting *h*. Secondary flow effects, like swirl generators, enhance mixing and turbulence, boosting overall efficiency. Surface modifications, such as ribbed surfaces, and the use of nanofluids elevate thermal conductivity for improved heat conduction

[13]. Integrating phase change materials (PCMs) and advanced fluid mixing strategies contributes to enhanced heat storage and distribution. Flow control devices and variable flow rates optimize fluid flow patterns, ensuring efficient heat exchange. Advanced computational fluid dynamics (CFD) modeling aids in precise design and identifying *HT* bottlenecks. Material selection prioritizes those with high thermal conductivity. These methods collectively aim to maximize *HT* rates, minimize thermal losses, and improve overall energy efficiency in HTHXs, making them adaptable to diverse operating conditions and applications [14-16]: Three techniques are employed to increase heat transfer within HTHXs, encompassing the responsibilities passive, active, and a combination of both. The passive approach involves geometric or surface adjustments without external power. This includes baffles in the shell side, TTs, extended surfaces like fins, and the use of various inserts, as illustrated in Fig. 2. Examples of such inserts include wire coils, TTs, coiled tubes, and surface tension devices. On the other hand, the active approach utilizes external power, incorporating methods such as fluid suction, and surface vibration. Lastly, the compound methodology, combining both active and passive procedures, presents a third option for enhancing *HT* within HTHXs. These methods collectively demonstrate a comprehensive approach to optimizing heat exchange efficiency, considering both geometric modifications and the application of external power where necessary.

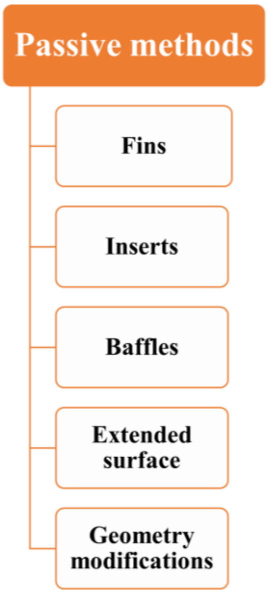


Fig. 2. Passive methods for heat transfer enhancement.

1.3 THERMAL-HYDRAULIC PARAMETERS

This section provides a comprehensive listing of the thermal performance parameters for (HTHX). Key parameters include ε, U, NTU, η_{ex}, as well as hydraulic parameters such as *ΔP* and *f*. The thermal and hydraulic performance parameter (THP) is also highlighted, offering a holistic view of the HTHX's efficiency and effectiveness in *HT*. These parameters collectively serve as crucial metrics for evaluating and optimizing the thermal and hydraulic performance of HTHXs in various applications.

1.3.1 Effectiveness

In a steady state, the effectiveness (ε) of the HTHX is determined by dividing the actual *HT* by the maximal *HT*. This calculation provides insight into the efficiency of the heat exchange process, with a higher ε indicating a more effective transfer of thermal energy within the HTHX [17] $\varepsilon = \frac{\dot{Q}}{\dot{Q}_{max}}$:

$$\varepsilon = \frac{\dot{m}_h c_{p,h}\left(T_{h,in} - T_{h,out}\right)}{\underbrace{\dot{m} \ \ c_p}_{\text{minimum}} \left(T_{h,in} - T_{c,in}\right)} = \frac{\dot{m}_c c_{p,c}\left(T_{c,out} - T_{c,in}\right)}{\underbrace{\dot{m} \ \ c_p}_{\text{minimum}} \left(T_{h,in} - T_{c,in}\right)} \quad (1)$$

1.3.2 Overall heat transfer coefficient

At first, the HTHX's average heat transfer rate ($\dot{Q}_{ave}$) may be calculated by using the following formulas:

$$\dot{Q}_{ave} = \frac{\dot{Q}_c + \dot{Q}_h}{2} \quad (2)$$

Where $\dot{Q}_c = \dot{m}_c c_{p,c}\left(T_{c,out} - T_{c,in}\right)$ and $\dot{Q}_h = \dot{m}_h c_{p,h}\left(T_{h,in} - T_{h,out}\right)$. The relationship may then be used to find the average value of (U) [18, 19]:

$$U = \frac{\dot{Q}_{Ave}}{A_{out} F \Delta T_{LMTD}} \quad (3)$$

In this context, ΔT_{LMTD} represents the logarithmic mean temperature difference between the flow rates of the hot and cold fluids. The variable F stands for the correlation factor associated with the logarithmic mean temperature difference, and this factor is influenced by the geometry of the HX as well as the temperatures at the input and output of the hot and cold fluid streams. The determination of F is crucial as it accounts for the specific characteristics of the HX, ensuring an accurate reflection of its geometric configuration and the thermal conditions of the fluid streams at various points in the system. [20], and A_{out} is the surface area where *HT* occurs cross.

1.3.3 Number of transfer units

The NTU is expressed as a fraction of the overall thermal sizing (UA) and the smallest storage capacity $\left(\dot{m}c_p\right)_{min}$[21]:

$$NTU = \frac{A_o U}{\underbrace{\dot{m} \ \ c_p}_{\text{minimum}}} \quad (4)$$

1.3.4 Thermal performance factor (TPF)

Numerous changes in HTHX aim to improve *HT*, often with a trade-off in hydraulic performance. Therefore, it is essential to elucidate the connection between thermal and hydraulic efficacy. The TPF can be calculated by [22].

$$\text{TPF} = \frac{(Nu/Nu_p)}{(f/f_p)^{1/3}} \qquad (5)$$

1.3.5 Exergy efficiency

Exergy analysis relies on the irreversibility associated with heat transmission. The computation of exergy loss for a steady-state open system is conducted as outlined below [23, 24]:

$$E = E_h + E_c \qquad (6)$$

Where,

$$E_h = T_o\left[\dot{m}_h\left(s_{h,out} - s_{h,in}\right) + \frac{\dot{Q}_h}{T_{surr}}\right] \qquad (7)$$

$$E_c = T_o\left[\dot{m}_h\left(s_{c,out} - s_{c,in}\right) - \frac{\dot{Q}_c}{T_{surr}}\right] \qquad (8)$$

Where the exergy loss is determined as [25, 26]:

$$E = T_o\left[\dot{m}_h c_{p,h}\, ln\left(\frac{T_{h,out}}{T_{h,in}}\right) + \dot{m}_c c_{p,c}\, ln\left(\frac{T_{c,out}}{T_{c,in}}\right)\right] \qquad (9)$$

The exergy efficiency can be assessed by considering the availability of the hot fluid stream on the tube side:

$$\eta_{ex} = \frac{E}{\dot{m}_h \Delta\psi_h} \qquad (10)$$

In this context, ψ represents the availability in joules per kilogram.

$$\Delta\psi = (h_{out} - h_{in}) - T_o(S_{out} - S_{in}) + \frac{u_{out}^2 - u_{in}^2}{2} + g(Z_{out} - Z_{in}) \qquad (11)$$

The exergy efficiency can be calculated as:

$$\eta_{ex} = 1 - \left\{\frac{T_o\left[\dot{m}_h c_{p,h}\, ln\left(\frac{T_{h,out}}{T_{h,in}}\right) + \dot{m}_c c_{p,c}\, ln\left(\frac{T_{c,out}}{T_{c,in}}\right)\right]}{\dot{m}_h c_{p,h}\left[\left(T_{h,out} - T_{h,in}\right) - T_o\, ln\left(\frac{T_{h,out}}{T_{h,in}}\right)\right]}\right\} \qquad (12)$$

Where T_o is the surrounding environmental temperature [27].

1.4 WORK JUSTIFICATION

The designs of HEs were reviewed in numerous studies [28-32] such as double tube HX [33-37], plate HXs [38-45], finned HXs [46-51], and shell and tube HXs [2, 52-55]. The authors aim to conduct an extensive examination of HTE methods in HTHX. The aims of the review are summarized:

- The review paper aims to apply a comprehensive and consolidated overview of the various methods used to enhance *HT* in HTHXs. It serves as a repository of existing knowledge, bringing together information dispersed across different studies.
- By reviewing multiple studies, the paper can identify trends and patterns in the methods employed for HTE. This analysis helps in understanding the most common and effective approaches in the field.
- The review allows for a critical evaluation of the effectiveness of different HTE methods. This assessment helps researchers and engineers in selecting the most suitable methods for specific applications.
- The paper can highlight recent innovations and emerging techniques in the field of HTE in HTHXs. This information is valuable for researchers seeking the latest advancements.
- Identifying gaps or limitations in existing research guides future investigations. The review paper can suggest areas where further studies are needed, contributing to the advancement of knowledge in the field.
- Practitioners and engineers can benefit from the review by gaining insights into practical applications of HTE methods. This information aids in the design and optimization of HTHXs for real-world scenarios.
- The review paper serves as an educational resource for students, researchers, and professionals interested in the field of HXs. It provides a structured and comprehensive overview of methods, facilitating learning and understanding.
- The paper synthesizes information from diverse sources, including research articles, conference papers, and other publications. This synthesis contributes to a holistic understanding of the subject.

1.5 THE REVIEW OBJECTIVES

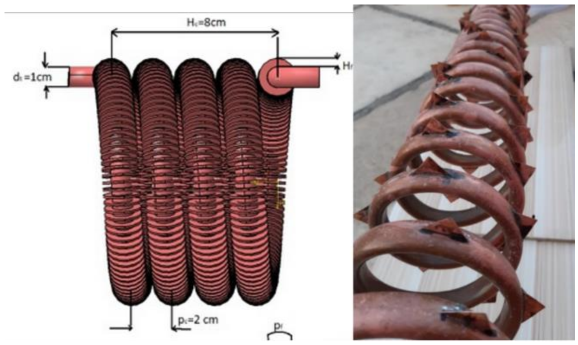
Due to the cost-effectiveness in the design and maintenance of HTHXs, many companies opt for their utilization. As a result, it is suggested that earlier studies on this type of HX be categorized to alleviate confusion when selecting the most appropriate HTE techniques. To the best of the authors' knowledge, no review papers dedicated to HTHXs have been published thus far. Addressing this gap, the primary objective of this review paper is to consolidate scattered knowledge from numerous studies and present a comprehensive synthesis. The field of HTE in HTHXs is expansive, with research outcomes scattered across various journals and conference proceedings. By consolidating this information into a single, comprehensive source, the review provides a valuable reference point, facilitating accessibility and understanding. the critical evaluation and comparison of different HTE methods are paramount. The diverse range of methodologies employed in these systems necessitates a thorough analysis to identify the most effective methods. The review undertakes this task, offering insights that can guide researchers and engineers in selecting optimal methods based on specific application requirements. the identification of trends and patterns in HTE is crucial for staying abreast of technological advancements. By elucidating emerging technologies and showcasing recent innovations, the review paper contributes to the continuous evolution of design and operation. Practical applications form a significant aspect of the review's justifications. The guidance provided for practitioners and engineers on the real-world implications and applications of HTE methods is invaluable. This practical insight aids decision-making in industrial settings, where efficient heat exchange systems are essential for energy optimization and process performance.

2. PASSIVE METHODS

Passive methods for HTE in helical tube HXs involve the use of geometric modifications or secondary devices to improve HT without the need for external power input. Here are some common passive methods for HTE in helical tube HXs. The turbo-electric effect method involves using helical fins on the inner or outer surface of the tube [56]. The helical fins induce swirl flow in the fluid, promoting turbulence and enhancing HT. The swirl flow creates a "turbo-electric" effect, which improves the U [57]. Inserting coiled wire inserts into the helical tube can induce swirl flow and turbulence, leading to improved HT. These inserts disturb the flow pattern, enhancing the mixing of fluid and increasing h [58, 59]. TT inserts can be placed inside the helical tube to disrupt the flow and create turbulence [60, 61]. The TT induces swirling motion, increasing the h. The choice of twist pitch and width can be adjusted to optimize HT performance. Adding ribs or grooves to the inner surface of the helical tube can enhance HT by promoting turbulence and improving the h [62]. These features disrupt the boundary layer and enhance fluid mixing. Placing vortex generators inside the helical tube can create controlled vortices, enhancing HT [63]. Vortex generators disturb the flow patterns, promoting turbulence and increasing convective HT [64]. Incorporating helical baffles within the tube can improve HT by creating a swirling motion in the fluid. The helical baffles function as turbulators, increasing turbulence and promoting better heat exchange between the fluid and the tube wall. The helical geometry of the tube itself induces swirl flow, which can enhance HT by promoting mixing and turbulence [64]. This natural swirl flow improves convective HT without the need for additional inserts or modifications. These passive methods aim to optimize the flow patterns inside the helical tube, increase turbulence, and disrupt the boundary layer, improving HT efficiency in HTHEs. The selection of the most suitable method depends on the specific requirements of the HX, and the fluid properties involved.

2.1 FINS IN HTHX

Adding fins to a HTHX is a common method to enhance *HT*. Fins are extended surfaces that increase the surface area available for *HT*, and they can significantly improve the U. Here's how fins contribute to HTE in HTHXs: Fins extend from the surface of the helical tube, effectively increasing the available surface area for *HT*. The larger surface area allows for more contact between the fluid inside the tube and the surrounding environment (or another fluid in a different tube), facilitating enhanced *HT*. Fins function as conduits for *HT*. They absorb heat from the primary fluid (inside the tube) and conduct it to the outer surface. This increased surface area and improved heat conduction result in more efficient *HT* between the fluid and the tube wall. Fins disrupt the boundary layer of the fluid flowing inside the tube. This disruption promotes convective *HT* by increasing fluid mixing and turbulence. As the fluid moves over the fin surface, heat is more effectively transferred to or from the fins, leading to better U. In applications where the HTHX is used for cooling purposes, fins help dissipate heat into the surrounding environment. The extended surface area provided by the fins allows for a more efficient release of heat, preventing the system from overheating. The presence of fins induces turbulence in the fluid flow, which further enhances *HT*. Turbulent flow disrupts the stagnant boundary layer and promotes more effective heat exchange between the fluid and the tube surface. Fins disrupt the thermal boundary layer on the surface of the tube, reducing the resistance to *HT*. This disruption allows for more effective heat exchange between the fluid and the tube, especially in cases where laminar flow might prevail. Fins help in achieving a more uniform temperature distribution along the length of the helical tube. This is particularly important in applications where maintaining a consistent temperature profile is crucial for optimal system performance. Fins can be designed and customized based on specific *HT* requirements. The geometry, size, and material of the fins can be tailored to optimize *HT* efficiency for a particular application. Kumar et al. [65] conducted a numerical investigation into the *HT* and *ΔP* characteristics of the micro fin in a HTHX. The study focused on Nu and *ΔP* with varying *Re*, fin number, coil diameter, and coil pitches. As the fin number and *Re* increase, both Nu and *ΔP* experience a simultaneous increase under identical operating conditions. Specifically, the micro fin helical coiled tube with a fin number of 12 exhibits significantly higher Nu and *ΔP* percentages, ranging from 39% to 51% and 22% to 36%, respectively, compared to the smooth helical coiled tube. The coil pitches of helical tubes also influence Nu, with a smooth helical coiled tube having a coil pitch of 25 mm showing approximately 0.86% and 1.71% higher Nu compared to tubes with coil pitches of 35 mm and 45 mm, respectively, at the constant *Re* of 20,000. Furthermore, as the coil diameter increases from 100 mm to 200 mm, the performance factor of a micro fin helical coiled tube with 8 fins decreases from 1.08 to 0.96. Sheikholeslami and Ganji [66] looked at the effects of perforated and regular helical fins on hydrothermal treatment in water-to-air HEs. The findings show that higher accessible area ratios provide superior thermal performance over lower ones. Naphon [67] investigated the HTHX's *ΔP* and thermal performance both with and without helical crimped fins. The HX was composed of two coil diameters in a HTHX. The operating fluids on the shell side and the tube side are, respectively, cold, and hot water. Via the helical tube, the cold water enters the HX at the outer channel and exits at the inner channel. Hot water travels along the helical tube as it enters the HX through the inner HTHX. There was a discussion of how the *HT* characteristics were affected by the intake conditions of the two working fluids passing through the test section. Etghani and Baboli [68] examined HTHX to determine the energy loss and *h*. Pitch coil, tube diameter, hot and cold flow rates. four design characteristics that were more important for HX performance were considered. The findings showed that the most important design parameters for heat transmission and energy loss, respectively, were tube diameter and cold flow rate. Additionally, higher cold and hot flow rates yield the largest Nu. Moreover, increasing the pitch coil reduces the *h*, while increasing the hot flow rate results in higher exergy loss. Hameed and Hamad [69] researched the application of unique triangular fins in a HTHX. The outcomes demonstrated an excellent enhancement ratio in comparison to the helical HX without fins. 16.5% was the improvement in the Nu. These findings demonstrated that adding fins to the HTHX changed and enhanced it, supporting the industrial design with increased efficiency. Amini and Amini [70] into the impact of tube fins on HTHX designs, considering both pitch and height parameters, and also explored the influence of helical-continuous fins. Their findings unveiled that segmented-vertical fins led to an increase in *HT* (q) and efficiency attributed to the generation of vortices. Notably, an increase in fin height positively affected q, while an increase in fin pitch had an opposing effect. Enhanced heat transmission was observed with a rise in Re to a certain surface roughness. The implementation of segmented vertical fins amplified the heat transmission rate by fostering vortex formation. In comparison to plain tubes without fins, finned tubes exhibited significantly faster *HT* and consequently a higher Nu number. While increasing the height of the fins positively impacted HT, an increase in fin pitch had an adverse effect. Additionally, increasing pitch resulted in a lower *ΔP* compared to increased height. Thus, determining the optimal combination of fin pitch and height was crucial for achieving maximal *HT* with minimal ΔP. Wang et al. [71] analyzed the impact of fin shape and the shell's intake mass flow rate on the energy loss of the HTHXs with an internal core and the newly designed cylindrical shell as seen in Fig. 3. The findings showed that the energy loss rises with increases in the shell- side's intake flowrate, fin height and number, NTU, *HT*, and fans power. Moreover, it was shown that the energy loss was consistently equivalent to 23.4% of the rate of heat transmission. Upon completion of this study, two correlations were suggested to determine the ideal values for the HX's geometrical and operational properties.



(a) (b)

Fig. 3. (a) the dimensions of annular fins used in tubes [71], (b) Triangular fins [69].

Digvijay and Dange [72] investigated the flow of heat in HTHXs with a cone form. For comparison, the coils' height, pitch, and length were all maintained constant. It was found that the plain helical coil had less HX efficacy than the cone-shaped helical coil. According to the results, the cone-shaped helical coil has greater *HT* rates than the standard helical coil. Solanki and Kumar [73] conducted investigational research on the condensation *h* and *ΔP* of R-134a inside a micro-fin HTHX for cooling. Miansari et al. [74] examined the thermal effectiveness of HTHX models, including the standard model, circular fins, and V-modified fins, as depicted in Fig. 4. The study revealed that transferring hot water across the coil enhances *HT*, while the circulation of cold-water in the shell increases velocities.

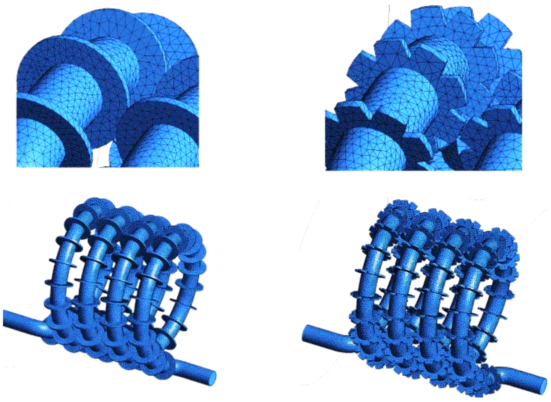


Fig. 4. Helical HTHX without a fin, and with circular fins [74].

2.2 INSERTS IN TUBES

HTE in HTHXs using inserts involves the strategic placement of structures inside the tube to optimize fluid flow and increase heat exchange efficiency. Inserts, such as TTs, and coiled wires play a crucial role in improving *HT* performance. These inserts disrupt the flow patterns within the helical tube, inducing turbulence in the fluid. Turbulence enhances convective *HT* by promoting better mixing of the fluid, which reduces the thermal boundary layer thickness [75, 76]. Additionally, inserts generate secondary flows and vortices, contributing to improved temperature distribution along the tube and enhancing U. The presence of inserts increases the effective surface area of the tube, providing more contact points for heat exchange between the fluid and the tube wall. This extended surface area, coupled with the induced turbulence, leads to a higher convective *h* and, consequently, more efficient thermal energy transfer. Inserts in HTHXs were customizable based on specific application requirements. Factors such as insert geometry, material, and arrangement can be tailored to optimize *HT* for different fluid characteristics and flow conditions. Overall, the use of inserts represents a passive and effective method for enhancing *HT* in HTHXs, benefiting applications across various industries. Akpinar [77] used helical wires within tubes and observed that, in comparison to smooth pipe, the Nu intensified by up to 2.65 times and the *f* rose by up to 2.75 times. Pitch or helical range and Re indicated that the increase in *f* was around 2.75 times that of the plain pipe. The dimensionless exergy loss in the helical configuration rose to 1.16 times higher than in the plain pipe. Empirical correlations expressing the outcomes were computed and analyzed. Kurnia et al. [78] used TT insert for enhancing secondary streams as seen in Fig. 5. The performance of heat transmission was improved by up to four times when compared to standard tubes. More heat transmission results from a lower twisting ratio. Vectors of velocity distributions at different twisting ratios were investigated in Fig. 6.

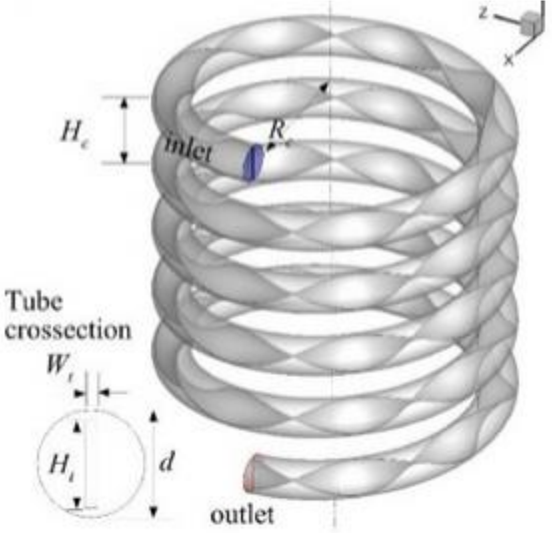


Fig. 5. Specifications of TT insert [77].

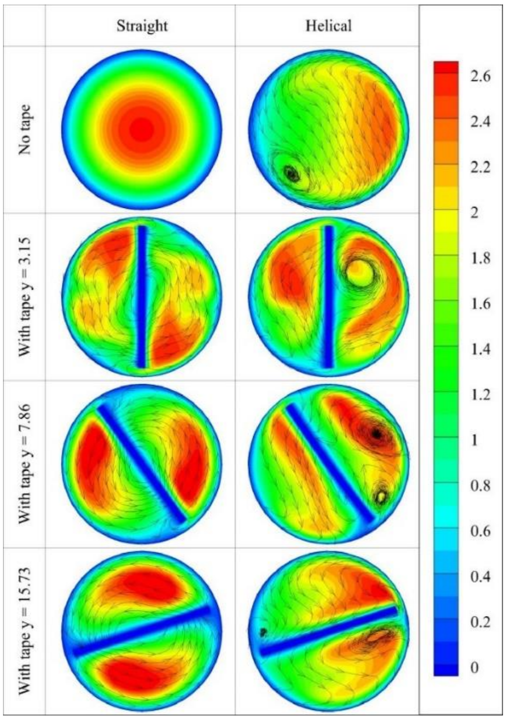


Fig. 6. Velocity distributions at different twisting ratios [77].

Verma et al. [79] worked on an experimental study examining the fluid flow properties and *HT* of a tubular HX equipped with redesigned helical coiled inserts. In comparison to plain tubes, the helically coiled inserts exhibit higher Nu and *f* values within the range of 1.42–2.62 and 3.4–27.4, respectively. In comparison to the smooth tube, the redesigned helical-coiled insertion demonstrated improvements in Nu and f values in the range of 1.49–3.14 and 11.2–19.9. The THP factors of the standard and modified helical-coiled insertions were 0.59–1.29 and 0.6–1.39, respectively. For helical coiled inserts, empirical relationships between the *f* and Nu were suggested. Eiamsa-ard and Promvonge [80] investigated the impact on HT and flow friction properties of inserting a helical screw tape, with or without a core rod, in a concentric HTHX. Yamamoto et al. [81] experimentally examined the effects of torsion on the flow with a circular cross-section throughout a range of Res. Tang et al. [82] investigated the flow properties and loss process within the large caliber, large scale Dean number helical pipe. to investigate the velocity distribution, pressure field, and secondary flow, numerical simulation was performed using different coil parameters, including coil pitch, curvature radius, and Dean number. Unsteady flow in the pipe was caused by the cross-sectional velocity gradient increasing along the pipe. Pawar and Sunnapwar [83] investigated both non-newtonian and newtonian fluids' isothermal steady-state and non-isothermal unsteady-state conditions in helical coils. There were two correlations for the *f* in non newtonian fluid, as well as several correlations for the computation of the nu for newtonian and non newtonian fluids. These established relationships were found to be in good accord when compared to the findings of previous researchers. Ma et al. [84] studied the design optimization performance of HTHX. Panahi and Zamzamian [85] employed an HTHX with helical wire as a turbulator as seen in Fig. 7. Water was the fluid of the coiled tube in the first mode, while air was the fluid in the second. Under various fluid flow rates, each mode was examined for both empty coiled tubes and those with turbulators. In every instance, the shell side fluid was hot water. The results demonstrated that this kind of turbulator may be used in coiled tubes, resulting in a notable increase in the ΔP and total h. Evaluation and discussion were held for the U, ΔP, efficacy, and NTU. The ΔP with wire turbulator was higher than the plain tube as seen in Fig. 8.

Fig. 7. Spring helical wire as a turbulator in HTHXs [85].

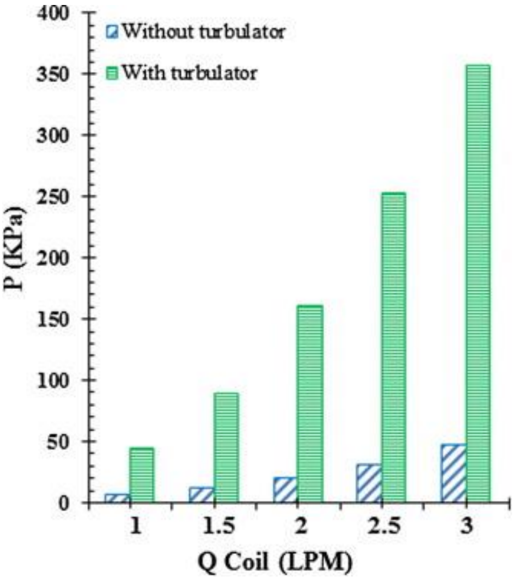


Fig. 8. ΔP with and without wire turbulator in HTHXs [85].

Khorasani et al. [58] examined the impact of geometric properties of helical wire turbulators on the thermal performance of a HTHX. Various coil pitches of the spiral turbulator and different wire diameters were analyzed. The study achieved a maximum augmentation of 73% for the Nusselt number by increasing the spring pitch and 70% by increasing the wire diameter, respectively. Sharifi et al. [86] investigated the use of the CFD approach to suggest three-dimensional modeling of the fluid flow in non-isothermal conditions. The *HT* and friction coefficients of twelve wire coil-inserted tubes were measured at various Reynolds ranges. To simulate heat exchangers and determine which kind operates best, a GA-ANN was utilized. The HX's overall enhancing efficiency may be unexpectedly reduced by selecting the incorrect wire inserts. Gholamalizadeh et al. [87] looked at the enhancement of ΔP and thermal energy transfer in HTHX using a coiled wire insert (Fig. 9). According to the results, adding coiled wire inserts with a circular cross-section will improve the Nu and *f* by 340.9% and 536.1%, respectively. Moreover, inserts with two rectangular cross-sections and a concentric circular cross-section with a diameter of 0.008 m were advised for enhancing *HT* at an intake mass flow rate of 0.05 kg/s, while all inserts were advised at 0.075 kg/s. A correlation was suggested as part of the study to estimate the Nu of these HXs. the introduction of circular wires with a larger diameter increases fluid temperature homogeneity and, thus, enhances heat transmission as seen in Fig. 10.

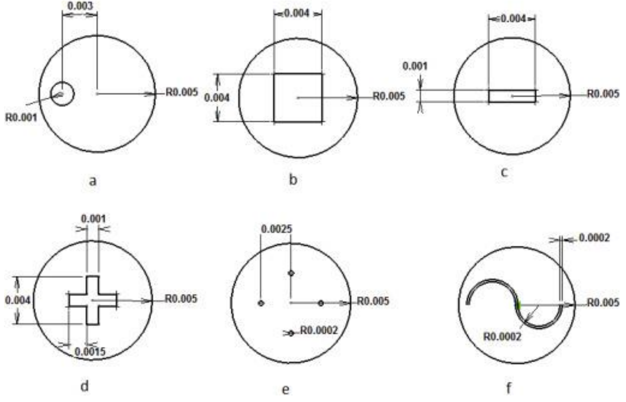


Fig. 9. *Different cross sections of the inserts [87].*

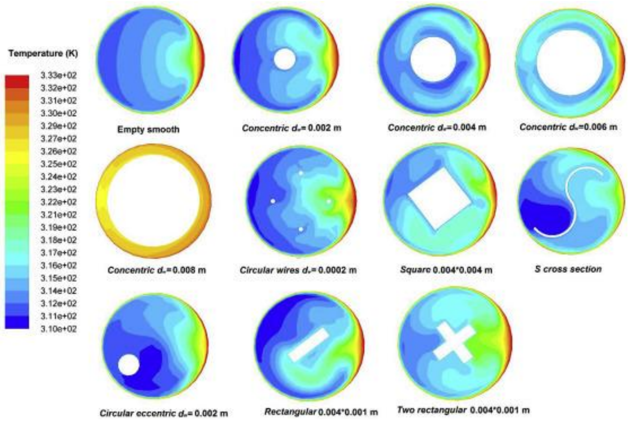
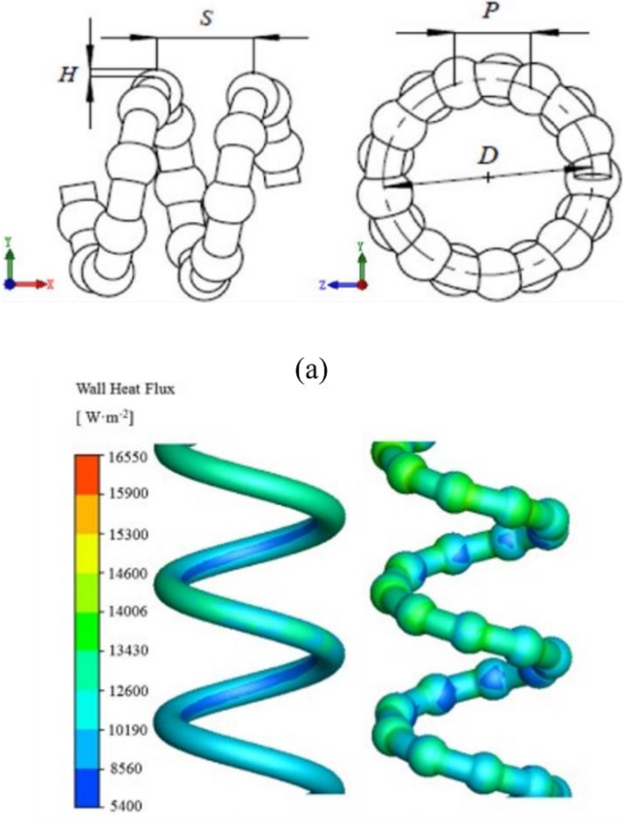


Fig. 10. Temperature distribution on the outlet surface [87].

2.3 GEOMETRY MODIFICATIONS

In a HTHX, Mozafari et al. [88] investigated the condensation and ΔP properties of R-600a using a helical coil with a diameter of 305 mm, pitch of 35 mm, height of 210 mm, and 6 coil turns. The *h* reached its highest and lowest values at 30° and 90° inclination angles, respectively, while the ΔP was most significant in the horizontal case. Compared to a horizontally straight condenser, the average *h* and ΔP of the horizontal helical condenser increased by 24–165% and 33–157%, respectively. Moreover, the performance index values of a horizontal helical condenser were 15–41% higher than those at a 90° inclination angle. For such heat exchangers, the study evaluated the influence of flow, thermodynamic, and geometrical factors on exergetic features, including exergy loss, dimensionless exergy loss, and second-law efficiency [89]. cold water flow rates result in higher exergy loss. The most significant increase in exergy loss was observed in a parallel flow configuration, while coil pitch had a minor impact. The dimensionless exergy loss exhibits a distinct curve behavior compared to exergy loss. Improving the second law efficiency of a heat exchanger can be achieved by increasing the hot-water flow rate with a lower input temperature and decreasing the cold-water flow rate with a higher inlet temperature. In another study conducted by Zhang et al. [90], a three-dimensional numerical simulation was employed to investigate heat transmission and pressure loss in a helically coiled tube with spherical corrugation. Various geometrical parameters of spherical corrugation in HTHXs were explored to optimize the *HT* rate. The results revealed that the secondary flow induced by centrifugal force significantly enhances the *h*. The eddy created by the corrugation structure disrupts the flow boundary layer, intensifies flow turbulence, and strengthens the *HT* process. Increasing the corrugation height (H) improves *HT* performance by about 1.05–1.7 times compared to a smooth helically coiled tube, but it also increases the *f* by about 1.01–1.24 times. Similarly, increasing the corrugation pitch (P) enhances heat transmission by 1.37–1.66 times and increases *f* by 1.18–1.28 times compared to a smooth helically coiled tube. Under the same conditions, a helically coiled tube with corrugation exhibits better total *HT* performance than a smooth helical tube. The performance evaluation criteria (PEC) in this context may have a value of up to 1.56.

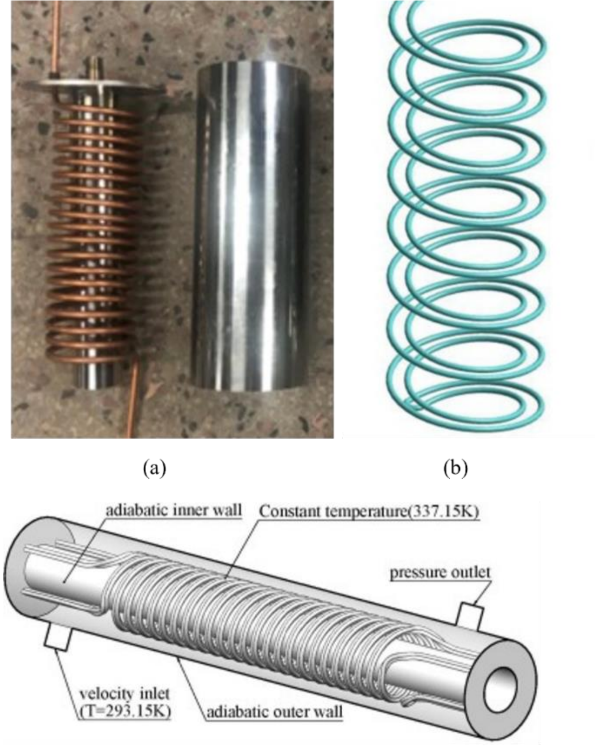


(a)

(b)

Fig. 11. (a) A HTHX with spherical corrugation (b)Heat flux for spherical corrugation tube and plain tube [90].

Sözen et al. [91] enhanced the performance of a HTHX by applying a novel modification. In this case, a hollow tube that was inserted into the shell side allows cold fluid to pass through and enter the HX. By incorporating a hollow tube into the HX's shell side, the fluid flow within the shell side was controlled, improving *HT*. A U of 1605–3152 W/m^2 K was measured. Additionally, the study's coil side *h* was found to be between 5,700 to 13,400 W/m^2 K. Additionally, there was an average 8% discrepancy between the modeling and experimental results. Various tube modifications were applied in HTHXs as seen in Fig. 12. Azzawi et al. [92] studied the effects of geometrical and operating parameters on *HT* and *f* of HTHXs numerically with experimental validation. At 1800 Re shell side, the Nu in a double coil tube was 18.3% higher than that of a single coil tube. Wang et al. [93] used both computational and experimental approaches to investigate *HT* and flow properties in the shell side of helically coiled trilobal tube heat exchangers (HCTT). In the shell side of HCTT, when Re increased, Nu increased, and *f* dropped. When compared to the helically coiled plain tube (HCPT), the augmentation in *HT* performance of HCTT was around 1.16–1.36 times, whereas f rose by 0.96–1.10 times.



(a) (b)

(c)

Fig. 12. Different geometry modifications (a) hollow tube integrated into the shell side and cold fluid [91] (b) Double tubes [92] and (c) trilobal tube [93].

Aldor et al. [94] explained a distinctive sine HTHX with a channel geometry that combines a helically coiled and a sine wave shape .Laminar flow was studied, with *Re*s ranging from 100 to 1400 depending on the hydraulic diameter and mean flow velocity. Higher temperature homogeneity was indicated by the sine helical flow's approximately 100% lower exit temperature coefficient of variation compared to the helical channel. The suggested novel HX has considerable potential for a wide range of laminar flow regime applications. Wang et al. [95] examined the THP of an upgraded structure using response surface analysis. The shell side performance verification of the revised structure showed that the optimized tube's performance evaluation criterion was 4% to 20% higher than that of the helically coiled plain tube. The improved tube's efficiency loss number decreases with increasing mass flow, suggesting a more efficient *HT* mechanism. An extensive analysis of the performance of the shell sides and tube shows that the optimized tube performs better when used in large mass flows. Zachár [96] examined the *HT* produced by natural convection across the outside of HTHX. Using the outer side *HT* rate along the helical tube axis, the effectiveness of the heat transport mechanism has been assessed at various points along the tube. It was found that the outer side *h* of any helical tube was slightly reliant on the inner flow rate in the case of improving temperature discrepancies between the coil input temperature and the tank operating fluid temperature. Genić et al. [97] investigated the eight parallel HTHXs' thermal performance. Measurements were taken at the substations of the Belgrade and Sremska Mitrovica district heating systems in Serbia. An investigation of HX thermal performance suggests that the hydraulic diameter-based correlation may be used to predict the shell side *h*. Shi and Dong [98] studied the creation of entropy concerning HT and frictional ΔP in a rotating HTHX with laminar convective flow under specific dimensionless parameters, such as HX duty and heat flux. The entropy generation by HT over a finite temperature difference reduces with a growing Dean number, which illustrates the role of centrifugal force-induced secondary flow in enhancing HT. An additional consequence of the increasing Dean number was that it boosted the formation of entropy from frictional ΔP through greater radial momentum transfer. This superposed effect led to a trend of total entropy generation that alternated between dropping and increasing, with a local low in the center. Mirgolbabaei et al. [99] tested the thermal performance of vertical HTHXs with variable shell-side mass flow rates, coil-to-tube diameter ratios, and dimensionless coil pitches .The boundary conditions for the helical coil are a significant distinction between this work and other investigations on comparable designs .This work considered a conjugate thermal boundary condition for the tube wall fluid-to-fluid *HT* mechanism, whereas most studies focus on simpler thermal circumstances such as constant wall temperature or heat flux on the coil surface. The computations are done for a three-dimensional system with steady-state conditions. To determine the best helical ground heat exchanger, Javadi et al. [100] evaluated eight new varieties of helical ground HXs to a single U tube HX in terms of the heat exchange rate, *ΔP*, thermal resistance, efficacy, and thermal performance capabilities. It was followed by ground HXs with double helix and helix that have similar thermal performance .In general, when compared to all helical ground HXs, a single U-tube HX has the worst thermal performance and the lowest *ΔP*.

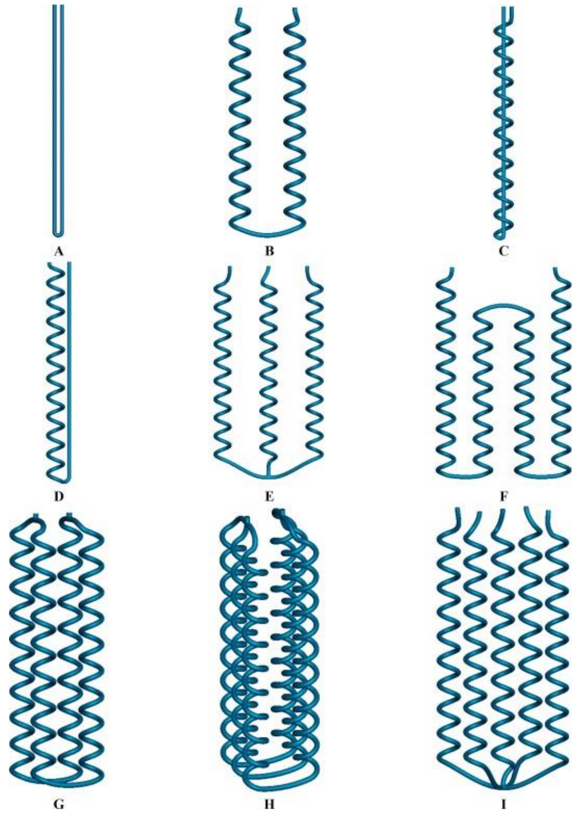


Fig. 13. Different Schematic of various HTHX single, double, and tribble tube configurations[100].

Awais et al. [101] thoroughly examined the THP of serpentine tube HXs using a CFD approach. Heat transfer and ΔP characteristics were examined about different volumetric flow rates (1 LPM to 5 LPM) and serpentine tube cross-section lengths, such as uniform, high to low to high, low to high to low, and low to high. Additionally, a thorough investigation was conducted into the impact of Al_2O_3/water-based Nano-fluid on THP, utilizing a range of volumetric flow rates (1-4 LPM) and nanoparticle concentrations (1%, 3%, and 5%). It was discovered that the L-H serpentine tube performed better at transmitting heat than the other examples. At the cost of very little ΔP, highly concentrated nanoparticles offered a greater *h*. Fan et al. [102] investigated the flow and *HT* in a helical annulus with various eccentricities. Results indicated that, under positive eccentricity, there was a noticeable increase in *HT* on the inner side of the annulus due to heightened axial velocity. Conversely, *HT* on the outer side experienced a slight decrease, attributed to secondary flow effects. Consequently, the average *HT* saw improvement under positive eccentricity, with a 10% increase in the Nu observed at e = 30% compared to the concentric case. On the contrary, negative eccentricity resulted in diminished axial velocity, leading to a weakening of *HT* on the inner side of the annulus. Although *HT* on the outer side exhibited a slight increase due to a minor rise in axial velocity and secondary flow intensity, the *U* decreased. In such instances, the Nu reached its lowest value at e = 50%, highlighting a 13.8% reduction compared to the concentric configuration. Notably, the thermal deformation in an aero engine's HTHX generated a negative eccentricity, suggesting the importance of designing it with a positive eccentricity to counteract the side effects of thermal deformation. Zachár [96] examined the natural convection-induced exterior *HT* in HTHEs. The inner side flow rate affected the outer side *HT* ratio of any helical tube in the presence of expanding temperature differences between the fluid in the tank and the input of the coil. Aboul Khail and Erişen [103] investigated numerically how to develop *HT* and performance for a brand-new plate HE. The dimensions of the plate profile and the hyperbolic tangent function's shape affected the flow characteristics were investigated. The findings demonstrated that *HT* was accelerated by improving the concavity of the hyperbolic tangent function, which in turn was accelerated by transverse disturbances of fluid motion. Lebbihiat et al. [104] studied experimentally the thermal performance of helical ground air HEs (HGAHE) in the summertime for an arid area. The results demonstrated that the entrance air temperature had a significant impact on the HGAHE's exit air temperature. The borehole's axial temperature distribution was greater at the top surface and gradually got lower as the HGAHE length increased. Heydari et al. [105] looked at a shell and a helical corrugated coiled tube HE in three dimensions while accounting for energy loss. Under low Res conditions, utilizing a helically corrugated coiled tube in the HE proved to be more successful than a helically plain coiled tube. Ariyo and Bello [106] researched the structural design of two stacked, horizontal microchannel heat sinks with high heat flow for cooling electronics. The study showed that high heat-producing devices were utilized to remove the necessary high heat flux by stacking two-microchannel heat sinks. Han et al. [107] looked at the HX's shell and helically coiled tube's Exergy analysis. The value representing the exergy loss during heat transmission was calculated. Rasslan et al. [108] used the electrochemical method to investigate the rates of mass and *HT* at the outside of a serpentine tube HX. Cunegatto et al. [109] created a theoretical analysis to enhance and optimize tube arrangement. It was conceivable to imagine the creation and assembly of systems with complicated designs that were previously impossible thanks to contemporary manufacturing technologies. Liu et al. [110] researched a tube-in-tube helical coil air and fuel HX for a chilled cooling air system to meet the demand for thermal protection in cutting-edge aero engines. The compressed air temperature dropped from 823.5 K to 519.3 K with a flow rate of 0.0057 kg/s, indicating that the HX effectively cooled the warm air. Using the Wilson plot approach, an empirical coefficient correlation for the annulus side was determined. Pathak et al. [111] developed an organic Rankine cycle prototype that was created using a new multi-coil evaporator and condenser as the waste heat source. Multi-helical coil HXs performed better at *HT* than single-helical coil HXs. Marzouk et al. [112] used novel fractal tube configurations in HTHX experimentally and numerically in Fig. 14. The results showed that the *U* ratio was around 289.1% with the new hap. The fractal tube configuration has the maximum exergy efficiency, and the exergy efficiency rises with the Re number. Marzouk et al. [113] applied contractual theory to investigate the effects of bifurcation angles on the THP in a new heat exchanger by computational and experimental methods. The temperature, velocity, and pressure distributions' contours, streamlines, and vectors allow for the examination of the fluid flow in the shell and tubes. Marzouk et al. [114] studied several unique tube configurations to examine the THP of a HTHX experimentally and numerically. The results demonstrated that the novel configurations had a larger U than the uniform tube distribution. In the two-pathway HTHE6 setup, the U has the largest enhancement ratio (125.2–185.1%).

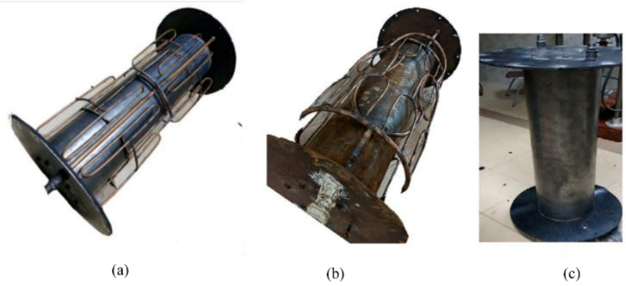


Fig. 14. (a) novel fractal tube configurations in HTHX [112], (b) and adopting contractual theory [113] (c) shell and core.

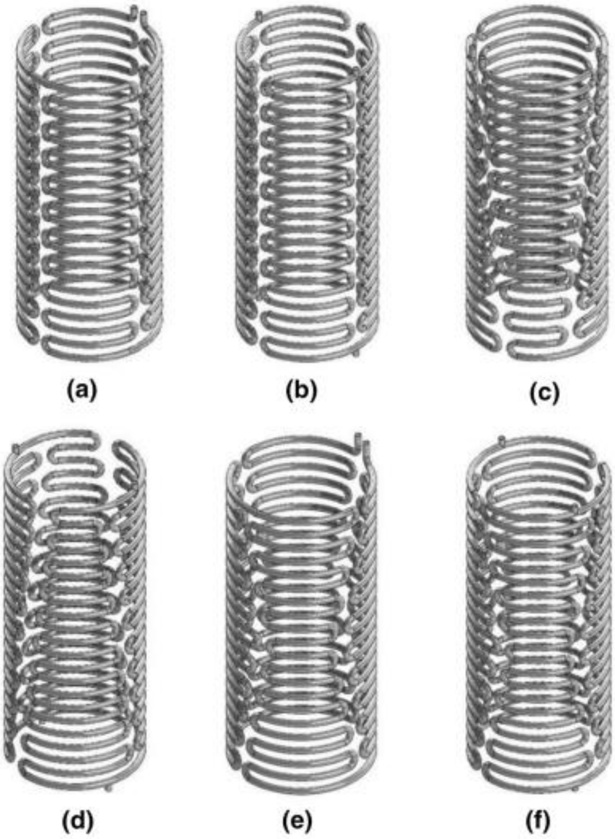
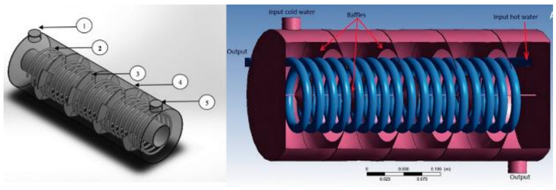


Fig. 15. The six configurations of the HTHX.

2.4 BAFFLES IN SHELL

Heat transfer augmentation in HTHXs using baffles involves the incorporation of helical structures within the tube to manipulate fluid flow and improve thermal performance. Helical baffles play a pivotal role in enhancing *HT* through several mechanisms. Baffles disrupt the flow patterns within the tube, inducing turbulence in the fluid. This turbulence enhances convective *HT* by promoting better mixing and reducing the thickness of the thermal boundary layer. The resulting increased turbulence leads to improved *HT* rates. baffles induce secondary flows or vortices within the tube. These secondary flows contribute to better fluid mixing and create a helical motion, ensuring that the entire fluid mass participates actively in the *HT* process. This promotes a more uniform temperature distribution along the tube. Baffles break up the laminar sublayer and promote *HT* augmentation by generating swirl flows. The increased convective *h* and disrupted boundary layer contribute to more efficient thermal energy transfer. Baffles help prevent short-circuiting of fluid within the tube, ensuring that the fluid travels the entire length of the helical path. This extended travel path enhances the residence time of the fluid within the HX, facilitating more effective heat exchange. Peng et al. [115] employed continuous helical baffles In two HTHXs. The two HTHXs under development had different shell designs, but the tube bundles were the same. A notable increase in h per unit ΔP was caused by the rotating and helical flow pattern on the shell side of the HE caused by the form of the continuous helical baffles. With the correct design, continuous helical baffles can reduce flow-induced vibration and minimize fouling on the shell side. Nondimensional correlations for hand ΔP were generated using experimental data for the proposed continuous helical baffle HEs with different shell shapes. Gholamalizadeh et al. [116] extended the coolant's resident duration in the HTHX's shell. This invention was used to increase the HTHX's heat transfer efficiency using flower baffle plates as seen in Fig. 16. The HX has a floral baffle plate in addition to a hollow shell and helical coil similar to those seen in a regular shell. By arranging the baffle plates in this way, the HX may achieve a fully developed flow while also reducing the ΔP and fouling. Through the HTHX flows the heated fluid. Within a 15% error percentage, the CFD findings and experiment results accord well. Additionally computed and displayed are the efficacy and energy efficiency of HX, as well as the tube and shell side output temperatures. To better transport heat through an HTHX's body, Koyun and Jumaah [117] mathematically examined the device's performance. The heat exchanger model consists of a shell, helical tubes, and baffles with cone-shaped baffles. Baffles are assumed to have an angle of 0° to 90° and a length of 10 cm to 35 cm, respectively. The findings demonstrated that the fluid travels inside the domain with continuous baffles and changes greatly because of the shell's baffle design. This led to a notable rise in the heat exchanger's *h*. The baffle's length of 30 cm and angle of 80° produced the highest amount of heat transmission.



(a) (b)

Fig. 16. (a) Flower baffle plates [87], (b) cone-shaped baffles [117].

Andrzejczyk et al. [118] investigated how different baffle layouts and locations affected the performance of the HX as seen in Fig. 17. It was shown how heat flux and water mass flow affected the HTHX. For the combinations under investigation, an experimental correlation was created. An investigation was conducted to identify the impact of secondary fluid motion on *HT*. It was shown how the effectiveness of the suggested shell coil design with baffles compared to common HX designs.

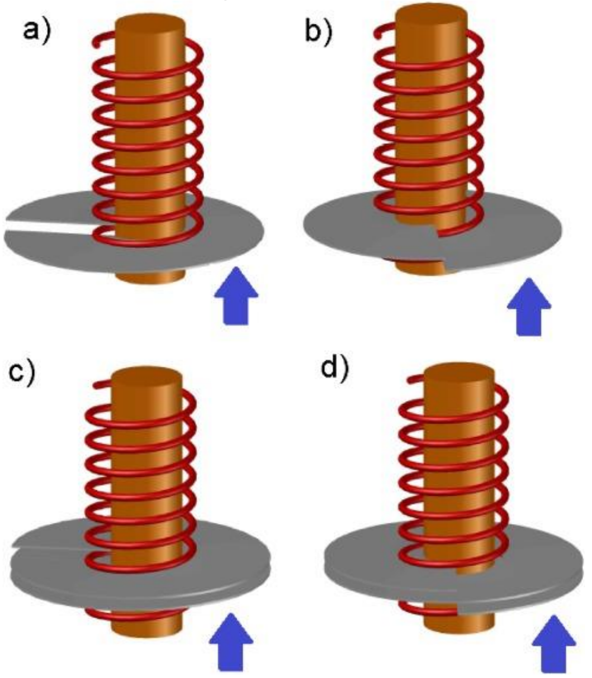


Fig. 17. Different Schematic view of baffles on shell side: (a) one baffle-gap on the left side, (b) one baffle-gap turned by 45°, (c) two baffles - gap on the left side, (d) two baffles-gap turned by 45°.

Andrzejczyk and Muszynski [119] introduced baffles as a passive *HT* augmentation technique to raise the HTHX's energy efficiency (Fig. 18). The efficiency of heat exchange in the HX shell-type coil may be effectively increased using baffle inserts, as this paper has successfully demonstrated. This study demonstrates that natural convection has a major impact on small values of Res and considerable heat flow because of mixed convection. Results are also greatly influenced by the baffle and intake arrangement. A good match between the experimental data and the presented basic experimental correlation was obtained. It was important to mention that the correlation holds for every HX setup. The relation between the Nu and Re for different baffles was presented Fig. 19.

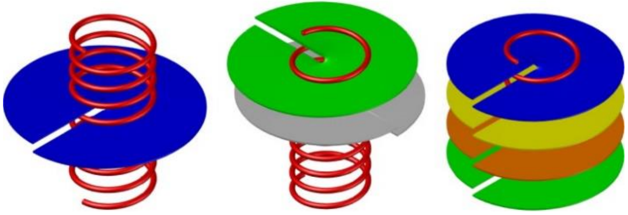


Fig. 18. Different baffle locations [119].

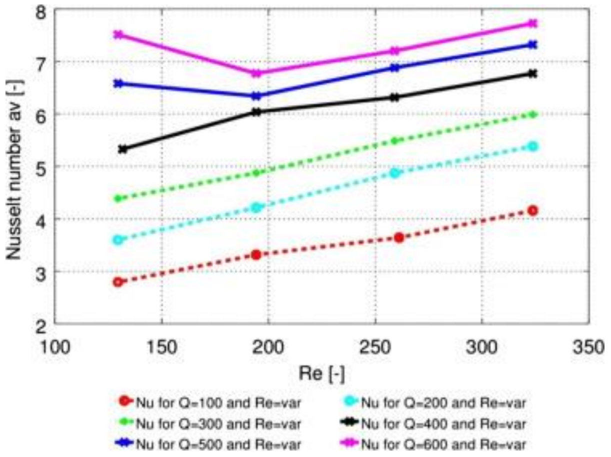


***Fig. 19.** The relation between the Nu and Re for different baffles.*

Using CFD modeling provided by the HEATX tool, Andrews and Master [120] assessed the performance of a helically baffled HE. The simulation considers the exit-entry nozzles, complex baffles with helical geometry, and leaks. Regarding the radial axis, there were three examples, each with a helix angle of 10°, 25°, or 40°. The external part of the simulated streams displays a plug flow feature, which was highly desired. The internal and external portions of the streams are separate. Recirculation zones are created in the inner region by back mixing at the tiny helix angle, which both achieves the required temperature uniformity and signals any vibration problems. The helically baffled HE has a fluid turn ratio of 0.64, 0.78, and 0.77 for the helix angles of the 10th, 25th, and 40th, respectively. Gowthaman and Sathish [121] investigated two different baffles in an HTHX quantitatively. HEs with low ΔP and high hand satisfy specific requirements. The ratio of heat to the greater cross-flow area causes a smaller mass flux over the shell than in an SB, which increases the ΔP.

Because there was less shell side fouling and less bypass influence, the helical baffle was noticeably larger than the SB. Gao et al. [122] looked at the increase of *HT* and *f* of various HTHXs with discontinuous helical baffles. According to the findings, HEs with smaller helix angles have higher shell side h and ΔP than HEs with larger helix angles. In second-law thermodynamic comparisons, the irreversibility of a HE was computed using entry dissipation and entropy production theories. The helical baffled HEs were more effective in certain shell-side Re. Bichkar et al. [123] investigated ΔP and thermal performance in HTHXs. The types of baffles utilized in dissimilar orientations and the direction of fluid flow both had an impact on thermal performance and ΔP. If double baffles are used instead of one, the vibrational damage was reduced. When helical baffles were utilized, dead zones were removed, resulting in a decrease in ΔP. A reduction in dead zones enhanced heat transmission. Because of the decreased ΔP, less pumping power was needed, which increased overall efficiency. The results showed that helical baffles perform better than the other two varieties of baffles. He and Li [124] examined the THP of HTHXs with various baffle configurations using simulation techniques. This study proposed a double-tube-pass (DTP-STHE) to improve the recovered heat quality from the perspective of exergy analysis. To assess the financial success of these three types of HEs, the *HT* per efficient pumping energy was provided. The results of the simulation showed that the flowery baffle had the highest *HT* per efficient pumping energy, while the SB had the lowest *HT* per efficient pumping energy. models were 30.3 and 14.8% for the DPCHSB, in that order. Bahiraei et al. [125] studied the *HT* performance of a water-Al_2O_3 nanofluid in the shell of a HTHX with the helical baffle. Heat transfer and ΔP increased as the volumetric flow and Re increased. The *f* rose when the Re was lowered, but the *f* did not change much when the volume fraction was raised at the same Re. It was demonstrated that, with a lower Re number, the particle volume % had a greater bearing on the heat transmission of the nanofluid. Models of the Nu and f in the HE were constructed using a neural network in terms of Re. To increase a HX's capacity to transport heat through its body, Koyun and Jumaah [117] quantitatively studied the performance of a shell and HTHX. Baffles are assumed to have an angle of 0° to 90° and a length of 10 cm to 35 cm, respectively. The primary conclusions of the thermal analyses demonstrate that the fluid travels inside the domain with continuous baffles and changes greatly because of the shell's baffle design. This has led to a large rise in the HX's heat transfer coefficient. The baffle's length of 30 cm and angle of 80° produced the highest amount of heat transmission.

4. Challenges and Future scope

Numerous studies that come within the several categories of HTE in HTHX have been conducted. The passive method uses geometrical or surface alterations that don't require external power, such as fines [57-67], inserts in tube sides [68-80] geometrical modifications [81-107] and baffles in shell sides [108-118]. Fig. 20 clarifies the ratios of the figures of papers completed to study each method for HTE. The fins, inserts, geometry modifications, and baffles have percentages of research 18.7%. 22.3%, 42.2%. 16.8%, respectively.

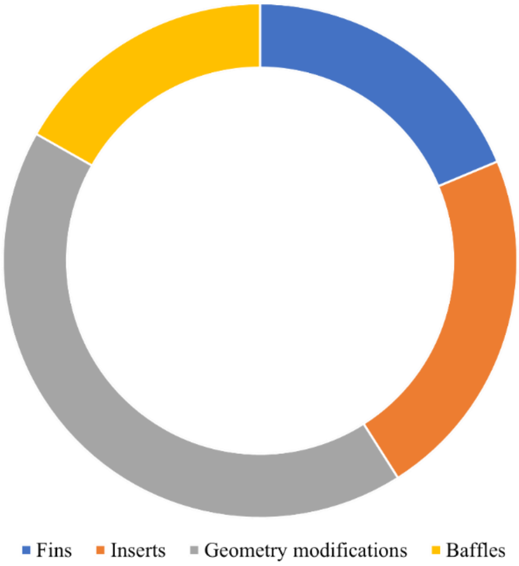


Fig. 20. The percentages of studies of various passive HTE methods.

Geometrical modifications in tube surfaces in HTHX are vital in the future and application material-coating to improve *HT*. Future research could focus on advanced materials, cost-effective fabrication, and integration with emerging technologies. Environmental considerations and a multidisciplinary approach are crucial, emphasizing sustainability and a comprehensive understanding of HTE. Addressing real-world challenges, such as fouling and corrosion, is imperative for the long-term reliability of enhanced HTHXs, paving the way for a more efficient and sustainable future in industrial *HT* applications.

3. CONCLUSIONS

Presently, HTHXs are a prominent focus within the energy sector, finding widespread application in industrial and technical contexts. These heat exchangers significantly influence the overall efficiency and size of systems. However, a notable gap exists in the literature, as there is a dearth of comprehensive reviews encompassing passive methods for enhancing *HT* in HTHXs. This paper seeks to address this gap by providing an up-to-date and systematic review of available passive methods for HTE in HTHXs. The evaluation of passive methods aids in the selection of the most effective approach tailored to specific situations. This comparative analysis is crucial for a comprehensive understanding of the advantages and limitations inherent in passive methods. The authors not only present an assessment of existing passive methods but also identify areas requiring further investigation in the future. The main points can be concluded:

- The passive methods examined, including fins, inserts, geometry modifications, and baffles, constitute varying proportions of research interest, with percentages of 18.7%, 22.3%, 42.2%, and 16.8%, respectively.
- In all passive approaches, the rate of heat transfer rises with an increase in the mass flow rate and Reynolds number.
- Heat transfer enhancement in tube flow via inserts like TT, wire coils, ribs, and dimples arise from flow blockage, partitioning, and secondary flow. These mechanisms enhance viscous effects and improve thermal contact resulting in improved heat transfer.
- The HTE to the fluid moving in the HTHX can be achieved by the beneficial method of baffles on the shell side. Under the same operating circumstances, the baffles have a higher rate of HT than those without.
- Compared to twisted tape, helical screw tape can aid to increase the rate of heat transfer exchange because its shorter pitch length causes a stronger swirling flow and a longer residence period in HTHX.
- Existing studies focus on experimental and numerical investigations related to heat transfer improvements in HTHXs. However, there is a recognized need for additional research to address the negative impact of flow-induced ΔP on tube sides.
- Future advancements in HTHX design are anticipated to incorporate geometric surface modifications, potentially enhanced using material coatings aimed at improving heat transfer efficiency.

DECLARATION OF COMPETING INTEREST

The authors affirm that they have no known financial or interpersonal conflicts that would have seemed to have an impact on the research presented in this study.

DATA AVAILABILITY

Data will be made available on request.

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