REPUBLIC OF TÜRKİYE

ALTINBAŞ UNIVERSITY

Institute of Graduate Studies

Mechanical Engineering

INVESTIGATION OF HEAT TRANSFER ENHANCEMENT BY COMPILING A HELICAL PIPE EXCHANGER TO THE OUTER SHELL OF SHELL AND TUBE HEAT EXCHANGER

Mohammed Salih Jabbar JABBAR

Master's Thesis

Supervisor

Asst. Prof. Dr. İbrahim KOÇ

İstanbul, 2024

INVESTIGATION OF HEAT TRANSFER ENHANCEMENT BY COMPILING A HELICAL PIPE EXCHANGER TO THE OUTER SHELL OF SHELL AND TUBE HEAT EXCHANGER

Mohammed Salih Jabbar JABBAR

Mechanical Engineering

Master's Thesis

ALTINBAŞ UNIVERSITY

2024

The thesis titled INVESTIGATION OF HEAT TRANSFER ENHANCEMENT BY COMPILING A HELICAL PIPE EXCHANGER TO THE OUTER SHELL OF SHELL AND TUBE HEAT EXCHANGER prepared and presented by MOHAMMED SALIH JABBAR and submitted on 00/00/2024 has been **accepted unanimously** for the degree of Master of Science in Mechanical Engineering.

____

Asst. Prof. Dr. İbrahim KOÇ

Supervisor

Thesis Defense Jury Members:

Asst. Prof. Dr.	Department of Mechanical Engineering, University	____________________
Asst. Prof. Dr.	Department of Mechanical Engineering, University	____________________
Asst. Prof. Dr.	Department of Mechanical Engineering, University	____________________

I hereby declare that this thesis meets all format and submission requirements of a Master’s thesis.

Submission date of the thesis to Institute of Graduate Studies: ___/___/___

I hereby declare that all information and data presented in this graduation project have been obtained in full accordance with academic rules and ethical conduct. I also declare that all unoriginal materials and conclusions have been cited in the text, and all references mentioned in the Reference List have been cited in the text, and vice versa, as required by the abovementioned rules and conduct.

Mohammed Salih Jabbar JABBAR

Signature

PREFACE

I wish to convey my sincere appreciation to Asst. Prof. Dr. İbrahim KOÇ, a faculty member in the Department of Mechanical Engineering at Altinbas University, who acted as my supervisor during the entirety of my research endeavor. His helpful mentorship, precise counsel, directives, and knowledge were crucial in guiding me towards the correct path. I wish to convey my appreciation to Assoc. Prof. Dr. Süleyman BAŞTÜRK, the Head of the Mechanical Engineering Department of Altınbaş University, for efficiently resolving the technical complications pertaining to the laboratories and other concerns. Additionally, I would like to extend my appreciation to every person I know who has offered assistance and encouragement, as well as shared vital advice and expertise.

ABSTRACT

INVESTIGATION OF HEAT TRANSFER ENHANCEMENT BY COMPILING A HELICAL PIPE EXCHANGER TO THE OUTER SHELL OF SHELL AND TUBE HEAT EXCHANGER

JABBAR, Mohammed Salih Jabbar

M.Sc., Mechanical Engineering, Altınbaş University

Supervisor: Asst. Prof. Dr. İbrahim KOÇ

Date: 07/2024

Pages: 103

This study investigates the enhancement of heat transfer in shell-and-tube heat exchangers, which are crucial in key industries such as energy, petroleum, and electrical power production. The focus is to assess the impact of adding a helical coil to these exchangers, a practice often utilized in refractory technology, to improve their efficiency. The approach includes a detailed numerical analysis of two HE models. The first is a conventional STHE, while the second is an innovative variant with a helical coil added to its outer shell. This modification aims to improve the HT process between oil and water.

The study's findings reveal that the second model, with the helical coil, significantly enhances the HEs efficiency. This conclusion is drawn from comprehensive numerical simulations, highlighting the effectiveness of this design change.

The originality of this thesis lies in its approach to combining traditional design elements with innovative modifications to improve HE efficiency. This strategy offers a practical solution for increasing thermal efficiency in industrial applications, marking a significant advancement in energy-efficient design practices.

Keywords: Heat Exchanger, Shell and Tube Heat Exchanger, Helical Coil, Numerical Simulations, Heat Exchanger Efficiency.

ÖZET

KABUK VE BORU EŞANJÖRÜNÜN DIŞ KABUKUNA HELİS BORU EŞANJÖR YERLEŞTİRİLMESİYLE ISI TRANSFERİNİN ARTIRILMASININ İNCELENMESİ

JABBAR, Muhammed Salih Jabbar

Yüksek Lisans, Makine Mühendisliği, Altınbaş Üniversitesi

Danışman: Dr. Öğr. Üyesi, İbrahim KOÇ

Tarih: 07/2024

Sayfa: 103

Bu çalışma, enerji, petrol ve elektrik enerjisi üretimi gibi kilit endüstrilerde hayati öneme sahip olan kabuk-borulu ısı değiştiricilerinde ısı transferinin arttırılmasını araştırmaktadır. Odak noktası, refrakter teknolojisinde sıklıkla kullanılan bir uygulama olan bu eşanjörlere, verimliliklerini artırmak için sarmal bir bobin eklemenin etkisini değerlendirmektir. Yaklaşım iki HE modelinin ayrıntılı sayısal analizini içermektedir. Birincisi geleneksel bir STHE, ikincisi ise dış kabuğuna sarmal bobin eklenmiş yenilikçi bir çeşittir. Bu değişiklik, yağ ve su arasındaki HT sürecini iyileştirmeyi amaçlamaktadır.

Çalışmanın bulguları, sarmal bobinli ikinci modelin HE'lerin verimliliğini önemli ölçüde artırdığını ortaya koyuyor. Bu sonuç, bu tasarım değişikliğinin etkinliğini vurgulayan kapsamlı sayısal simülasyonlardan çıkarılmıştır.

Bu tezin özgünlüğü, HE verimliliğini artırmak için geleneksel tasarım öğelerini yenilikçi değişikliklerle birleştirme yaklaşımında yatmaktadır. Bu strateji, endüstriyel uygulamalarda termal verimliliğin artırılmasına yönelik pratik bir çözüm sunarak, enerji verimli tasarım uygulamalarında önemli bir ilerlemeye işaret ediyor.

Anahtar Kelimeler: Isı Değiştirici, Kabuk ve Borulu Isı Değiştirici, Helisel Bobin, Sayısal Simülasyonlar, Isı Değiştirici Verimliliği.

TABLE OF CONTENTS

Pages

LIST OF TABLES

Pages

LIST OF FIGURES

Pages

ABBREVIATIONS

CFD	:	Computational Fluid Dynamic
HT	:	Heat Transfer
HE	:	Heat Exchanger
HDP	:	High Density Polyethylene
LMTD	:	Log Mean Temperature Difference
NTU	:	Number of Transfer Units
Nu	:	Nusselt Number
RC	:	Resistance Factor
Re	:	Reynolds Number
STHE	:	Shell and Tube Heat Exchanger
SD	:	Streamline Distribution
TEMA	:	Pressure Drops Across the Channel
TD	:	Temperature Distribution
L/D ratio	:	The Screw's Flighted Length to Outer Diameter Ratio
PVT	:	Photovoltaic Thermal System
Pr	:	Prandtl Number
Si cells	:	Crystalline Silicon Cell
mV	:	Millivolt
mA	:	Milliampere
K	:	Degrees Kelvin
I-V	:	Current-volt Curve
P-V	:	Power-volt Curve

LIST OF SYMBOLS

C : Heat Capacity

CP : Specific Heat at Constant Pressure

$\dot{m}$: Mass Flow Rate

P : Pressure

T : Temperature

$\dot{Q}$: Heat Transfer Rate

$\dot{W}$: Work Rate

η : Efficiency

ρ : Density

K : Thermal Conductivity

W : Angular Velocity

μ : Viscosity

h : Channel Depth in Millimetres

γ : Shear Rate in the Round Channel

R : Radius of the Hole

Q : Volumetric Flow Rate

K : Resistance Factor

L : Channel Length

ΔP : Pressure Drops Across the Channel

σ : Shear STRESS

F : Force Applied

A : Unit Area

1. INTRODUCTION

1.1 BACKGROUND

Exponential rise in energy usage may be attributed to the quick increase in the global population and rapid technological advancement. The use of fossil fuels, which account for an essential portion of the world's energy supply, is fraught with resource and environmental challenges [1],[2]. Researchers typically mitigate these kinds of environmental impacts by making existing industrial processes more efficient, designing effective and sustainable devices [3], Using eco-friendly materials [4], and implementing renewable energy sources that are environmentally favorable [5]. Even though depending on renewable resources is the most promising alternative to fossil fuels, it is still expensive, which limits its spread. Furthermore, it is necessary to have an appropriate energy storage medium to address the sporadic nature of sources of renewable energy [6]. Because of this, substantial effort is made to improve the overall energy efficiency by recovering waste heat, which is vital in enhancing the overall energy efficiency [5].

Heat exchangers facilitate the transfer of thermal energy from one fluid to another, and they are commonly used in energy and industry. Recent research efforts concentrate on using curved tubes to recover waste heat [7]. Other research projects investigated thermal devices that worked better, like refrigerators and HE [8]. This led to the creation of new ways to improve heat transfer, mostly by lowering the thermal resistance of heat exchangers [9]. Passive and active heat transfer enhancement approaches are the two primary categories that may be broken further into subcategories. The active method is intended to use an additional supply of energy. In contrast, the passive method uses modifications made to the configuration of the system and other components of the system to improve flow mixing. In addition, the active method inhibits the establishment of the thermal boundary layer, resulting in an increased HT rate [10]. The focus of passive approaches is on the generation of swirl flows, which contribute to improved flow mixing. This often results in a significant enhancement of the HT coefficient. As is apparent in Figure 1.1, a typical HE is presented, serving as a visual reference for discussions on passive methods of enhancing heat transfer.

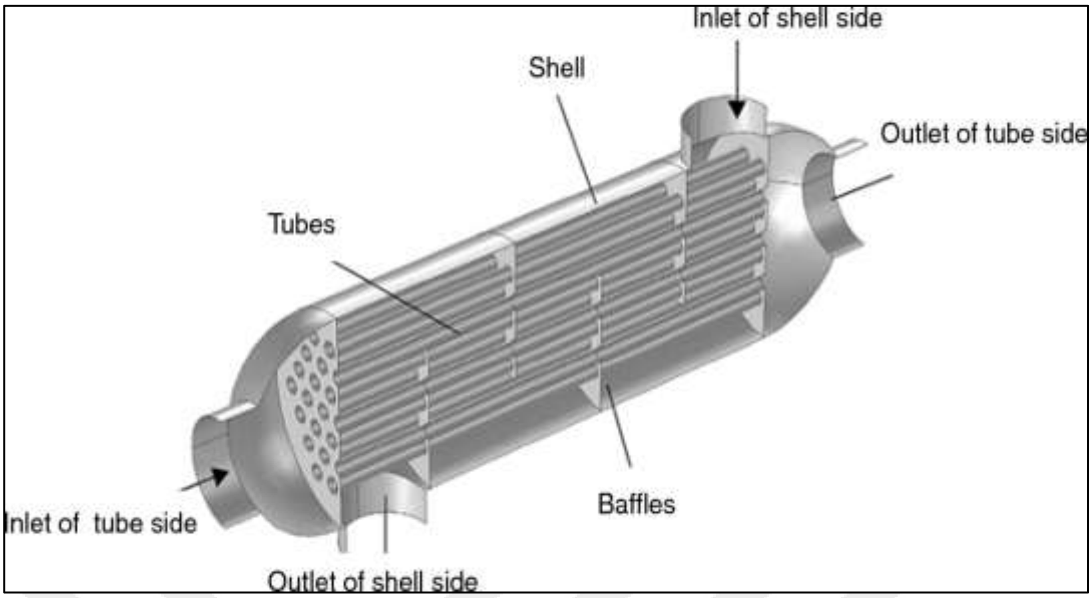


Figure 1.1: An Instance of the Structure of a Heat Exchanger [11].

Common thermal exchangers include cooling towers, evaporators, condensers, air preheaters, and STHE. If the two fluids inside the exchanger do not change states, we call it a tangible thermal exchanger [12]. The exchange mechanisms could encompass internal power sources, comprising materials of nuclear nature and electrically powered warmers. In fluidized-bed exchangers, fired heaters, boilers, and similar machinery, combustion and chemical reactions may occur inside the exchanger. When the fluids are unable to mix, the interface between them acts as a surface for transferring heat, it is common practice to eliminate the separation wall, as observed in direct-contact heat exchangers [13].

Industrial products currently available on the market incorporate HEs as critical components. Industrial operations, transportation, petroleum, alternative fuels, cryogenics, and refrigeration are just a few of the many fields that make use of this common equipment. Different methods exist for classifying these exchangers, showcasing their versatility and boundless utility [14].

1.2 HEAT EXCHANGERS AND THEIR IMPORTANCE IN VARIOUS INDUSTRIES

Heat exchangers are essential components in many industrial processes, serving the vital function of efficiently transferring heat between fluids to achieve precise temperature control. These devices find widespread applications in industries such as energy, petroleum, chemical, and manufacturing. The fundamental purpose of HEs is to optimize energy usage by capturing and redistributing heat, thereby enhancing the overall efficiency of industrial processes.

HEs serve specific purposes and are designed accordingly. One prevalent type is the shell-and-tube HT system, which involves an array of tubes located within the shell. Fluids flow through both the tubes and the surrounding shell, facilitating HT between them. Due to their versatility and reliability, STHEs are indispensable in industries requiring heating, cooling, or heat exchange processes.

1.3 MOTIVATION

The motivation for this research is driven by the critical role of STHE in key industrial sectors and the ongoing need for advancements in heat transfer efficiency. These exchangers are pivotal in many processes, yet there is a continuous need for improvement to meet rising environmental and energy efficiency standards.

Current challenges in STHE, like restricted heat transfer rates and issues related to pressure drops, underscore the urgency of this research. Addressing these issues not only enhances the operational efficiency of these exchangers but also contributes significantly to reducing energy consumption and environmental impact.

The innovative approach of incorporating a helical coil into the outer shell of the HE presents a potential breakthrough in overcoming these limitations. The research is centered on conducting a detailed numerical analysis to ascertain the efficacy of this modification. By potentially improving heat transfer efficiency significantly, this study aims to set a new benchmark in heat exchanger technology, offering substantial benefits in terms of performance, sustainability, and cost-effectiveness.

1.4 HEAT EXCHANGERS CATEGORIZATION

Different applications of HEs different kinds of equipment and arrangements for heat transfer. A multitude of inventive heat exchanger designs were created to meet the specific HT needs while adhering to the given limitations [5].

1.4.1 Categorization Depending on Function and Construction

According to their design and machinery, the following represent some of the most common kinds of heat exchangers [15]:

1.4.1.1 Understanding heat exchangers with double- pipe

The fundamental configuration of a heat exchanger is achieved by arranging two pipes concentrically with different diameters. In a HE including two pipes, one fluid flows through the smaller pipe, while the other fluid flows through the annular gap between the two pipes.. Figure 1.2 demonstrates that double-pipe heat exchangers provide the most efficient heat transmission per unit length, with the smallest surface area allocated to this purpose. They have a very slight decrease in pressure. This kind of heat exchanger is used in many sectors for several reasons, including processing materials, food production, and air conditioning [16].

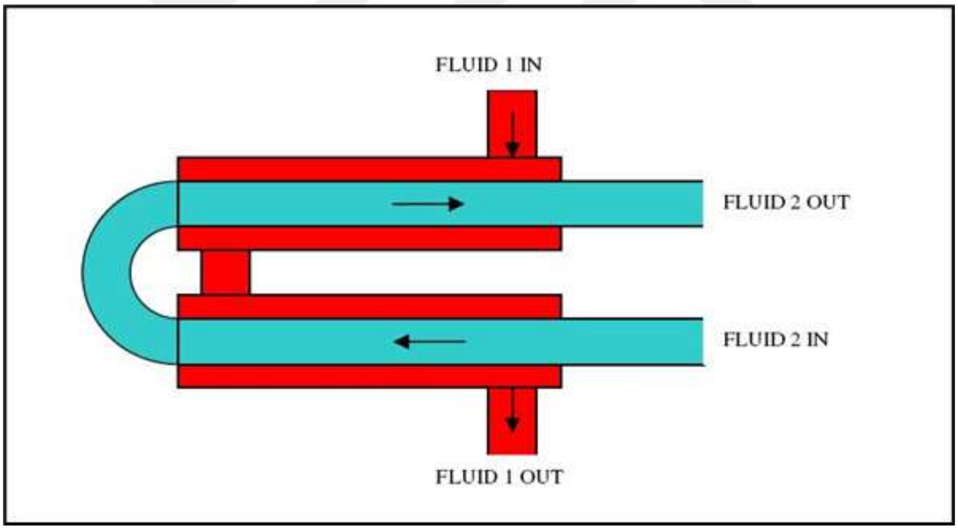


Figure 1.2: Double Pipe HE [17].

1.4.1.2 Shell and tube heat exchanger

Due to their many advantages over other types of HEs, shells and tubes are now widely used in the industry. They can manage various operating fluids and are reasonably easy to put together. High-pressure applications, characterized by temperatures exceeding 260 degrees Celsius and pressures exceeding 30 bar, frequently utilize STHE [18]. See Figure 1.3.

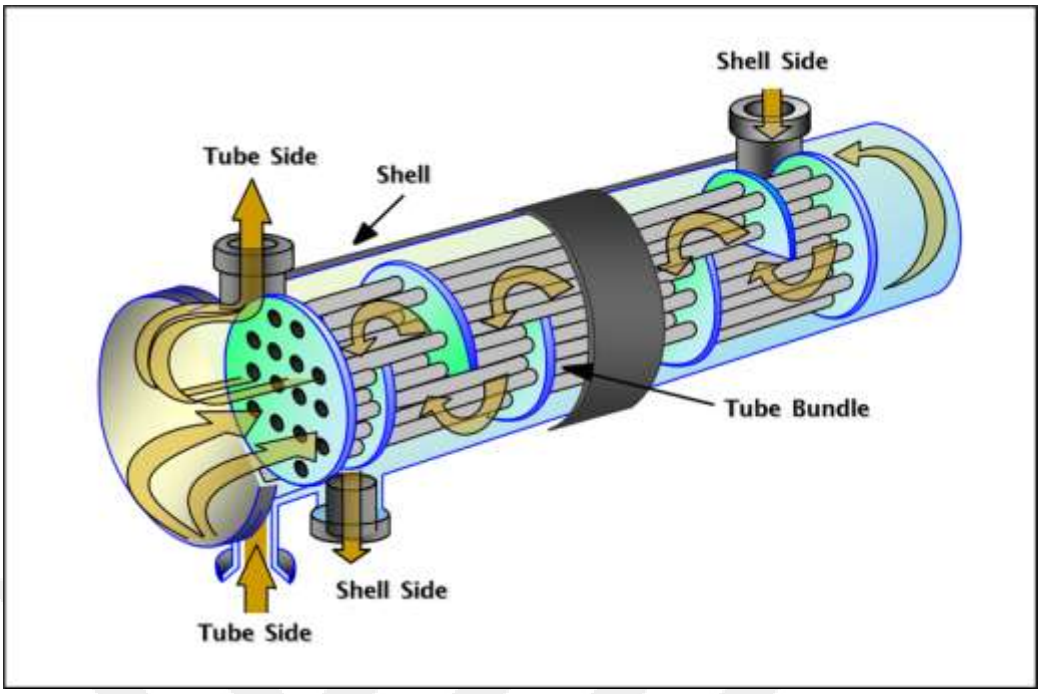


Figure 1.3: The STHE Component [19].

1.4.1.3 Plate heat exchanger

The plate HEs are made up of several plates linked to one another and stacked on top to give the assembly the necessary support. Typically, the plates have four flow ports and attach to a frame using aligned bushes or nozzles. These ports connect to the outside pipes, which carry the two liquid streams [20]. The brewing, dairy, food, petroleum, and chemical sectors are some of the ideal applications for the plate HEs regarding heat recovery responsibilities [21].

1.4.1.4 Plate fin heat exchanger

Plate fin or matrix HE is greatly compact heat-transfer surfaces, especially in situations where it is necessary to maintain the separation of fluids. These heat exchangers employ matrices, fins, and plates as means of heat transfer. The construction of these exchangers involves the utilization of multiple layers of matrices or sandwich-folded metallic sheets that are separated by parting sheets [22]. This kind of HE is distinguished by its alternating hot and cold channels between parallel plates, with the plates themselves including fins to optimize the heat transfer process. When transferring heat from liquid to gas, fins are only utilized on one side; however, when transferring heat from gas to gas, fins are utilized on both sides. In applications involving waste heat recovery, this particular kind of heat exchanger is often employed [23]. Figure 1.4 showcases a plate fin HE, pertinent to passive heat transfer methods.

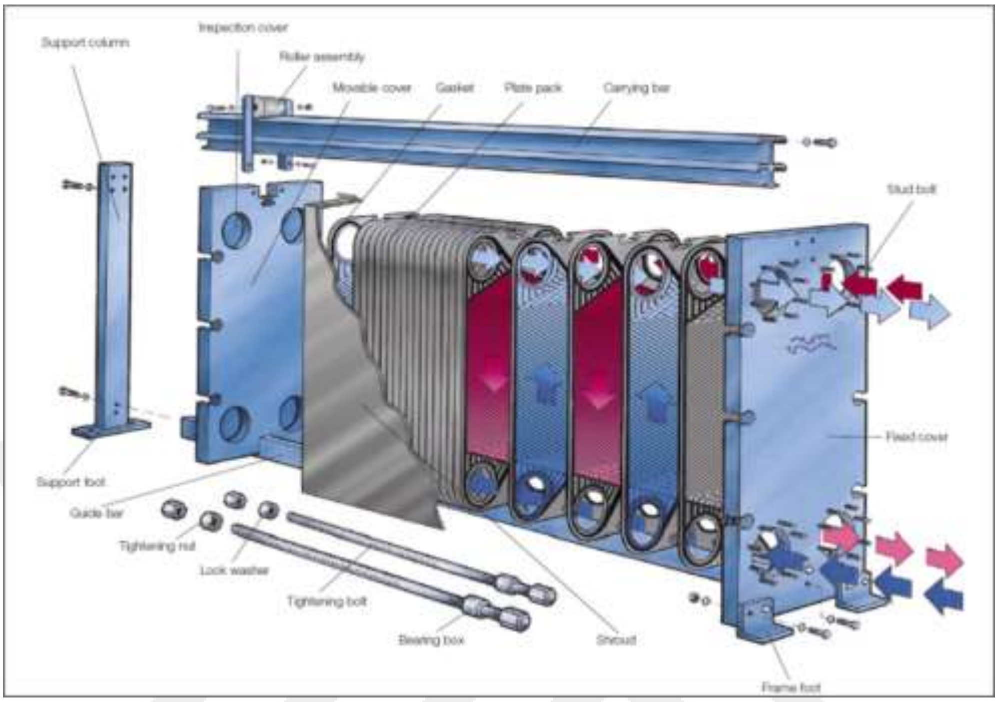


Figure 1.4: Plate Fin Heat Exchanger [24].

1.4.1.5 Compact heat exchanger

The plate-fin HE is a compact, highly efficient device consisting of alternating layers of plates and fins. These fins create channels that allow heat to be exchanged between fluids and are commonly used in aerospace, automotive, and HVAC systems due to their space-saving design. While they excel at effectively transferring heat within confined spaces and high-pressure environments, their complex structure can pose challenges in cleaning and maintenance. However, their ability to efficiently transfer heat in various industries that require compact and efficient heat exchange solutions continues to make them widely used.[25]. Figure 1.5 provides a visual representation of a compact HE.

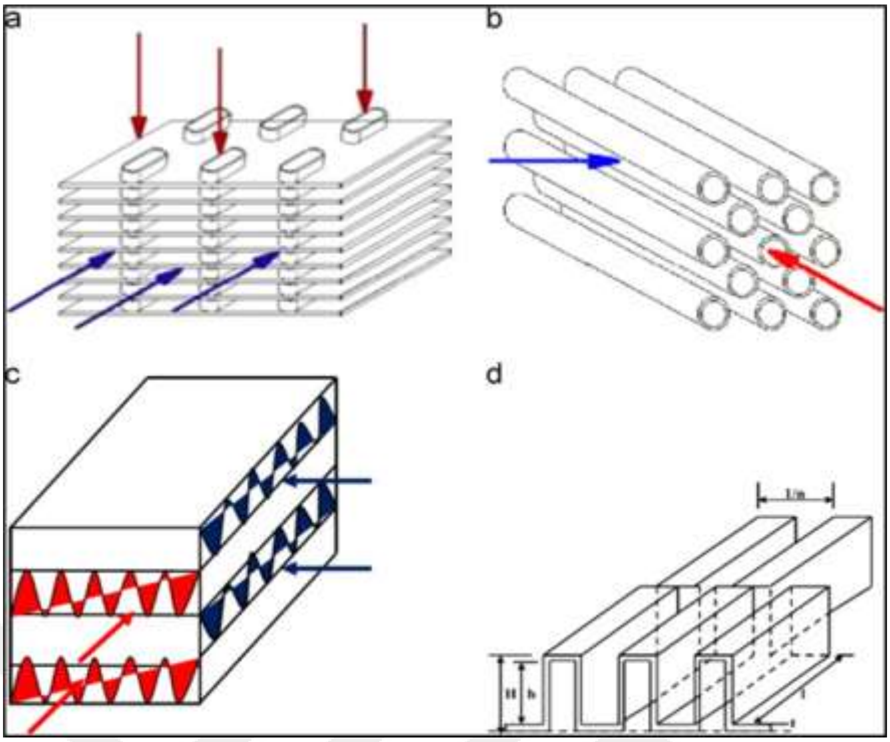


Figure 1.5: Compact Heat Exchanger [25].

1.4.1.6 Regenerative heat exchanger

In a regenerative HE, the heat generated by one operation is utilized to heat the fluids for subsequent processes ,this system utilizes the same fluids on both sides of the exchanger, which can be arranged in configurations such as STHE or plate-and-frame designs. These exchangers were designed exclusively for transferring heat between gas mediums and not for any kind of HT between liquid substances. Their functioning was restricted exclusively to procedures involving the exchange of heat between gases [26]. Figure 1.6 shows a regenerative exchanger, expanding heat transfer enhancement research.

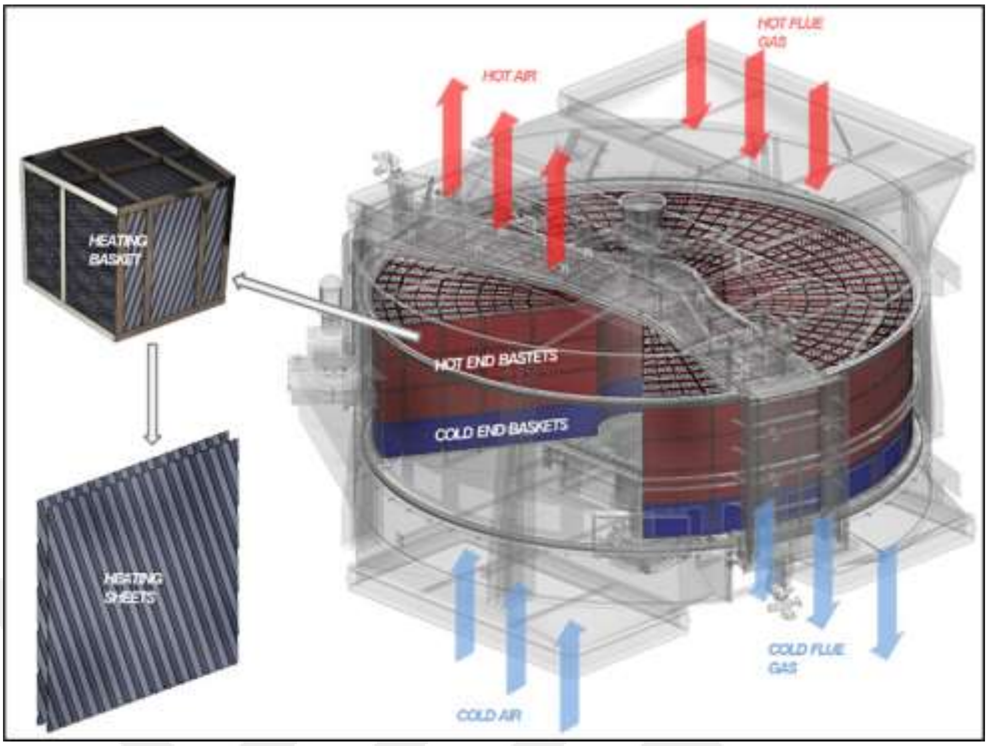


Figure 1.6: Regenerative Heat Exchanger [26].

1.4.1.7 Adiabatic wheel heat exchanger

The medium for heat transmission in an adiabatic HE might be an intermediate solid or a liquid, depending on the type. There is continual motion of the solid between the scalding and freezing liquids. The object's temperature increases as it travels through the heated fluid because it absorbs thermal energy in tangible form. Once the wheel moves through the cool fluid, it transfers all this thermal energy back into the fluid. The adiabatic wheel and the fluid heat exchanger are two instances of this device. The adiabatic wheel is a big wheel with small threads that rotates through cold and hot fluids [27].

1.4.1.8 Phase change heat exchanger

HE are useful for various processes, including those involving a single phase, those involving a two-phase flow combination, and those involving a three-phase combination. HEs that undergo a phase shift may either be of the condenser or evaporator kind, with the former converting vapours to liquids and the latter turning liquids into vapours [28].

1.4.2 Categorization Depending on the Configuration of the Flow

The relative flow configuration of a HE, which refers to the collection of geometric relationships between the streams, is an essential aspect of the design of the device [29]. It must be brought to the reader's attention that the configurations presented are idealizations of what takes place; in actuality, it is impossible to ensure that the flow patterns adhere to the ideal. The HEs can be categorized based on the configuration of flow [30].

1.4.2.1 Parallel flow

In the parallel flow heat configuration, both fluids transport heat in the identical direction, flowing alongside each other. Still, this setting doesn't really show how different the temperatures of the two streams of fluid are. In contrast to most other flow designs, this one offers a more homogeneous distribution of wall temperature. When effectiveness is of the utmost concern, a parallel flow design should be avoided if possible [31]. Figure 1.7 depicts the parallel flow configuration, integral to heat transfer research.

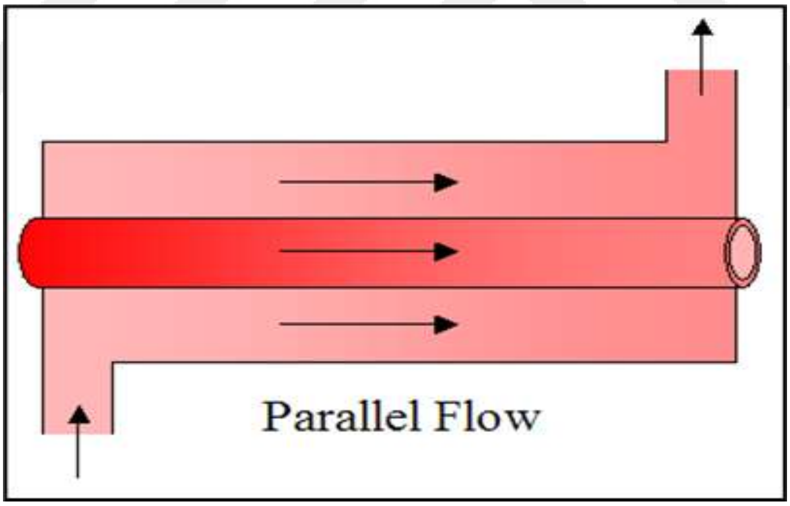


Figure 1.7: Parallel Flow Configuration [32].

1.4.2.2 Counter flow

In a configuration known as counter-flow, the two working fluids are directed to flow in a manner that is parallel to one another but in the opposite direction. The most effective heat exchangers are counter-flow exchangers because they make the most of the obtainable temperature difference and can achieve the greatest temperature difference between the two fluids being exchanged [33]. Figure 1.8 displays the crossflow configuration.

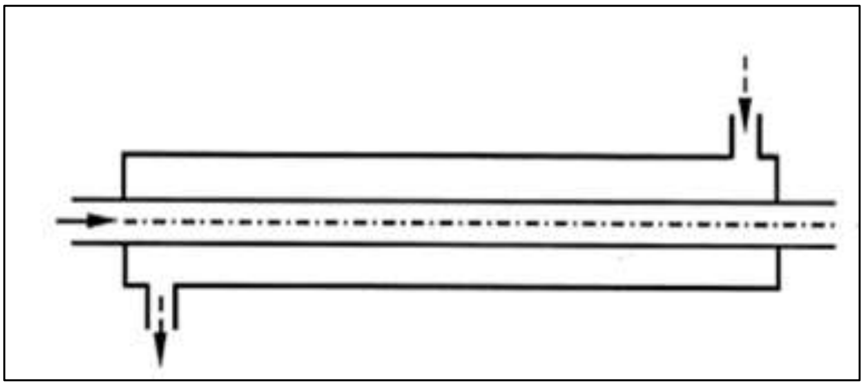


Figure 1.8: Crossflow Configuration [33].

In this configuration, the two fluids circulate in directions that are perpendicular to one another. A diagrammatic representation of the crossflow arrangement may be seen in Figure 1.9. This layout falls somewhere in the middle of counter and parallel flow patterns regarding effectiveness. They are less difficult to put together. The radiator of an automobile is an essential instance of crossflow [32].

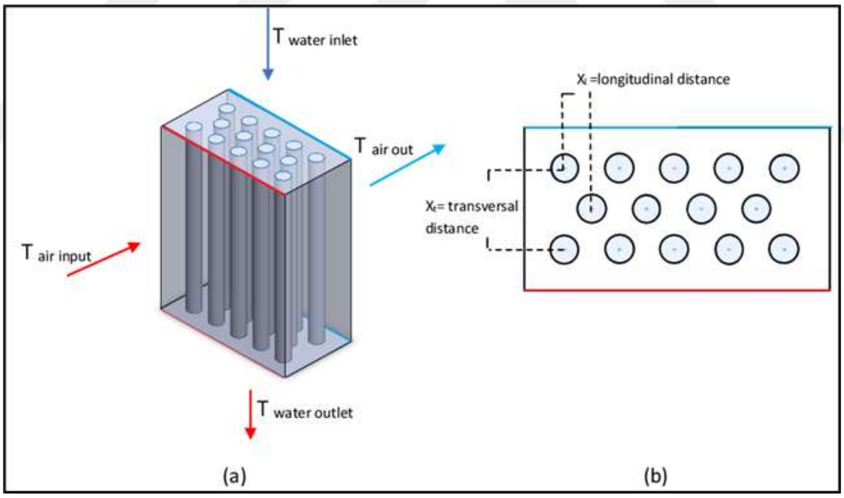


Figure 1.9: Cross Flow Configuration A) Physical Model, B) Pipes Distribution [32].

The four types of heat exchangers depicted in Fig 1.10 include concurrent flow, counter current flow, crossflow, and cross/counter flow (hybrid). In cocurrent flow HE, hot and cold fluids move in the identical direction, allowing for efficient HT but diminishing the temperature difference along the exchanger's length. Countercurrent flow HEs, on the other hand, feature fluids moving in opposite directions, maintaining a greater temperature difference, and enhancing overall efficiency. Crossflow heat exchangers involve perpendicular flows of hot and cold fluids, beneficial for applications requiring separation between the two. Lastly, the cross/counter flow, or hybrid, design combines elements of both countercurrent and crossflow arrangements, aiming to optimize heat transfer efficiency by balancing advantages from each.

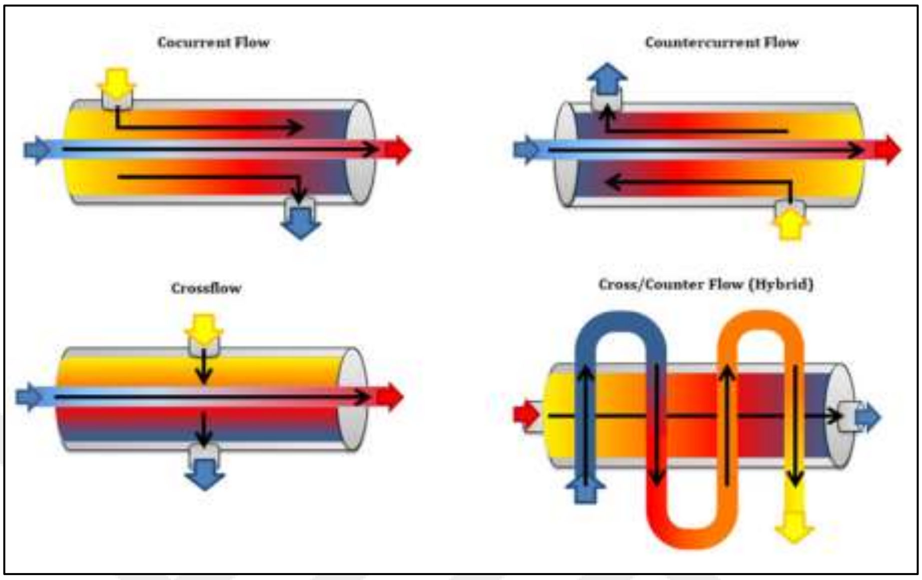


Figure 1.10: Heat Exchanger Flow Configurations [34].

1.4.2.3 Cross counter flow

There are occasions when the actual flow arrangements of heat exchangers come close to conforming to the idealizations presented in Figure. These kinds of exchangers are known as cross-counter-flow exchangers. There is a choice between a two-pass, a three-pass, and a four-pass option, and the total number of passes purchased is endless. Exchangers that use a cross- 30 counter flow are a compromise between the two desirable characteristics of effectiveness and simplicity more the number of times something is passed; the nearer one gets to achieving a counter-flow economy [35].

1.2.4.4 Multipass shell and tube flow

Inside the identical HE, it is possible to combine parallel-flow and counter-flow characteristics, such as tubes double back, either once more than once, within a single shell, and the same impact may be obtained, with straight tubes, by the supply of appropriately split headers. The U-tube, also known as the hairpin configuration, has the benefit of being simple to create since it only requires one end of the shell to be perforated rather than both [36]. Multipass shell and tube flow, as it is clear in Figure 1.11.

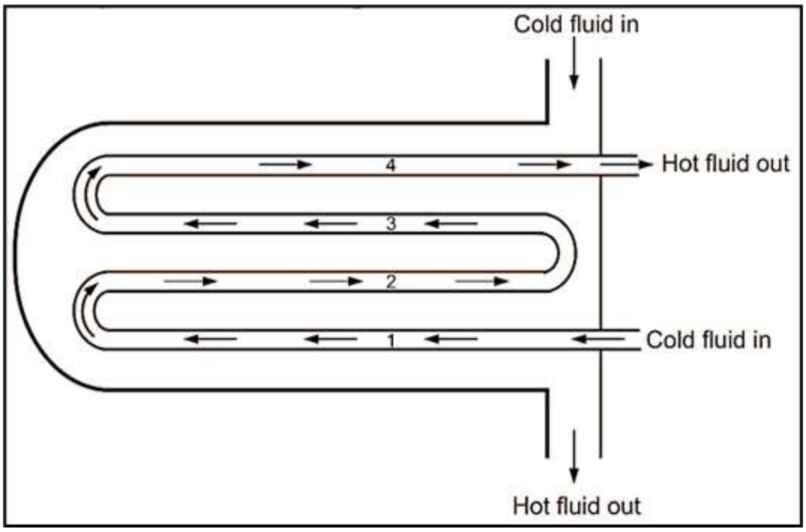


Figure 1.11: Multipass STHE Flow Configuration [37].

An interface allows a HEs two working fluids to communicate and exchange information. They may come into touch with one another in several different ways, which is why heat exchangers could be categorized in several various ways. Sprays, films, matrix arrangements, finned tubes, and plain tubes are many fluid-interface kinds [38].

1.4.3 Categorization Depending on the kind of Temperature Change Pattern

HEs can be classified into different kinds depending on the way temperature changes take place [39]:

1.4.3.1 Single phase heat exchangers

Just heat in the form of latent energy is transferred across the single-phase boundary of a heat exchanger. At no time is there any involvement of latent heat in this process. When it exits the exchanger, the working fluid is in the same phase that it was in when it first entered. Because of this circumstance, a discernible difference manifests in the temperatures of the two streams. When leaving, the cold stream's temperature rises, while the hot stream's temperature lowers to a similar level. Single-phase heat exchangers constitute the majority of those observed in operational settings today [40].

1.4.3.2 Phase change heat exchangers

The exchanger may need to alter the working fluid phases in certain circumstances. In this instance, there is also an involvement of latent heat, the isothermal nature of a stream is characterized by the fact that its temperature remains relatively constant regardless of its phase. Phase change heat exchangers are the name given to this specific kind of heat exchanger. The condenser and the evaporator, as well as the boiler, are all kinds of phase-change heat exchangers [28].

1.5 PROBLEM STATEMENT

HEs, Important for a variety of industrial applications, facilitate HT between solid objects and fluids, or amongst different fluids. A key challenge in this field is enhancing the efficiency of these devices, particularly in energy-intensive industries. Market demands for high-efficiency heat exchangers are pressing, necessitating innovative approaches to optimize their performance. This study addresses the challenge by examining the effect of surface area augmentation on HT. The focus is specifically on the implementation of a helical coil on the outer shell of a STHE. This modification is hypothesized to significantly reduce thermal losses to the atmosphere, thereby improving the exchanger's performance. The research contrasts the thermal behaviors of a standard STHE with a modified version that includes the helical coil, providing insights into the efficiency gains achievable through this design innovation.

1.6 AIM OF THE THESIS

The primary aim of this thesis is to conduct a comprehensive investigation into enhancing the efficiency of HT in a STHE by integrating a helical coil into its outer shell. Utilizing the ANSYS simulation program, this research seeks to deepen the understanding of thermal behaviour and fluid dynamics within the exchanger. The specific objectives are refined as follows:

i. Optimization of Heat Transfer:

a. Employ numerical simulations in ANSYS to evaluate how different Reynolds numbers within the pipe section influence heat transfer.

a. Analyse the impact of the helical coil on flow dynamics and its subsequent impact on overall heat transfer efficiency.

a. Establish a relationship between the variations in Reynolds numbers and the resulting HT characteristics to identify the most effective flow conditions.

ii. Performance Evaluation:

a. Compare the heat exchanger's performance before and after incorporating the helical coil to quantify the efficiency improvement.

b. Use data from ANSYS simulations to measure advancements in the exchanger's heat transfer capabilities.

c. Evaluate changes in pressure drop, temperature profiles, and other critical parameters to determine the enhancement's overall effectiveness.

iii. Effect of Flow Direction:

a. Examine the role of fluid flow direction in influencing mass flow rates and heat transfer efficiencies.

b. Investigate how the introduction of the helical coil alters flow direction within the exchanger and its effects.

c. Provide insights on how changes in flow direction can contribute to improved mass flow rates and enhanced heat transfer efficiency.

By reaching these goals, the study hopes to make significant enhancements to the field of designing and using heat exchangers , particularly in maximizing HT while minimizing energy consumption and pressure losses in STHEs.

1.7 THESIS LAYOUT

The recent thesis consists of five chapters with the following information distributions:

i. Chapter 1: Presents basic information about HEs, their types, the issues addressed in this study, the problem statement, and the aims and objectives of the search.

ii. Chapter 2: Covers essential concepts of shell and tube HEs, including key equations and a review of related literature to provide a background for the study.

iii. Chapter 3: Focuses on the theoretical analysis with a description of the model using the ANSYS software, details about the mesh generation, and the equations used in the analysis.

iv. Chapter 4: Summarizes and analyses the data collected from the study, compares the findings with other relevant research to put the results into context.

v. Chapter 5: presents a concise overview of the study's results and proposes recommendations for further investigation in this field.

2. LITERATURE REVIEW

2.1 INTRODUCTION

The energy Transfer can occur through three main mechanisms: radiation, convection, and conduction. Heat transfer is a phenomenon that takes place whenever there exists a disparity in temperature between two entities, and it proceeds in the direction of diminishing temp, specifically from a great-temperature entity to a low-temperature entity. Despite the distinct mechanisms and laws that govern the three modes of heat transfer, they may simultaneously manifest in everyday processes, including the act of boiling water over an exposed flame [41]. The formula for heat transfer can be mathematically represented as $Q = m \times c \times \Delta T$, in this context, Q indicates the quantity of heat transmitted, m denotes the mass of the item, c represents the specific heat capacity, and ΔT indicates the temperature change. It is understood that heat is a form of kinetic energy associated with the particles within a given system. The temperature of a system has a direct impact on the kinetic energy of its particles, increasing in kinetic energy as the temperature rises. This discussion delves into the heat transfer equation and includes several fundamental questions. The process of moving thermal energy from one object to another is known as HT, due to a temperature difference between them, which is often the case when individuals possess varying body temperatures. In the context of thermal dynamics, it is a commonly observed phenomenon that when object A possesses a greater temperature than object B, there exists a transfer of thermal energy from object A to object B until a state of thermal equilibrium is attained. This equilibrium is characterized by the equalization of the temperatures of the two objects [42]. Figure 2.1 below illustrates a simplified representation of the heat transfer mechanism.

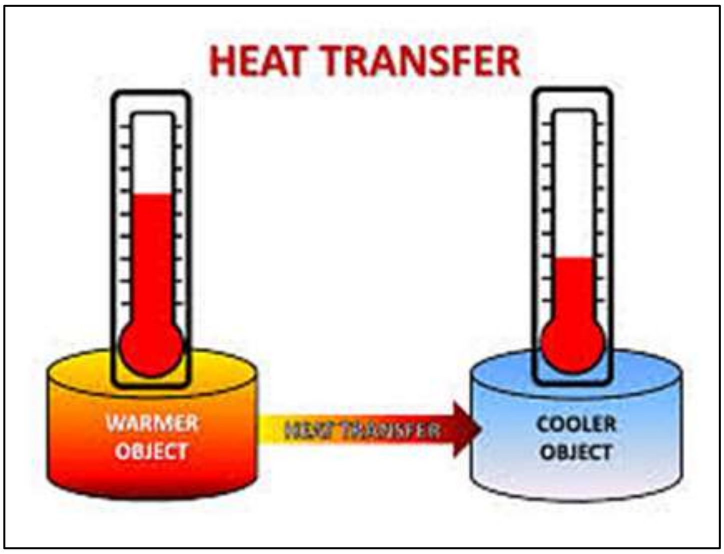


Figure 2.1: Heat Transfer [42].

2.2 METHODS OF HEAT TRANSFER

Heat transfer also takes place through three additional distinct processes. The three modes of HT have been radiation, convection, and conduction, Figure 2.2 illustrates the heat transfer concept [43].

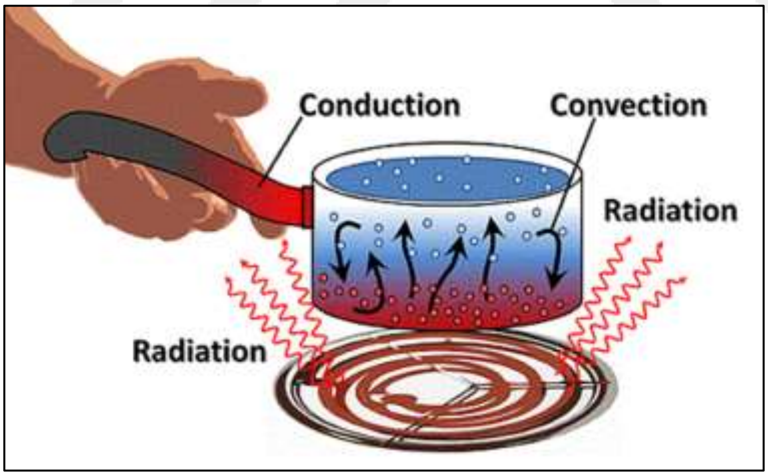


Figure 2.2: Concept of HT [43].

2.2.1 Conduction

In this type of heat transfer, objects in contact with each other exchange both kinetic and potential energy through a process known as conduction. Once a higher-temperature object meets a lower-temperature object, over some time, the temperature of the higher-temperature object eventually reach equilibrium with that of the lower-temperature object. The process of heat conduction, or the transmission of thermal energy that travels from a hotter to a colder item, is responsible for this effect [44]. When different metals come into direct contact with each other, they do not exchange heat since metals are efficient conductors. Instead, they transfer an equal amount of heat through their surfaces when those surfaces have equal temperatures. Gases and liquids also exhibit good thermal conductivity, albeit lower than that of solids due to their free movement along their length, which solid materials do not permit [45]. The equation for the HT through conduction is expressed as [46]:

$$q_{\text{cond}} = -k \cdot \frac{dT}{dx} \tag{2.1}$$

In this equation, q_{cond} represents the rate of HT by conduction, measured in Watts (W). The variable k denotes the thermal conductivity of the material, expressed in Watts per meter-Kelvin (W/m·K). It quantifies the material's ability to conduct heat. The term $\frac{dT}{dx}$ is the temperature gradient in the direction of HT, measured in Kelvin per meter (K/m). This gradient is the rate of change of temperature with respect to distance in the material.

2.2.2 Convection

Convection is a process of heat transmission when objects in direct contact with each other exchange either potential or kinetic energy. When a hotter object contacts a cooler object, over time, the temperature of the hotter object equalizes that of the cooler object. This process occurs through convection or the HT from the greater temperature object to the lower temperature object [47]. The equation governing heat transfer through convection [46]:

$$q_{\text{conv}} = h \cdot A(T_{\text{surface}} - T_{\text{fluid}}) \tag{2.2}$$

In this convection equation, is the HT rate due to convection, measured in Watts (W). The factor is the convective HT coefficient, in Watts per square meter-Kelvin (W/m²·K), representing the effectiveness of convection per unit area and temperature difference. T_{surface} and T_{fluid} are the temperatures of the surface and the fluid, respectively, both measured in Kelvin (K). The difference between these two temperatures drives the convective heat transfer.

2.2.3 Radiation

The convection is a heat transfer mechanism in which objects that are in physical contact with each other exchange both potential and Thermal radiation refers to the mechanism through which heat is exchanged between two bodies via the emission and absorption of electromagnetic waves. This phenomenon arises once a great-temperature object emits thermal radiation that is instantaneously absorbed by another object, increasing in the latter's temperature. Radiative heat transfer exhibits omnidirectional characteristics, in contrast to conduction and convection which are limited to unidirectional heat flow [48].

The equation governing heat transfer through radiation [46]:

$$q_{\text{rad}} = \epsilon \cdot \sigma \cdot A(T_{\text{surface}}^4 - T_{\text{surroundings}}^4) \tag{2.3}$$

In the Stefan-Boltzmann law, q_{rad} refers to the rate of HT by radiation, measured in Watts (W). The variable ϵ is the emissivity of the surface, a dimensionless factor indicating how effectively a surface emits radiation compared to a perfect blackbody. The constant σ is the Stefan-Boltzmann constant, valued at 5.67×10^{-8} Watts per square meter-Kelvin to the fourth ($W/m^2 \cdot K^4$). It is a universal constant for blackbody radiation. T_{surface} and $T_{\text{surroundings}}$ are the temperatures of the radiating surface and its surroundings, respectively, in Kelvin (K). The fourth power of these temperatures is used in the equation, highlighting the strong temperature dependence of radiative heat transfer.

2.3 SHELL AND TUBE HEAT EXCHANGER

A STHE consists of a cylindrical container that holds a collection of tubes, referred to as the tube bundle. These tubes contain a fluid that is maintained at a particular temperature and is submerged in another fluid with different temperatures. Thermal energy is transferred between these two fluids because of disparities in temperature. The fluid that moves through the tubes is often known as the "tube side" fluid, while the fluid that circulates outside the tubes is commonly referred to as the "shell side" fluid. This arrangement facilitates efficient thermal transfer between the fluids while also ensuring their independent flow routes [49]. STHEs, with their diverse structural variations, are widely recognized as the predominant and extensively employed fundamental configuration of heat exchangers within process industries. HEs are commonly employed in various industries, including nuclear power stations, and conventional and process industries. They are used for many things, like heat feed water, making steam in power plants with pressurized water reactors, and cooling things down. Additionally, heat exchangers find applications in alternative energy sectors such as ocean, thermal, and geothermal energy systems. Furthermore, they are utilized in certain air conditioning and refrigeration systems [50]. There are multiple reasons for the widespread acceptance of this phenomenon. STHE offers a favourable proportion between the surface area available for the HT and the volume and weight of the system. The surface is presented in a manner that facilitates its manufacturing process across various dimensions, offering relative ease and versatility. Moreover, it possesses mechanical durability that enables it to withstand typical stresses encountered during fabrication, transportation, field assembly, and regular operational conditions. Various adaptations of the fundamental structure can be employed to cater to specific services. The STHEs possess a convenient cleaning mechanism, allowing for efficient maintenance. Furthermore, the components that are most susceptible to malfunction, namely gaskets and tubes, could be readily replaced. There are established design methods and ample resources worldwide for the successful design of heat with tubes and shells [50]. Figure 2.3 displays the most basic configuration of a HE is consisting of a STHE, wherein the upper portion of the shell is the entry point for warm kerosene. Baffle plates serve the purpose of directing the movement of kerosene within the heat exchanger's tubes, ensuring that it follows the intended route. Once the kerosene reaches the necessary temperature, it discharges through the nozzle situated on the lower side of the shell. Strategically positioned baffle supports along the brace and tubes further reinforce the tube bundle, which is securely fastened between two tube sheets. The flow on the tube side initiates from the bottom left section of the tube bundle and progresses towards the top left section, with a horizontal baffle plate dividing the two flows on the tube side. This arrangement is widely recognized as a 1-2 exchanger, indicating that the outer shell has one flow while the inner tubes have two flows [51].

Figure 2.3: An Example of a Fixed Tube STHE [19].

The reboiler depicted in Figure 2.4 illustrates the process of generating isobutene vapor through the application of heat to liquid isobutene. The reboiler variant being referred to is commonly known as a "kettle" kind reboiler due to the additional surface area located above the tube bundle, which facilitates the separation of vapor.

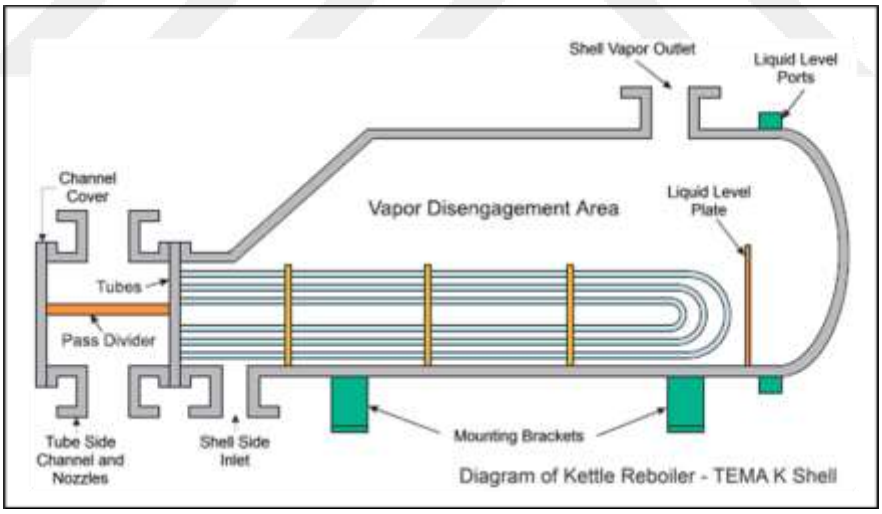


Figure 2.4: A U-Tube Kettle Kind Reboiler [19].

Another arrangement involves installing a STHE vertically next to the processing tower. The thermal energy of steam facilitates the separation of liquid propane and propylene in this setup, creating a two-phase mixture that includes both liquid and gaseous phases. This configuration is frequently observed within the gas processing sector. The supports of the exchanger should be meticulously designed due to the thermal expansions of the tubes [52].

2.4 CLASSIFICATION OF SHELL AND TUBE HEAT EXCHANGERS

One of the criteria for classifying HE depends on the design of the STHE configuration [53]:

2.4.1 Fixed Tube Shell and Tube Heat Exchanger

The tubes of a fixed-tube sheet HE elongate and securely connect to the carapace at both ends via tube sheets connected to the tube. The system components may consist of detachable channel covers, bonnet-style, or tube sheets that are an integral part of the structure [54].

2.4.1.1 Advantages

i. The primary benefit of utilizing the fixed tube sheet configuration lies in its cost-effectiveness, which is attributed to its straightforward design. The fixed tube sheet is considered the most cost-effective construction method, assuming that no expansion joint is necessary.

ii. The tubes have the potential to undergo mechanical cleaning following the elimination of the channel cover or bonnet.

iii. The occurrence of fluid leakage on the shell side is reduced due to the absence of flanged joints. Additionally, this configuration necessitates a lower number of gaskets compared to alternative configurations [55].

2.4.1.2 Disadvantages

i. One drawback of this design is that due to the fixed attachment of the bundle to the shell, the external surfaces of the tubes are not amenable to mechanical cleaning. Therefore, the scope of its implementation is restricted to sanitary services within the shell domain. Nevertheless, if an effective chemical cleaning program could be implemented, the fixed-tube sheet architecture is selected for fouled activities on the shell side.

ii. In situations where there is an essential temperature difference between the tubes and the shell, the tube sheets may not be able to effectively manage the resulting stress differential. Consequently, the inclusion of an expansion joint becomes imperative. This essentially diminishes the cost advantage.

iii. The absence of an expansion joint limits the maximum variation in temperature between fluids to roughly 200 ^{o}F [55].

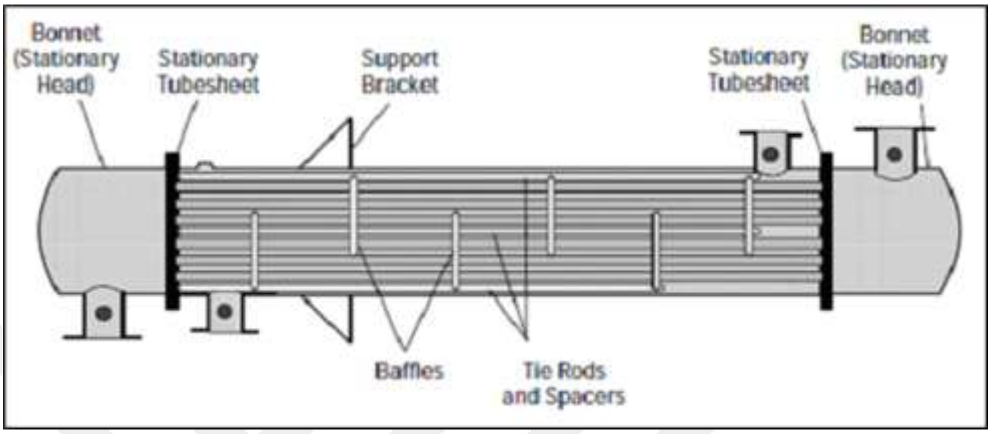


Figure 2.5: A Fixed Tube Sheet STHE [56].

This type of HT derives its name from the characteristic U-shaped configuration of its tubes. A U-tube heat exchanger typically employs a single tube sheet. Nevertheless, the extra expenses accrued throughout the tube bending procedure and the marginally increased shell diameter due to the modest U-bend radius counterbalance the cost benefits linked to employing a solitary tube sheet. Figure 2.6 illustrates a U-tube STHE [57].

Figure 2.6: A U-Tube STHE [58].

2.4.1.3 Advantages

a. The U-tube HE offers the benefit of allowing the bundle to expand or contract depending on stress differentials, due to the presence of one free end.

b. The external surfaces of the tubes are capable of being cleaned due to the removable nature of the tube bundle.

c. The cost of this kind of exchanger is lower compared to a fixed tub or floating head exchanger. Additionally, the need for an inner gasketed joint is dismissed. Furthermore, the tube bundle can be easily removed and replaced [59].

2.4.1.4 Disadvantages

a. One drawback of the U-tube structure is the limited effectiveness of cleaning the interior of the tubes, as the U-bends necessitate the use of flexible-end drill shafts for thorough cleaning.

b. U-tube HE is not suitable for applications involving the circulation of contaminated fluids within the tubes.

c. The utilization of U-shaped tubes findings in a decrease in the number of tubes that could be installed. Additionally, the tubes are not capable of being replaced individually [57]

2.4.2 Floating Head STHE

The conventional STHE has several variants, one of which is called a Floating Head STHE. The "floating head" design is what sets it apart from similar products on the market. Because this structure includes a floating tube sheet, one end of the tube bundle that is contained within the cylindrical shell has the ability to move. This mobility is a practical solution that accommodates thermal expansion and contraction of the tubes, which is vital for effective and dependable heat exchange. Specifically, this mobility allows the tubes to expand and contract as the temperature changes., Figure 2.7 depicts the TEMA shell configuration, a significant aspect of our discussions [60].

2.4.2.1 Advantages

a. The system exhibits the capability to effectively manage fluids that are contaminated and possess great temperature differentials.
b. Both the head and tubes of the system could be thoroughly cleaned.
c. It is possible to remove and substitute individual tubes [61].

2.4.2.2 Disadvantages

a. Fixed tube HEs are associated with lower costs compared to their counterparts.
b. The increased number of gaskets in fixed tube heat exchangers could potentially lead to leakage issues [62].

2.5 KINDS OF FLOATING HEAD CONSTRUCTION

There are several variations of floating-head construction. The following are the two prevalent ones [19]:

i. Pull-through with backing device (TEMA S)
ii. Pull through (TEMA T).

2.5.1 Classification Based on Service

Heat exchangers made of tubes and shells could be categorized into various kinds depending on their respective functions [63]:

a. A reboiler is a specific category of heat exchanger utilized in distillation columns to facilitate the heat transfer to a liquid, resulting in the generation of a two-phase gas-liquid mixture.

b. Thermosiphon A reboiler is a particular kind of HE that facilitates the natural circulation of a boiling fluid through the utilization of a static liquid head. 45 c.

c. A forced circulation reboiler is a kind of reboiler that employs a pump to facilitate the movement of liquid through the heat exchanger, thereby transferring heat to the distillation column.

d. A condenser is a kind of HE that facilitates the condensation process by extracting heat from the vapours of a liquid.

e. A partial condenser is a kind of heat exchanger that is specifically engineered to achieve partial condensation of gas, to transfer heat to another medium to meet specific process requirements. The residual gas undergoes recirculation and recycling by passing through a heater. One prevalent utilization of a partial condenser in a distillation column involves employing surplus steam to elevate the temperature of a process fluid.

f. The final condenser is a HE that facilitates the condensation of all the gas while transferring all the heat to another medium.

g. A steam generator, also known as A heat exchanger, is equipment that generates steam, and it most commonly takes the shape of a boiler, to supply energy for the specific needs of a given process. One prominent illustration is the traditional steam locomotive, characterized by its HE with a shell and tube configuration that is affixed to a mobile platform, enabling the utilization of steam as a propulsive force for the locomotive. The unit in question is a vessel that has undergone the process of firing, and its design is not subject to regulation under Division VIII of the ASME Section.

h. A vaporizer is a device that facilitates the complete or partial vaporization of a liquid.

i. A chiller is a heat exchanger that facilitates the cooling of a process medium through the utilization of a refrigerant, or by employing cooling and heat mechanisms with minimal or negligible phase alteration [64]. Figure 2.7 displays the TEMA shell configuration.

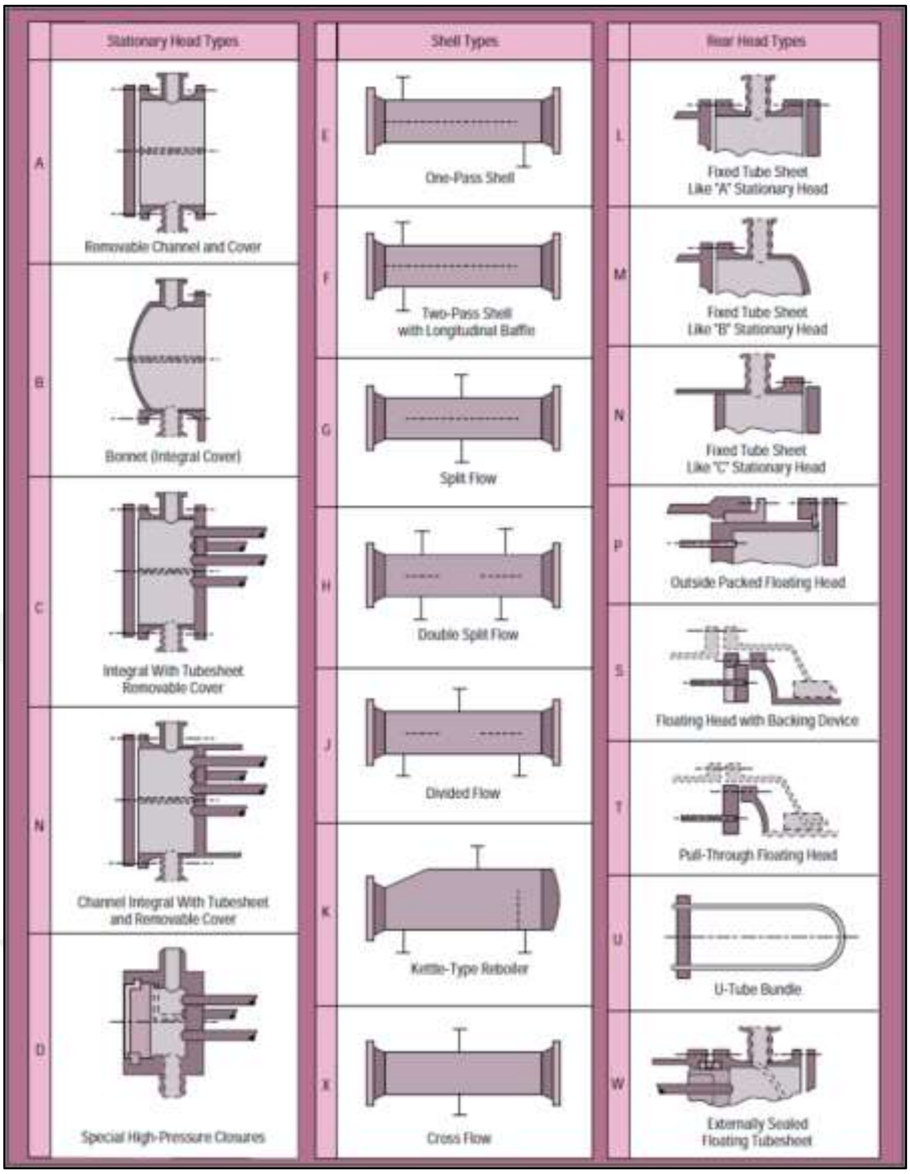


Figure 2.7: TEMA Shell Configuration [63].

2.6 HELICAL COILS

Extensive literature supports the idea that heat transfer rates in spiral coils exceed those in straight tubes. As a result, spiral coil heat exchanger finds widespread use across multiple industrial sectors, such as the food industry, refrigeration, heat recovery systems, process plants, nuclear industry, and power generation. This popularity stems from its compact structure and significantly higher heat transfer coefficients [65]. HEs with helical coils are often used in systems that get rid of leftover heat in nuclear reactors that are either on land or on a barge. These systems harness nuclear energy for seawater desalination. The study conducted by [66] changed several process parameters to see how they affected the performance of a system that uses a "helically coiled heat exchanger" to get rid of residual heat [67].

2.6.1 Definition of Terminology for Helically Coiled Pipes

The helical coil's schematic is shown in Figure. 2.8. The pipe is $2r$ in diameter inside. $2R_c$ (estimated between the centers of the pipes) is used to denote the coil diameter. The pitch is the separation of two neighbouring turns. Pitch circle diameter is another name for coil diameter. The curvature proportion, or r/Rc, is a proportion of pipe diameter/coil diameter. Nondimensional pitch, λ, is the proportion of pitch to the evolved length of one turn $(H/2\ \pi Rc)$. Think about the coil's projection on a plane that passes across its axis. The helix angle, α, is the angle formed by one turn of the coil projected onto a plane perpendicular to the axis. Consider any pipe cross-section produced by a plane running across the coil axis. The pipe wall side closest to the coil plane is commonly referred to as the internal side of the coil, while the pipe wall side that is further away is known as the external side of the coil. Dean number is utilized to describe the flow in a helical pipe, much as the Reynolds number is for describing flow in pipes. Figure 2.8 presents the fundamental helical pipe geometry sketch [68].

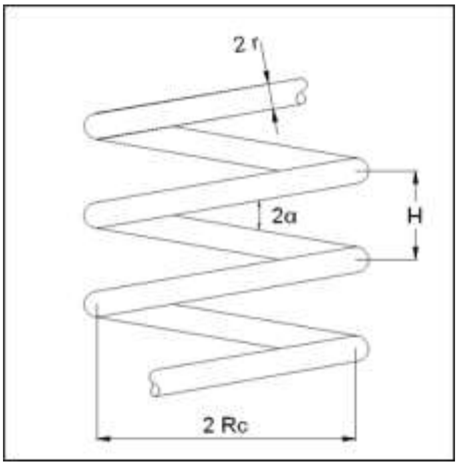


Figure 2.8: Sketch of FUNDAMENTAL HELICAL PIPE Geometry [68].

2.6.2 The Transfer of Flow and Heat in a Single Phase

Single-phase flow and HT are essential to fluid dynamics and thermal physics, with many engineering applications. Understanding these processes improves efficiency and safety in aircraft, automotive, energy, and manufacturing. Single-phase flow moves a homogenous liquid or gas. Pipelines, cooling systems, and heat exchangers use it to ensure efficient and cost-effective procedures. Single-phase flow involves fluid dynamics, flow regimes (laminar and turbulent), and accurate flow measurement for monitoring and control. For efficient cooling, heat, and energy systems, heat transmission is essential. Conduction, convection, and radiation are used in insulation, heat exchangers, and solar energy harvesting [69]. Yamamoto et al.[70] Employing experimental methods, this study investigated the influence that torsion has on the flow of fluid inside a helical tube that has a circular cross section. The Reynolds number range covered by the research was around 500–20,000. The research of fluid flow through curved tubes holds significance within the medical field due to the prevalence of curved arteries [71]. Figure 2.9 illustrates the fundamental helical pipe geometry.

2.7 THEORETICAL BACKGROUND

The concentrated tube HE has become known as a prevalent example of the conductive-convective heat exchanger category. Parallel flow is characterized by the entry of both fluids into the concentrated HE tube from the same sides and their subsequent flow in the same directions. In contrast, counter flow is characterized by the entry of both fluids from opposite sides and their subsequent flow in opposite directions. The prevailing assertion posits that the counter flow configuration exhibits greater efficiency compared to the parallel flow configuration. The focus of this analysis is on a heat exchanger with two pipes. The equation that represents the HT rate at a specific distance x along the tubes connecting the hot and cold fluids is expressed as follows:

$$q_x = UA\,(T_h - T_c) \tag{2.4}$$

A is area for transmission of heat that conforms to the definition of U, Th is temperature of hot fluid; Tc is temperature of cold fluid; U depends on either the inner or exterior area of the tube, the total HT coefficient. Indeed, it is observed that the temperature of both the cold and hot fluids undergo variation along the length of the tube. Hence, to determine the HT between the two fluids, it is necessary to integrate the equation 2.4 over the range of both inlets and outlets situations, resulting in the following expression:

$$q = UA\Delta T_{lm} \tag{2.5}$$

where ΔT_{lm} is the average temperature variation across the heat exchanger, and it could be specified as:

$$\Delta T_{lm} = \frac{\Delta Tin - \Delta Tout}{ln\ (\Delta Tin\ /\ \Delta Tout)} \tag{2.6}$$

The temperature variance discussed here is commonly referred to as the log mean temperature difference (LMTD), which holds true for both flow conditions. The derivation presented above is based on two major presumptions: firstly, that the specific heats of the fluid do not change with temp, and secondly, that the coefficients of heat transfer for convection remain constant across the entire exchanger. The second hypothesis can be affected by factors such as entrance impacts, variations in fluid viscosity, and alterations in thermal conductivity. The quantification of heat loss resulting from the flow of hot fluid within the internal tube could be ascertained by employing the following methodology [71]. Whereas:

$$\dot{Q}_h = \dot{m}_h\ c_{ph}(\ T_{hin} - T_{hout}\ ) \tag{2.7}$$

$\dot{m}_h$ *is* mass flow rate of hot water,c_{ph} is specific heat of hot water, T_{hin} is temperature of hot fluid at entrance, T_{hout} is temperature of hot fluid at exit. In a similar vein, the thermal energy acquired by the colder fluid as it traverses the region between both the interior and exterior pipes could be determined through the application of appropriate calculations.

$$q_c = \dot{m}_c\ c_{pc}\ (Tc_{in} - Tc_{out}) \tag{2.8}$$

Where $\dot{m}_c$ is mass flow rate of cold water, Cp_c is specific heat of cold water.

Tc_{in} is temperature of cold fluid at entrance, Tc_{out} is temperature of cold fluid at exit. If the rate of heat transfer q_c is smaller than the HT rate Q_h, it can be inferred that a certain amount of heat is dissipated through the insulating material into the surrounding air. This occurs while the exterior surface of the concentric tube remains thermally insulated. Hence, the effectiveness could be derived from [72].

$$\eta = \frac{q_C}{q_H} \tag{2.9}$$

Where the effectiveness of an exchanger for heat is characterized as follows:

$$\varepsilon = \frac{\text{actual heat transfer}}{\text{Maximum Possible Heat Transfer}} \tag{2.10}$$

where the determination of the actual heat transfer value can be achieved by evaluating the energy dissipated by the hot fluid using the equation (2.7), or by determining the energy acquired by the cold fluid using the equation (2.8). Given that the energy acquired by the cold fluid is dissipated to the ambient air via the insulating material, it is more advantageous to replace the energy lost by the hot fluid with the actual heat transfer magnitude in the equation (2.10). To ascertain the upper limit of the HT for the HE, one of the fluids must experience a temperature alteration that corresponds to the maximum temperature differential observed within the HE. This differential is defined as the disparity between the temperatures of the hot and cold fluids upon entering the HE. Similarly, the fluid possesses the lowest value of mass flow rate multiplied by specific heat capacity ($\dot{m}cp$). Therefore, the expression for the maximum potential heat transfer could be derived as follows:

$$q_{max} = \left(\dot{m}_{cp}\right)_{min} (T_{hin} - T_{out}) \tag{2.11}$$

The determination of the minimum fluid can be influenced by factors such as mass flow rates and specific heats. Consequently, the efficiency (ε) is subject to variation based on these considerations.

$$\varepsilon = \frac{q_H}{q_{max}} x\ 100\% \tag{2.12}$$

2.8 LITERATURE REVIEW

Crossflow heat exchangers employing an elliptical tube arrangement exhibit enhanced heat transfer surface area in comparison to those utilizing a circular tube arrangement. As a result, these interactions have received much attention recently. However, while improved HT can be beneficial, it often results in the pump's increased electricity usage. Hence, it is crucial to strike a balance between improving HT efficiency and reducing the energy consumption required by the pump [73]. Empirical research is often characterized by its time-consuming nature and high costs, making it unsuitable for conducting a comprehensive analysis of factors in heat exchanger prototypes [74]. Researchers have widely documented the use of modeling and simulation techniques for HEs in the scientific literature [75]. Considerable research has focused on comprehensively documenting the performance of HE designs across various domains and applying them in engineering processes to achieve the most effective modeling methods [76]. Zaversky et al. [77] introduced a meticulous modelling approach for this category of heat exchangers. Hence, in addition to empirical research, various computational methods are extensively employed to assess the attributes of HEs [74]. Boukhadia and Karima [78] demonstrated that the utilization of perforated fins, as opposed to plain fins, leads to an augmentation in the Nusselt number and convection coefficient HT.

Improving heat transfer is a critical element in enhancing the efficiency of STHE. To understand the mechanisms of HT and fluid flow within these systems, it becomes necessary to examine both the HT and pressure drop attributes. Xie et al. [79] demonstrated that HT rates are increased in dimer tubes compared to normal tubes. These findings suggest that the increased HT rates in dimer tubes can effectively enhance the performance of the HT. In their study, Matos et al. [80] performed a comparative analysis of 12 elliptical and circular tubes across a spectrum of Reynolds numbers spanning from 300 to 800. The utilization of elliptical tubes resulted in a heightened efficiency, leading to a 20 percent increase in HT. This reduction in the fouling rate resulted in an increase in the HT area and a decrease in pressure drop. The HT and flow properties of single cam-shaped tubes were investigated in [81]. In a study performed by Moawed [82], empirical research was performed to analyse the phenomenon of forced convection occurring on the outer surface of spiral tubes. Rosen and Dincer (year) demonstrated that smaller variations in temperature in heat exchangers can be achieved, and increasing the efficiency of HEs helps to mitigate temperature degradation. A mixture of multiple shell-pass STHX of different kinds was patented and empirically and numerically analysed by Mroue and Hassan [83]. The current design exhibits numerous enhancements in comparison to its predecessor. The outer shell passes had been designed with a series of uninterrupted helical baffles, while the internal pass was equipped with alternative kinds of baffles. The positioning of the external and internal shell-pass baffles does not necessarily have to be fixed on the same helical surface, as the existence of inner sleeve tubes allows for flexibility in their placement. The exterior and interior shell passes are seamlessly combined at one extremity of the shell side. One design involves the concurrent flow of the working fluid through each of the external and internal shell passes, referred to as a parallel combined multiple shell and tube HE. In contrast, another design entails the sequential flow of the working fluid through the external and internal shell passes, known as a series, mixed multiple STHX. Debnath and Pradhan [84]investigated heat transfer enhancement through the integration of a helical pipe exchanger into the outer shell of a STHEs encompass a multitude of facets, including the choice of material, design of baffles, assessment of pressure drops, and enhancement of HT. The consistent alignment between the numerical results obtained by Chen and Wang and existing experimental studies confirms the reliability and validity of their computational model. This represents a major step forward in understanding turbulent convection heat transfer inside spiral tubes. Pawar et al.[85] performed an empirical study on HT of Newtonian and non-Newtonian fluids in turbulence using three coiled tubes of varying curvatures (0.0757, 0.0064, and 0.0757). Furthermore, the study obtained correlations between Nusselt numbers and friction factor. Additionally, it has been detected that the total HT coefficient transfer reduced as the coiled diameter increased, while maintaining an identical velocity. Nada et al. [86] started a numerical study to find out how secondary flow patterns affect HT while studying the details of laminar flow through helically coiled tubes. Their research focused on the fully developed and inlet parts of helical coils and showed that secondary flow has a big effect on how heat moves through them. Notably, the empirical data obtained from their investigation confirmed the predictive outcomes and further proposed a theoretical relationship between the Nusselt numbers. In a similar vein, Kumar and Manish [87] performed numerical studies on the HT properties of fully evolved laminar flow inside helically coiled tubes. Their research showed that secondary flow weakens when a fluid cools, which may be due to the fluid's temperature-dependent viscosity, leading to relatively lower Nusselt numbers. Moawed [82] performed empirical research to examine the impact of various structural variables on HT by forced convection in helically coiled tubes. The study's findings suggest that there is a positive correlation between the Nusselt number and the P/d0 ratio, while keeping the D/d0 ratio constant. Wang and Guanghui et al. [88] performed empirical research on the performance of HT within the shell side of a helically coiled HE tube. Furthermore, the study examined the impact of various structural variables, such as axial spacing, radial spacing, and coiling angle, on the HT coefficient transfer of the shell side.

Furthermore, researchers extracted experimental correlations of the Nusselt number by fitting them to the experimental data by Wang, Karen Lee [89] conducted a numerical analysis focusing on spirally wound HE tubes, exploring the influence of various structural properties Anusha et al.[90] Focus on enhancing HT efficiency and speed through the design of STHEs, with particular emphasis on barrier design. Initial research focuses on heat exchangers' effects from spiral wire inserts with consistent geometric properties. These studies include straight and helical tubes. Furthermore, Anantha et al. [91] provides significant insights regarding the enhancement of HT in double-pipe HEs, encompassing the implementation of compound HT enhancement techniques and the utilization of helical baffles. The second research area examines spiral wire qualities, particularly non-uniform geometric attributes, in straight tubes. Few research has focused on helical tubes in this context. To understand the thermal behaviour of helical tubes, specialist investigations that explicitly examine spiral wire geometric qualities are needed. The flow properties and amount of helical and straight tubes differ greatly. To increase the efficiency of HT in helical HEs, a special turbulator called a spiral wire can be simply put into the tubes. Therefore, it is crucial to study how spiral wire geometry affects helical HE thermal efficiency [92].

The correlation between the HT coefficient transfer gained through numerical calculation and the empirical data was found to be consistent. Salimpour [93] conducted experiments to determine the optimal curvature and pitch of spiral-wound tubes for optimal HT in HEs, Kücük, Hasan et al. [94] The research looked at both straight-through and cross-current arrangements. Assuming a constant wall temperature and counter-current flow, numerical computations yield an empirical formula for the tube-side and shell-side HT coefficients for small De. The empirical equation for parallel flow tends to underestimate the observed coefficients. Furthermore, researchers developed correlations to estimate HT coefficients on both the shell and tube sides. Salem et al.[95] colleagues conducted research to explore the effect of torsional curvature on HT and fluid dynamics inside a helically coiled tubular HE. The research also demonstrates that thermal transfer is directly affected by operating parameters and warping curvature. As the tube or shell's radius of curvature shrank, the Nusselt number increased. Both the shell and tube sides of the spiral wound tube HE provide average or typical values of the Nusselt number and coefficient of friction. Naphon and Wongwises [96] investigated the thermal transfer coefficient in a helically coiled tube when subjected to chilling and dehumidification. The lack of a HT correlation coefficient determined, especially for the spirally coiled tube configuration, prompted us to conduct this investigation [97]. To fill this knowledge gap, the researchers used mathematical models and empirical methods. The results show that the developed model's results are generally consistent with the empirical results. Excellent thermal performance, simplicity of manufacture, and a space-saving shape make helical tubes a popular choice for use in curved heat transfer. These kinds of heat exchangers find wide application in various industries and processes, including heat recovery, refrigeration, nuclear industries, food processing, and power generation [98], [99]. Among the various techniques available for enhancing HT, both active and passive, the utilization of turbulators stands out as a particularly practical and cost-effective approach to HT improvement. The utilization of helically coiled wires in HT instruments is greatly advantageous due to their straightforward assembly and production methods. The implementation of wire coils as turbulators has been observed to significantly enhance the HT rate. By creating turbulence disruptions in the boundary layer's progression, this is possible. The implementation of turbulators results in a decrease in the tube's cross-sectional area, thereby leading to an increase in the average velocity of the fluid flow. Consequently, this results in a rise in the temperature gradient and the effective axial Reynolds number. These phenomena have the potential to induce a transition from laminar to a turbulent flow system, as well as an increase in turbulence intensity. Therefore, this leads to enhanced momentum and heat flux transfer, as well as improved mixing processes within the boundary layer. Ultimately, these effects contribute to an increase in the HT coefficient transfer [100].

The subsequent examinations pertaining to helical tubes or spiral wires are succinctly outlined. The working fluids employed in the empirical had been water propylene glycol and water. They considered both turbulent and laminar flow systems. Adding helical wire coils to circular tubes does not substantially change heat transmission in low Reynolds number activities, according to the study. The study observed a 200 percent increase in HT rate in the transient flow regime compared to the smooth tube.

Balaji et al.[101] used spiral wire inserts. Empirical analysis was used to look at collectors' HT and pumping power. Better thermal transfer mechanisms, such as wire-coil inserts, were investigated by Hobbi and Siddiqui [102] for their potential effect on flat-plate solar collectors. Their research shows that a flat-plate solar collector's rate of HT does not significantly benefit from the usage of such devices when mixed convection and free convection are the dominant modes of convection. In their study, El Maakoul and Anas, et al [103]. Conducted a comprehensive empirical investigation. Their study aimed to assess the effect of this novel heat transfer augmentation approach on the total heat exchange process. The analysis revealed a significant enhancement in HT efficiency with the incorporation of the helical pipe exchanger.

Lokhande and Atharva[104], also in [105] performed an empirical analysis to examine the phenomenon of producing entropy and the improvement of HT in a circular straight tube that was equipped with coiled-wire inserts featuring a triangle with an equilateral cross section. Moreover, Patel and Sharma [106] conducted a numerical analysis on the same subject. They explored the intricate fluid dynamics and HT characteristics associated with this novel configuration. Their results confirmed the feasibility of enhancing HT efficiency through the inclusion of a helical pipe exchanger in the outer "shell of the STHEs.

In the most recent research performed by Mashoofi et al. [107], the researchers examined the impact of helical wire insertion on the thermal characteristics of "tube-in-tube-helically coiled tube HEs". While there exists a considerable body of research on the impact of spiral wire turbulators, there remain certain areas that require more study. This research could be categorized into two distinct groups. Two categories of case studies have been conducted to investigate the thermal behavior of HEs with spiral wires. The first group includes studies that only look at how the consistent geometric properties of spiral wires affect HEs, which can be either straight or helical tubes. In the second category, researchers consider various properties of spiral wires, including non-uniform geometrical properties, but limit their investigations to straight tubes. Remarkably, there have been relatively few studies carried out on helical tubes in this context. To comprehensively understand the thermal properties of helical tubes, it becomes imperative to undertake dedicated investigations that specifically explore the influence of the geometric features of spiral wires. This necessity arises from the significant disparities in both flow quality and quantity between helical tubes and straight tubes. Additionally, spiral wires represent the sole type of turbulator that can be readily incorporated into helical tubes to enhance HT rates in helical HEs. Consequently, it is of utmost importance to analyze the influence of the geometric properties of spiral wires on the thermal efficiency of helical HEs.

2.8.1 The Experimental Study

Boomsma et al., [108] performed empirical using water as a basis for estimating the performance of HEs when utilized with a solution consisting of 50 percent water and ethylene glycol. Metallic foams with a mean cell diameter of 2.3 mm were produced using aluminum alloy (6101-T6). These foams were then compressed and shaped into compact HEs with dimensions of (40×40×2 mm) and a surface area/volume proportion approximately equal to (10,000 m^2/m^3). The specimens were subjected to a convection apparatus setup, with water serving as the coolant. The heat fluxes observed at the interface between the heater and foam material exhibited a maximum value of 688 kW/m^2. This value correlated to a Nusselt number of up to 134, After careful deliberation, the dimensions of the heater-foam interface were determined to be 1600 mm^2, with a coolant flow velocity of approximately 1.4 m/s following Darcian principles. The heat exchangers made of compressed open-cell aluminium foam exhibited thermal resistance of approximately 2-3 times lower than those of the most efficient alternatives.

Sahiti et al.,[109] provided evidence to support the superiority of the suggested method for exchange upgrades over existing strategies. The findings indicate that the suggested method leads to an essential increase in both the exchange area of pin fins and the HT coefficient exchange. The work demonstrated notable advancements through the implementation of small cylindrical rods on the heat exchangers surfaces.

Wang et al., [110] performed empirical research on a STHE. The researchers employed sealers to obstruct the spaces between the baffle and the shell. The closure of small gaps on the shell side leads to an essential enhancement in the HT coefficient, resulting in an increase ranging from 18.2 to 25 percent. Moreover, this improvement in HT extends to the total HT coefficient transfer, which experiences a boost ranging from 15.6 to 19.7 percent. Additionally, the closure of these gaps has a positive impact on the exergy effectiveness, leading to an increase ranging from 12.9 to 14.1 percent. The losses in pressure exhibit an increase within the range of 44.6 to 48.8 percent. However, the corresponding increase in pump power may be disregarded when compared to the rise in "heat flux".

Qasim et al., [111] tested a HE in a lab. The HE had wire coils in different-pitch tubes. The Reynolds number was gradually changed from 5000 to 4000. The exchanger used water in counterflow on both sides. The results indicate that heat transmission and friction factors increase with coil intensity or coiling pitch. Wire coil performance improves more at lower Reynolds numbers than at higher Reynolds numbers. Nusselt number rises to a maximum of 2.43 inside Reynolds numbers. Friction increases 4.75-fold with this increment.

In their Santhosh Cibi et al., [112] investigated the utilization of a system comprising a HE made up of a shell and tube. The graphite powder is combined with water to create a graphite aqueous solution. The solution is prepared by incorporating varying weight percentages (0.025, 0.05, and 0.075) of the graphite in water. The mass flow rate of the hotter fluid remains constant at 1 LPM, while the mass flow rate of the cold water varies between 1 and 5 LPM. The findings of the study indicate a positive correlation between the amount and thermal conductivity, whereby an increase in amount leads to an increase in thermal conductivity. By incorporating varying weight percentages of 0.025, 0.05, 0.075, the thermal conductivity of the substance is expected to decrease within the range of 1.8, 3.2, 4.3, which is essentially greater than that of water, which stands at a mere 0.618W/m. k.

2.8.2 The Numerical Study

Vijay et al., [113] developed a HE and performed empirical testing. The internal tube of the HE had been engineered to be corrugated and twisted, while the exterior tube remained a standard, non-modified tube. The numerical analysis performed using ANSYS FLUENT 14.0 software revealed that the rate of HT and distribution of temperatures are higher in corrugated twisted tubes compared to normal tubes in HE.

Shweta et al.,[114] performed a comparative analysis of a water/water HE made of shells and tubes. The objective was to assess the HT coefficient transfer and pressure decrease across a range of mass flow rates and temperature outlets. To achieve this, the researchers employed the Kern, Bell, and Bell Delaware methods. The results suggest that there is a direct relationship between the HT coefficient transfer on the shell side and the mass flow rate in all three approaches. However, the Bell Delaware method demonstrates a greater HT compared to the other two methods. Furthermore, it has been detected that the pressure on the shell side exhibited an essential and rapid increase as the flow rate increased. Notably, this increase was found to be more pronounced in the Bell Delaware technique in comparison to other methods.

Tyagi and Kumar [115] performed theoretical research on the impact of fin tube thickness on mass and temperatures as well as flow rate. The ANSYS software is utilized in the process of carrying out the CFD analysis. The study examined the effects of three different materials (copper, aluminium, and steel) on various outcomes. It has been detected that there were minimal changes in weight and speed as the thickness of the blade increased. Additionally, it was found that the copper and aluminium materials experienced greater temps at the outlet compared to steel. once the thickness of the balance is increased, the temperature of the cold liquid at the outlet of the HE also increases. By reducing the mass flow rate, the temperature value increases.

Sekhar et al., [116] performed numerical research on the differences in pressure drop in a multi-tube pass STHE. Additionally, they gained the HT coefficient transfer. The pressure drops for a HEmade of tubes and shells with 1, 2, 4, and 6 tube passes were determined using the "C PROGRAMING" language and subsequently compared with values obtained from the "Bell Manual Method." The study determined that a 4-tube pass configuration is preferable to a 6-tube pass configuration because the former exhibits a lower pressure drop, which falls within the acceptable range.

Nawaz and Sultan [117] conducted an experimental study of a double-pipe HE, comparing convex and concave corrugated-tube designs for heat transmission and pressure drop. The corrugation process involved the utilization of a specialized machine to create ridges on both the exterior and interior of the tubes. The coefficient for convective HT has been identified through the utilization of Wilson plots.

Shinde Digvijay and Dange [118] performed an analysis of exergy on a STHE consisting of a corrugated shell and tube. The primary goal of this research is to provide empirical evidence for how external tube (shell) corrugations affect the rate of HT, the size of the energy loss, and the number of HT units in a STHE. Different configurations of convex and concave corrugated tubes were also examined. The findings indicate that employing a corrugated "tube in a shell and tube HE " leads to a dimensionless exergy loss increase ranging from 4% to 31%. However, when both the "shell and tube" are corrugated, the dimensionless exergy loss experiences a more substantial increase, ranging from 17 to 81 percent.

When comparing the effects of corrugation on a smooth tube versus a smooth shell, it is observed that the Number of Transfer Units increases by approximately 12 - 19 percent when only the tube is corrugated. However, when both the tube and the shell are corrugated, the NTU increases by approximately 34% - 60 percent. Therefore, the HE composed of a corrugated tube and corrugated shell yielded the greatest NTU value.

Date and Khond [119] performed empirical research focused on the HT dynamics within a cone-shaped helical coil HE. The researchers also performed a comparative analysis of HT between a cone-shaped helical coil HE and a conventional helical coil HE. To conduct a comparative analysis, the researchers utilized two kinds of coils. The first coil had an outer diameter of 9.53mm, an inner diameter of 8.41mm, and an axial length of 6096mm. This coil consisted of 7 turns. The second coil, known as a conical coil, also had an outer diameter of 9.53mm and an inner diameter of 8.41mm. However, it had a longer axial length of 6096mm and consisted of 10 turns. The conical coil had a cone angle of 65 degrees. The empirical is performed using various flow rates, and subsequent calculations are executed. According to the study results, the HE with a conical coil shows superior efficiency compared to the HE with a standard spiral coil. Spiral-cone HEs exhibit higher Nusselt numbers than their straight-walled counterparts, indicating improved HT capabilities. This study revealed that a conical spiral coil facilitates faster HT compared to a standard spiral coil. A conical spiral coil facilitates HT 1.18 to 1.38 times greater than a regular spiral coil. Perumal et al. [120] performed a comprehensive review of advanced methodologies aimed at improving the efficiency of HT processes. There are primarily two techniques: active methods and passive methods. The researchers performed analysis and empirical research on various methods, including coiled tubes, swirling flow devices, rough surfaces, and treated surfaces. Research has demonstrated that the HT rate of improved methods surpasses that of a plain tube. The findings obtained from the modelling and empirical analysis indicate that an elevation in turbulence intensity may contribute to the enhanced performance observed in augmentation techniques applied to plain tube HEs. By comparing the HT coefficients of corrugated tubes, dimpled tubes, and wire coils with those of plain tubes, it becomes clear that modified surfaces exhibit higher HT coefficients.

Ghorbani et al., [121] studied mixed convection HT. The study examined a wide variety of configurations, including different ratios of tube and coil diameters and dimensionless coil pitches, as well as different values for the Reynolds and Rayleigh numbers. The main goal of this study was to find out how different factors, such as "tube diameter, coil pitch, shell-side mass flow rate, and tube-side mass flow rate”, affect the performance and overall efficiency of vertical helical coiled tube HEs. The steady-state conditions were estimated, and subsequent empirical studies of turbulent and laminar flow phenomena within the coil were conducted. Researchers found that the HEs axial temperature profiles were significantly affected by the mass flow rate's distribution between the shell and tube sides [122]. Table 2.1 presents a concise summary of the literature review, highlighting key findings and insights gathered from various studies.

Table 2.1: Summary of Literature Review.

No	Authors	Kind of Research	Finding
1	Boomsma et al., [109]	Empirically	At a coolant velocity of 1.4 m/s, the compressed open-cell aluminum foam HEs produced thermal resistance that was 2-3 times lower than the optimum
2	Sahiti et al, [110]	Empirically	Considerable enhancements were demonstrated in the work by using small cylindrical pins on HE surfaces.
3	Wang et al., [111]	Empirically	Enhance both the HT coefficient and the overall HT coefficient.
4	Chinaruk et al., [124]	Empirically	At Re =12000 – 24000, detected that the HT coefficient transfer and factor of friction in the blended devices increases as the twist proportion (y/w) and pitch proportion (PR) reduce.
5	Qasim et al, [112]	Empirically	At the condition [Re=5000-40000, m=0.1-0.15 kg/s, Thi=60-70°C, Tci= 20°C]. Improvement by wire coils is greatly effective at low Reynolds number magnitudes than great magnitudes, Re = 5000 –40000.
6	Vijay et al, [114]	Numerically	At [Thi=100°C, Tci=30°C] the distribution of temperature and HT rate was better in the corrugated twisted tubes than in normal tubes in HEs.
7	Shweta et al., [125]	Numerically	At [Re = 200-400, ṁ=0.01-0.04 kg/s] the HT specified by Bell and Kern techniques is lower than the Bell Delaware technique
8	Resat et al., [126]	Numerically	Genetic algorithms (GA) were effectively applied for the optimum HE design.
9	Tyagi and Kumar [116]	Numerically	At the condition [Re = 1000-1500, Tin = 313 k, ṁ=0.320 kg/s]. Once the fin thickness increase, the temperature of the cold fluid at the external of the HE increases.

Table 2.1: Summary of Literature Review "Table Continued".

10	B. Chandra et al., [117]	Numerically	At the situation, [Q oil= 43.33 m3/hr, Q water = 200 m3/hr. Tiw= 32°c]. The analysis suggests that a 4-tube pass configuration is more favorable compared to a 6-tube pass configuration since the estimated pressure drop for the former is lower than its permissible pressure drop.

3. NUMARICAL ANALYSIS

3.1 INTRODUCTION

This chapter of the thesis presents a detailed numerical analysis of a STHEs, focusing on a significant modification: the addition of a helical coil to its outer shell. The study employs ANSYS, a well-known software for computational analysis, to thoroughly examine the HEs thermal performance and efficiency. The application of ANSYS in this research enables a precise investigation of how HTs within the system, examining the temperature distribution, fluid flow patterns, and overall HT rates. This chapter details the process of creating the heat exchanger's geometry, setting up the mesh for simulation, and establishing the required boundary conditions. It also describes the approach for formulating the necessary equations and extracting analytical results. The aim of this numerical analysis is to provide insightful understanding into the HT mechanisms in the HE, especially with the integration of the helical coil. This section is essential in showcasing the effective use of computational simulations to predict and enhance the performance of HE designs.

3.2 VALIDATION 1

The validation process in this research plays a crucial role in establishing the accuracy and trustworthiness of the computational simulations conducted using ANSYS. This section rigorously compares the model's predictions against empirical or real-world data, focusing on the alignment of simulated flow patterns with expected physical behaviours. In the context of this heat exchanger study, the validation of ANSYS streamline results for Case 1 (standard configuration) is essential. It involves ensuring that the simulated fluid dynamics within the heat exchanger are consistent with established physical principles. This validation is not just a procedural step but a cornerstone in confirming the fidelity of the numerical model, making sure it accurately reflects the HEs performance. Effective validation is critical in bolstering confidence in the simulation outcomes. It provides a solid foundation for making informed design decisions and drawing reliable conclusions. As a fundamental aspect of the study's methodology, validation strengthens the overall credibility of the insights obtained from the ANSYS analyses. The juxtaposition of validation results from the previous study and this current research, as illustrated in Table 3.1, offers a comprehensive assessment of the computational model's accuracy. The alignment in parameters such as B (m), A_s (m^2), Reo, and thermal characteristics (h_o, U_c, U_f between the studies underscores the success of the validation process. The slight variations in parameters like h_o, U_c, and U_f, falling within acceptable ranges, further attest to the reliability of the ANSYS simulations in this study. These results collectively validate that the numerical model accurately represents the physical behavior of the HE system and confirms the appropriateness of the simulated streamlines and heat flux patterns, enhancing the reliability and applicability of the findings derived from the ANSYS analyses.

Table 3.1: Validation Results between the Previous Study [125] and the Current Study

	Previous Study				Current study
Parameter	Design A	Design B	Design C	Design D	
$B(m)$	382×10^{-3}	427×10^{-3}	472×10^{-3}	517×10^{-3}	382×10^{-3}
$A_s(m^2)$	70.04×10^{-3}	78.29×10^{-3}	86.54×10^{-3}	94.79×10^{-3}	70.04×10^{-3}
Re_o	28851.07	25810.82	23350.24	21317.96	28851.07
$h_o(W/m^2K)$	1183.96	1113.63	1053.92	1002.44	1190
$U_c(W/m^2K)$	471.64	460.06	449.54	439.90	470
$U_f(W/m^2K)$	386.08	378.28	371.14	364.55	405

In this chapter, a comprehensive 3D model of the heat exchanger was developed.

3.3 VALIDATION 2

Validation plays a crucial role in this study. Validation 2 work was to ensure that the ANSYS works within a good range and that the results obtained are reasonably close to experimental reality. Reference [125] is relied upon to take dimensions and conditions. The limit, as shown in Figure 3.1, is the model for which the simulation is performed. In Figure 3.2, the results were obtained from the ANSYS software for Temperature Distribution contour for previous and current study respectively, with an error rate not exceeding 10% in comparison with the previous researcher.

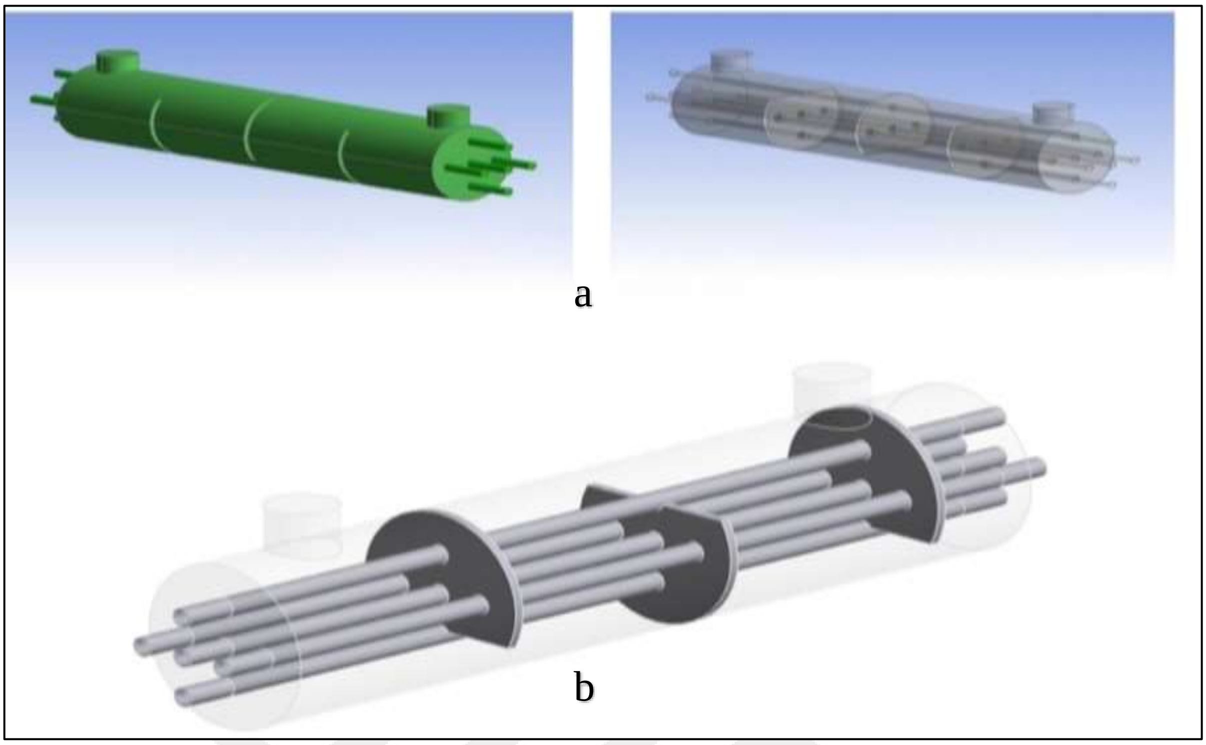
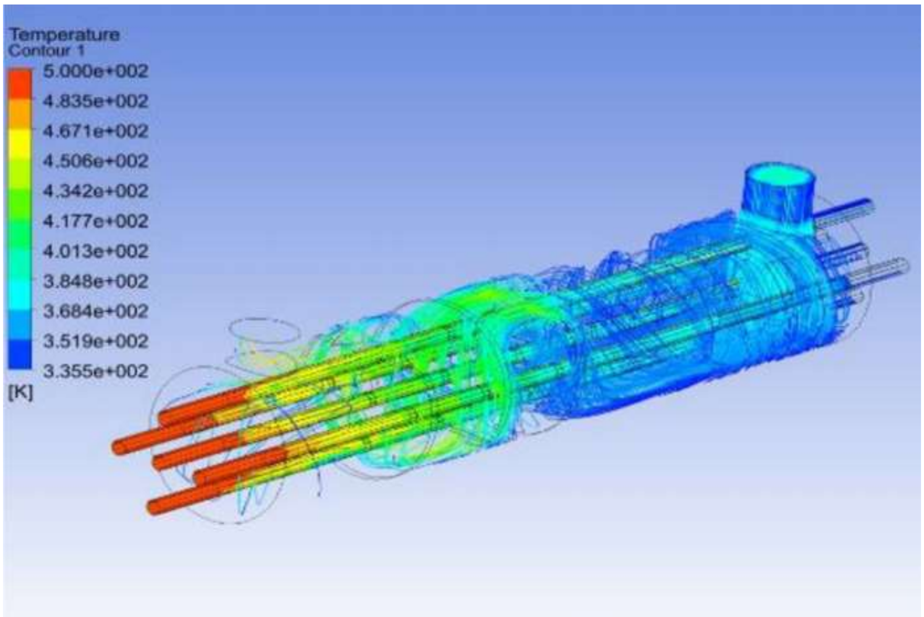
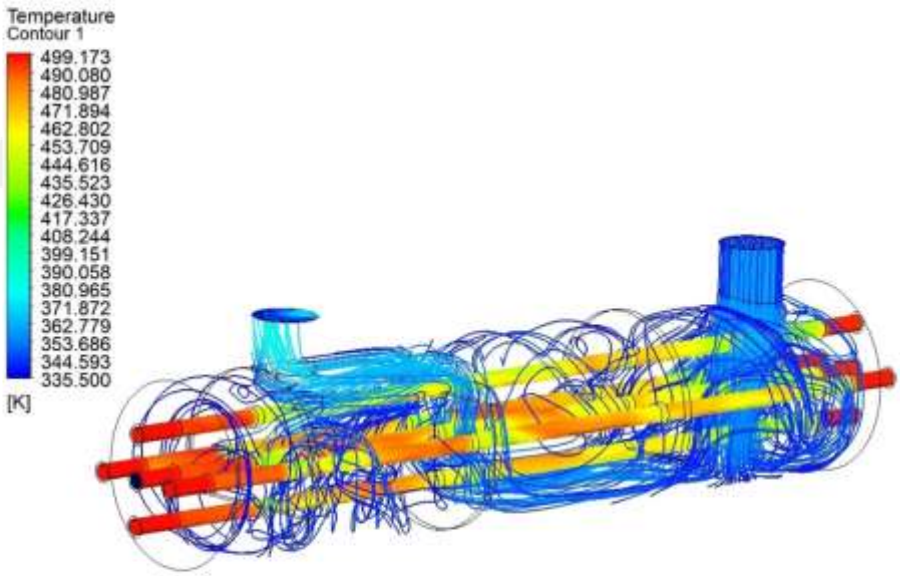


Figure 3.1: (a): Geometry of Previous Study, (B): Geometry Of Validation Current Study [124].



(a)



(b)

Figure 3.2: (a): Temperature Distribution Contour for Previous Research [124], (B): Temperature Distribution Contour for Current Study.

3.3.1 Physical Model

A detailed and comprehensive 3D model of the HE was meticulously developed to facilitate the numerical simulations conducted in the ANSYS program. The physical model encompasses two distinct cases, each meticulously crafted to represent specific configurations within the heat exchanger system.

3.3.1.1 Case 1: shell and tube HE (Reference Case)

The first case serves as the reference model, embodying a traditional STHE. This widely recognized configuration forms the baseline for comparison. Figures 3.3 and 3.4 provide a visual representation of this reference case. The model is designed to accurately capture the structural and geometric intricacies inherent in standard STHEs.

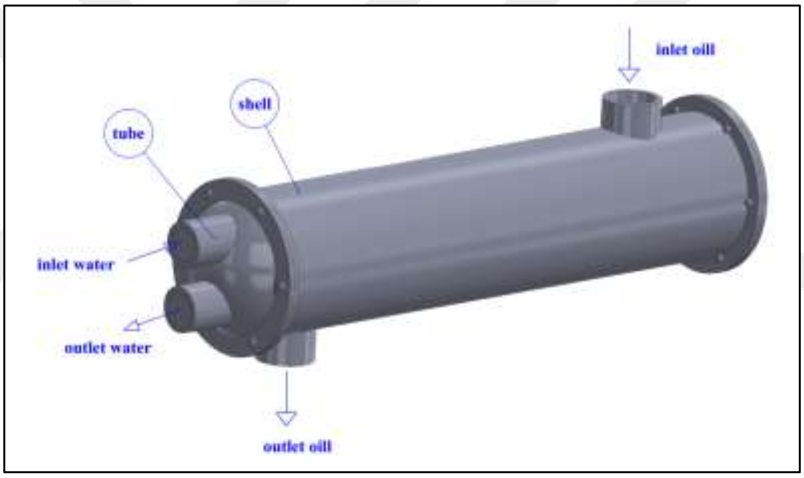


Figure 3.3: Geometric Model of Shell for Case 1.

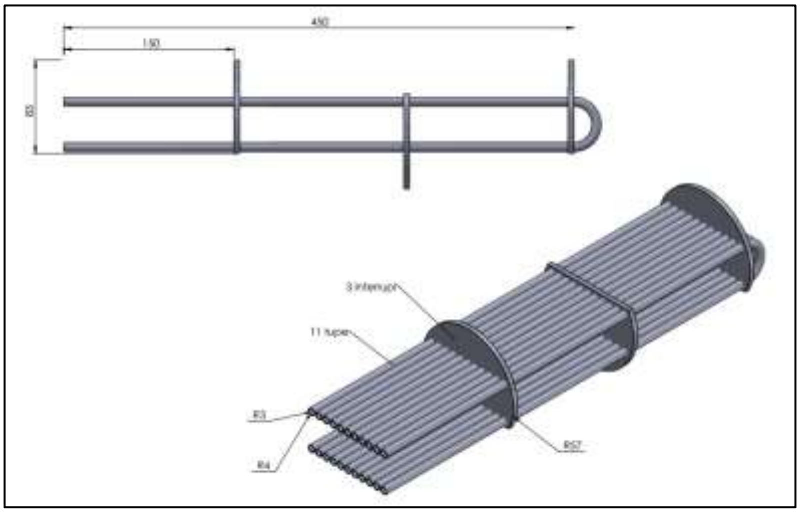


Figure 3.4: Geometric Model of Tubes for Case 1.

3.3.1.2 Case 2: Helical Pipe Exchanger Integrated into shell and tube HE.

The second case introduces a novel modification, incorporating a helical pipe exchanger onto the outer shell of the traditional STHE. Figure 3.5 illustrates this innovative design, showcasing the helical coil seamlessly integrated into the system. This modification aims to enhance heat transfer efficiency by optimizing fluid dynamics and increasing the available surface area for HEs.

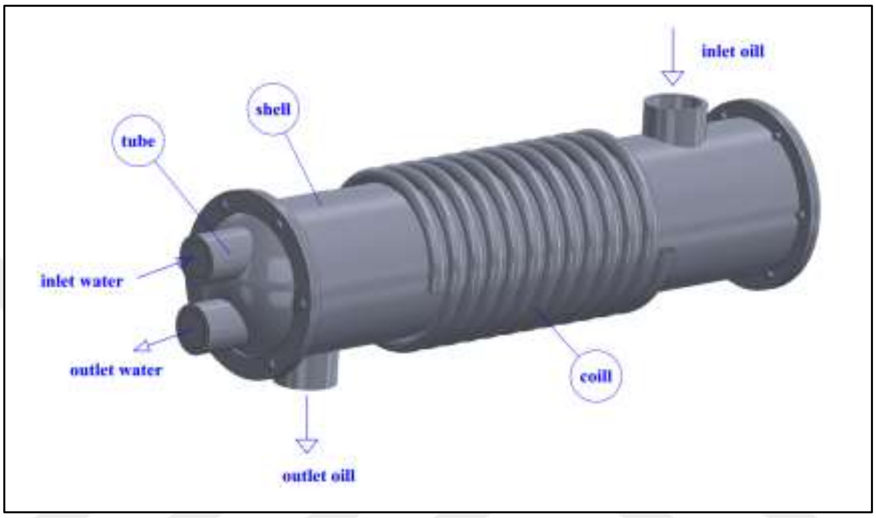


Figure 3.5: Geometric Model for Case 2.

To give a deeper comprehension of the geometric model, Figure 3.6 presents a cross-sectional view. This view encapsulates the intricate details of the modified HE, illustrating the spatial relationship between the helical coil and the conventional shell-and-tube components.

The physical model serves as the foundation for the subsequent numerical simulations conducted in the ANSYS program. Through these simulations, the research endeavours to quantify and analyse the thermal performance and fluid dynamics of both the reference and modified heat exchanger configurations. The intricate details embedded in the physical model are crucial for accurately capturing the complex interactions and variations in HT characteristics.

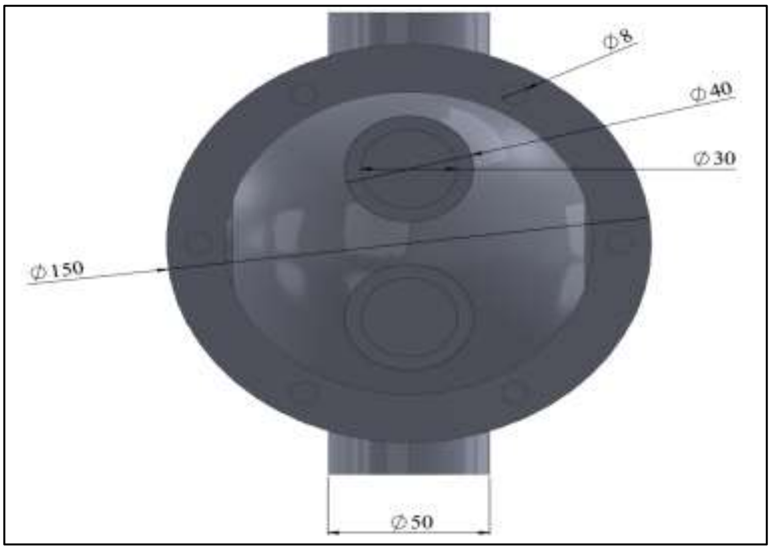


Figure 3.6: Sectional View for Geometric Model.

Figure 3.7 displays a sectional view of the geometric model for the tube.

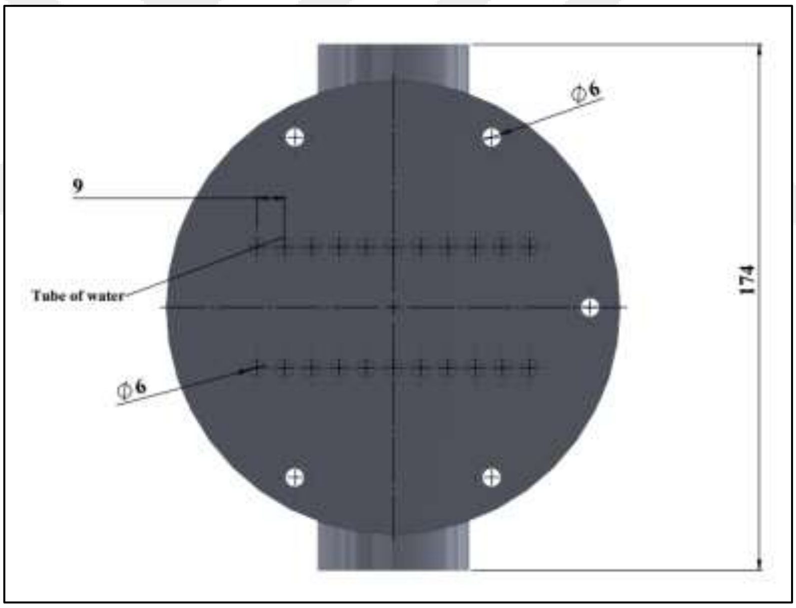


Figure 3.7: Sectional View for Geometric Model for the Tube.

Figure 3.8 displays a second sectional view of the geometric model, and Figure 3.9 provides a cross-sectional perspective of the geometric mode.

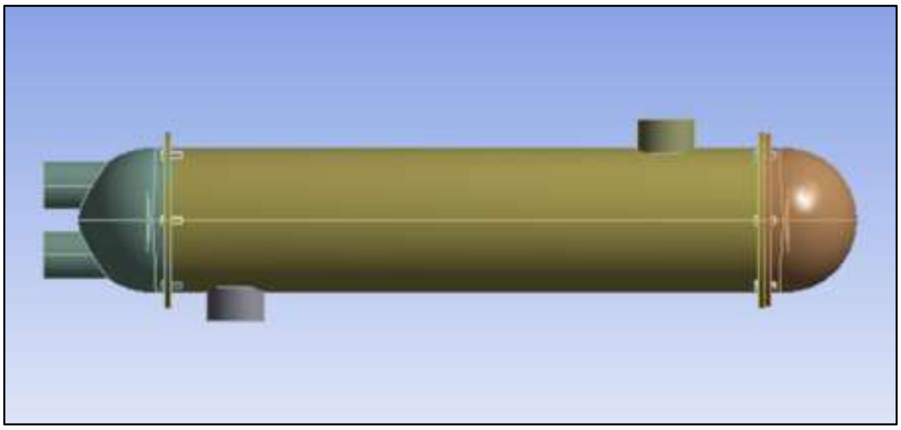


Figure 3.8: Second Sectional View for Geometric Model.

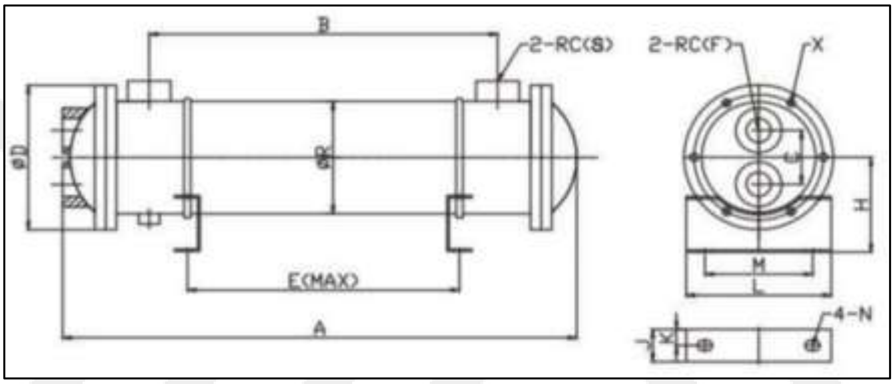


Figure 3.9: A Cross Sectional View for Geometric Model.

Table 3.2 displays the characteristics of the shell's geometry.

Table 3.2: Shell Geometry.

A (mm)	B (mm)	C (mm)	R (mm)	D (mm)	E (mm)	H (mm)
555	390	60	114	150	280	104

The considered HE consists of: The shell is made of carbon steel. Copper tubes, 11 letters U, 22 slots Another sectional view for a geometric model of the tube is shown in Figure 3.10.

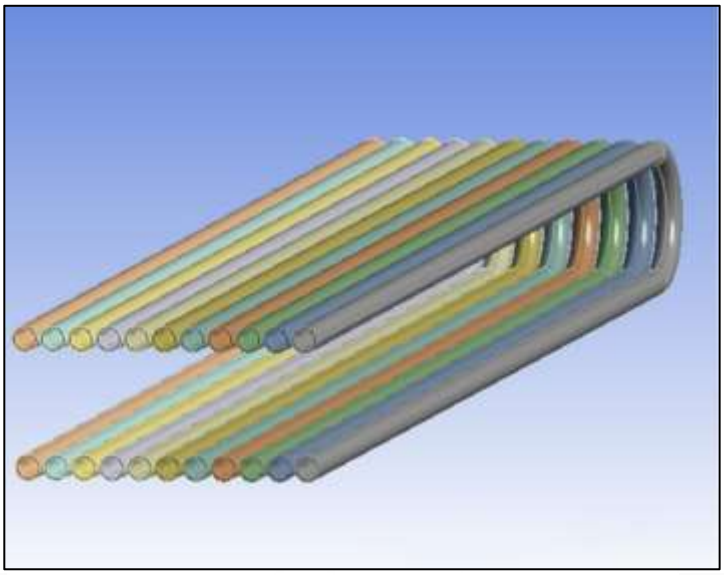


Figure 3.2: Sectional View for A Geometric Model of the Tube.

Oil and water are pumped in the same quantities into the exchanger. The oil is pumped into the shell, while the water is pumped into the copper tubes. The second case is based on the installation of a spiral tube of circular cross-section around the outer shell of the HE. Water flows through this tube, which enters the HE tubes. In this case, a helical coil is added, which is a tube connected to the same tube feeding the water covering the surface area of the crust, to increase the HE efficiency and benefit from the surface area at the lowest cost. Table 3.3 presents the specifications for the geometry of the helical coil.

Table 3.3: Helical Coil Geometry.

Geometrical	Specification
Number of turns	12
Spacing between consecutive coil turns	3 cm
Outer diameter of tube	1.5 cm
Inner diameter of tube	1.2 cm
Diameter of helix (coil)	12.2 cm
Height of coil	40 cm
Diameter of shell	220 cm
Height of shell	52 cm

In general, the surface area greatly affects the amount of heat transferred in the HE, in other words, increasing the surface area increases the performance of the HE. The surface of the heat exchanger is a large area, and it exposed to the atmosphere, so this is in turn represents part of the heat loss for any exchanger. Adding a spiral tube coil on the outer shell of the outer surface of the exchanger helps greatly in reducing the heat exchangers heat loss in the atmosphere, and thus increasing the performance of the exchanger thermal. Figure 3.11 illustrates the model and dimensions of the helical coil.

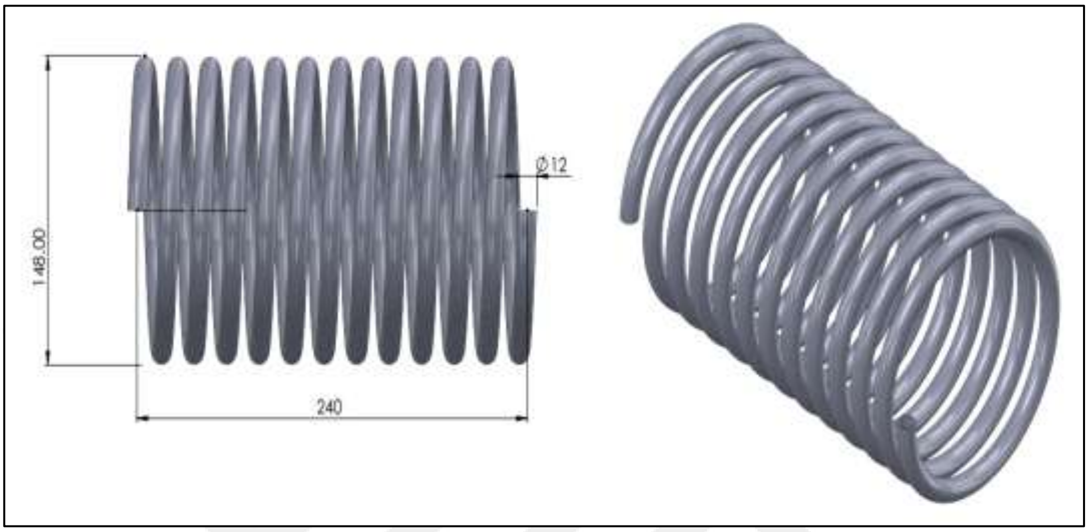


Figure 3.3: Model and Dimensions of the Helical Coil.

3.4 MESH GENERATION

The geometry is designed for the two cases of the exchanger studied, and the networking is done by a program ANSYS FLUENT program The type of network is determined in these models in the form of a tetrahedral network, and it consists of triangle elements. Figure 3.12 illustrates the process of generating a mesh in the exchanger for case 1.

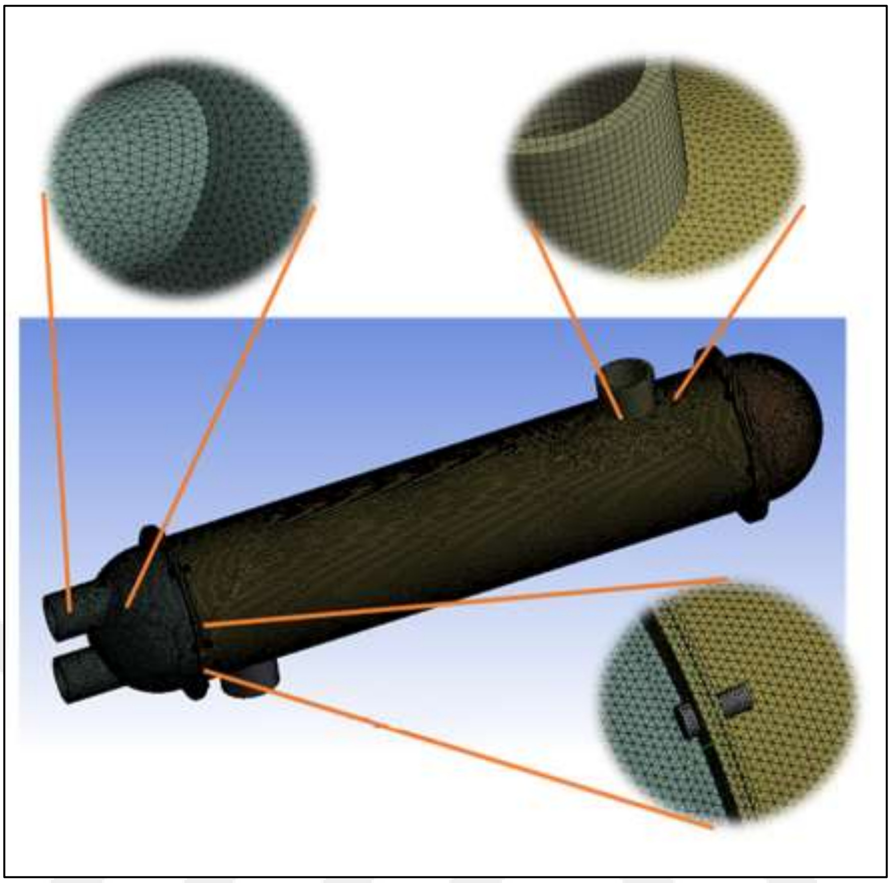


Figure 3.4: Mesh Generation in the Exchanger, Case 1.

Table 3.4 presents the mesh information for the exchanger in Example 1.

Table 3.4: Mesh Information for the Exchanger, Case 1.

Nodes	2692160
Elements	1723782

Table 3.5 presents the mesh information for case 2 of the exchanger with the helical coil.

Table 3.5: Mesh Information for the Exchanger with the Helical Coil, Case 2.

Nodes	3219174
Elements	1987101

Figure 3.13 illustrates the generation of a mesh in the exchanger with a helical coil, specifically in Example 2.

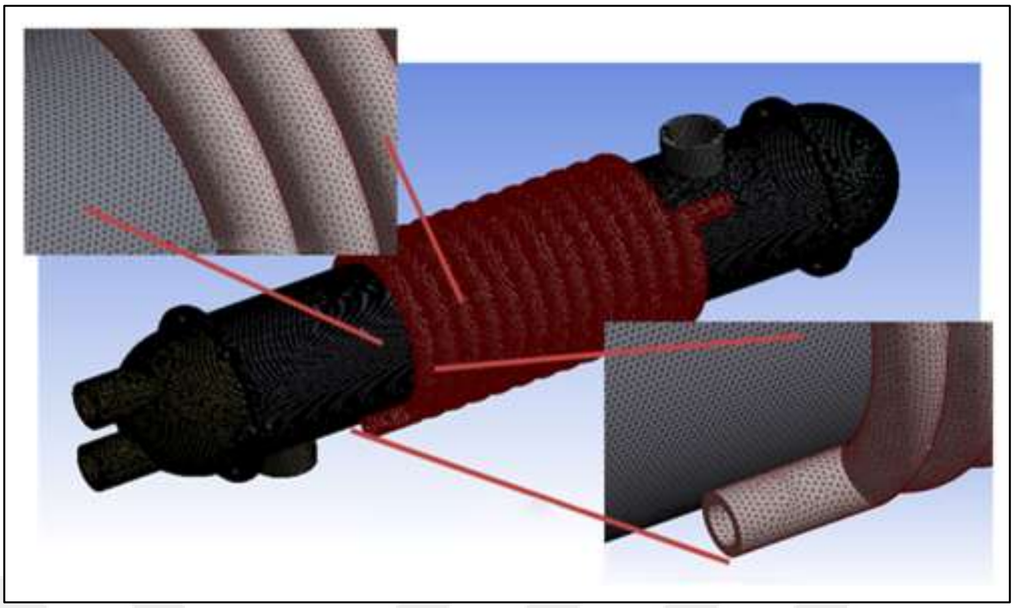


Figure 3.5: Mesh Generation in the Exchanger with Helical Coil, Case 2.

Figure 3.14 illustrates the mesh of the tubes for both instance 1 and case 2.

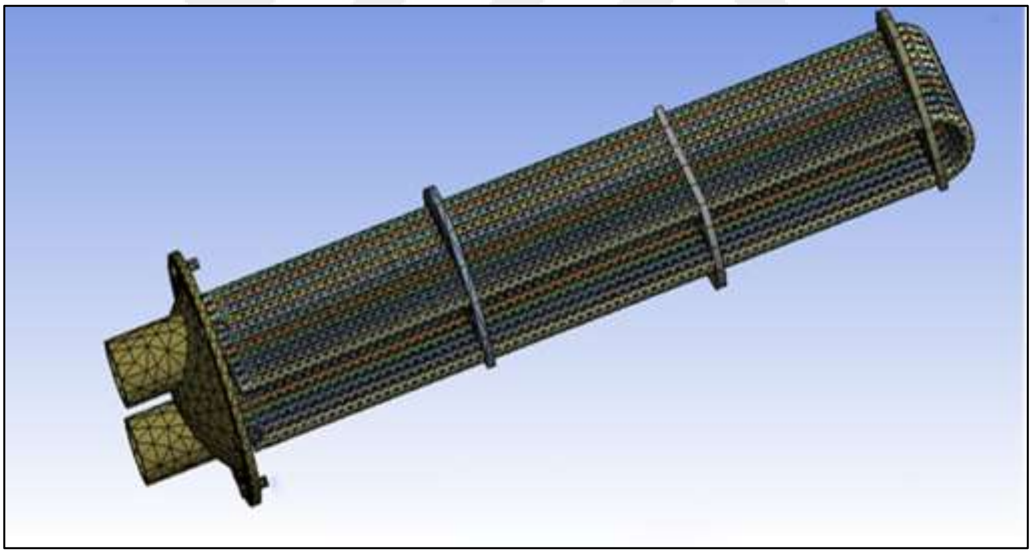


Figure 3.6: Mesh Generation in the Tube, Case 1 & Case 2.

Figure 3.15 displays a cross-sectional view of the mesh grid used for the tubes and the shell. In

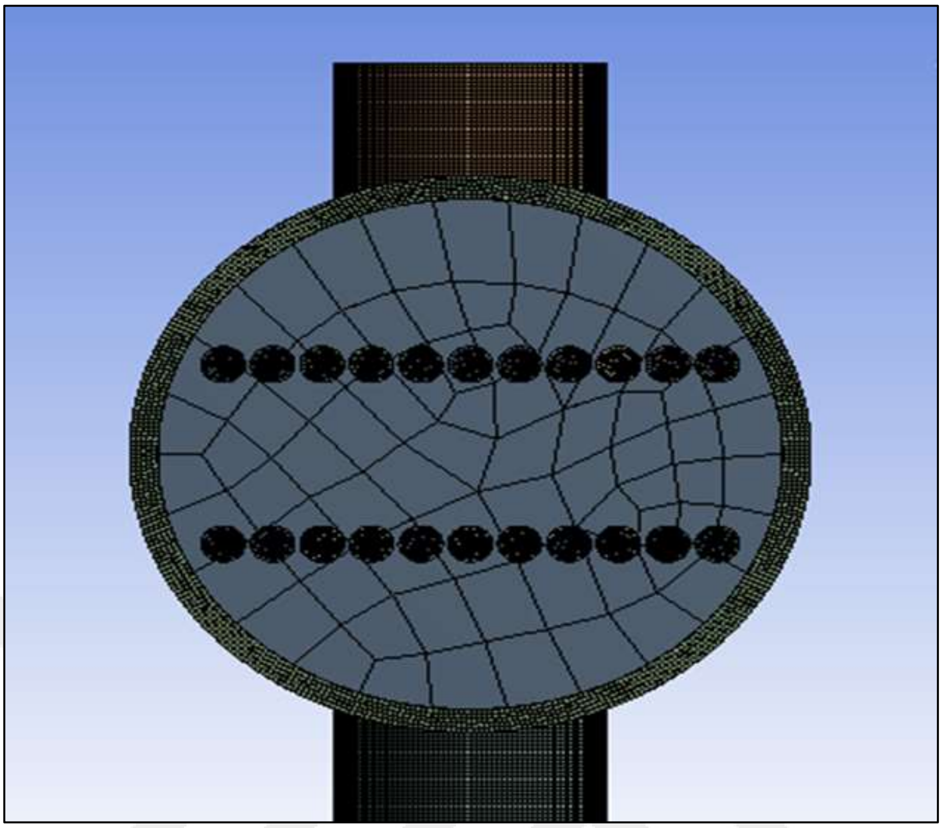


Figure 3.7: Cross-Sectional View on the Mesh Grid for the Tubes and the Shell.

In Figure 3.16, a cross-sectional view of the mesh grid for the tubes is depicted.

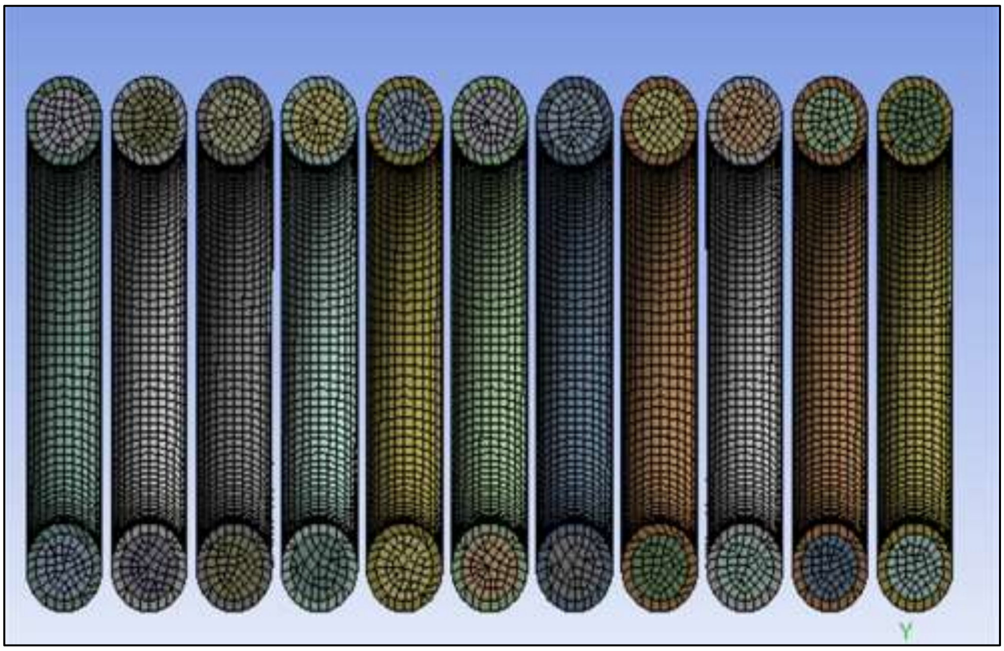


Figure 3.8: Cross-Sectional View on the Mesh Grid for the Tubes.

A cross-sectional view of the mesh grid used for the body and tubes is shown in Figure 3.17.

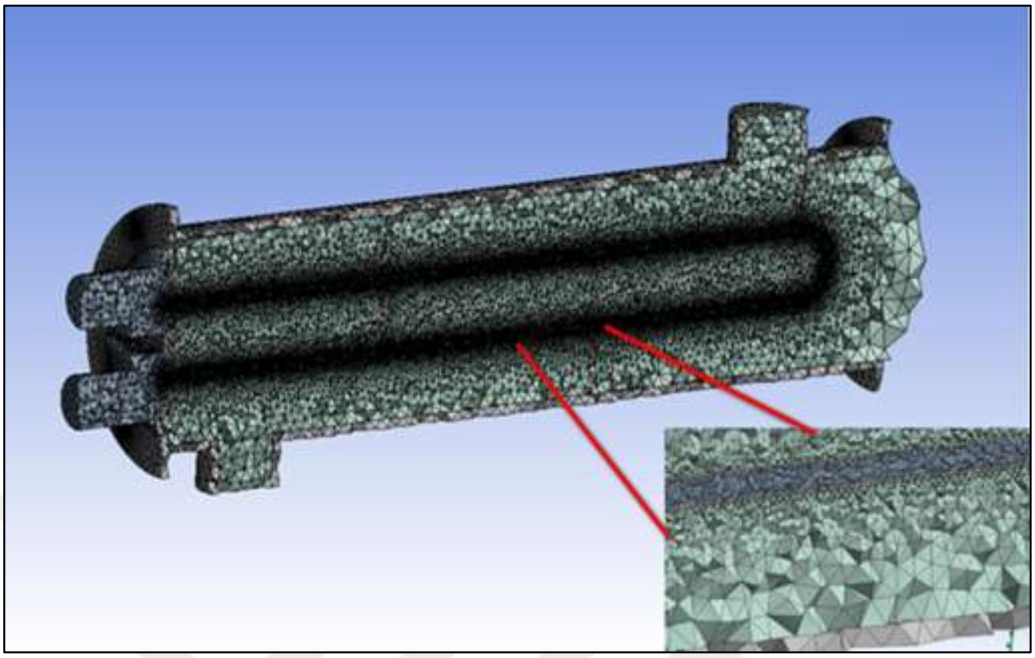


Figure 3.9: Cross-Sectional View on the Mesh Grid for the Body and Tubes.

3.5 HEAT TRANSFER COEFFICIENT

Calculation of, Reynolds, Prandtl and Nusselt numbers are as follows [46]:

$$Re = \frac{uD}{\nu} \tag{3.1}$$

Where u is Velocity of the fluid, D *is* Characteristic dimension or diameter and, ν is Kinematic viscosity of the fluid. The Reynolds number is a dimensionless quantity that helps predict flow patterns in different fluid flow situations. It is used to characterize the type of flow, whether it be laminar or turbulent.

$$\mathrm{p_r} = \frac{\mathrm{v}}{\alpha} \tag{3.2}$$

Where ν is Kinematic viscosity of the fluid, and α is Thermal diffusivity of the fluid. The Prandtl number is a dimensionless number that signifies the ratio of momentum diffusivity (kinematic viscosity) to thermal diffusivity. It indicates the relative thickness of the momentum layer to the thermal layer in fluid flow and is crucial in heat transfer analysis.

$$Nu = \frac{h_c\, l}{k} \tag{3.3}$$

Where h_c is Convective HT coefficient, l Characteristic length, and K is Thermal conductivity of the fluid. The Nusselt number is a dimensionless number that provides a measure of the convective HT occurring at a surface, relative to the conductive HT through the fluid. It is essential for calculating the rate of HT in convective systems.

Table 3.6 presents the boundary conditions employed in the simulation for both cases.

Table 3.6: The Boundary Conditions Used During the Simulation for the Two Cases.

Type	Boundary Condition
Shell inlet temperature for oil	80 ^{0}C
Tube inlet temperature for water	38 ^{0}C
Mass flow rate	2 – 3.5 kg/s

Table 3.7 displays the thermal and optical parameters of the heat exchanger material.

Table 3.7: Thermal Properties of HE Material.

Material	K (W/m K)	C (J/kg K)	ρ (kg/m^3)	Emissivity
Copper	400	385	8700	0.05

Table 3.8 presents the characteristics of the oil.

Table 3.8: The Properties of the Oil and Water.

The metal	ρ (kg/m^3)	Cp (kJ/kg K)	k (W/m K)
The oil	400	385	8700
The water	997	2260	0.608

3.6 THE ITERATION AND CONVERGENCE

The observation residuals for each variable are stable which indicates a true operation of the steady state problem as shown in Figures 3.18, 3.19 respectively.

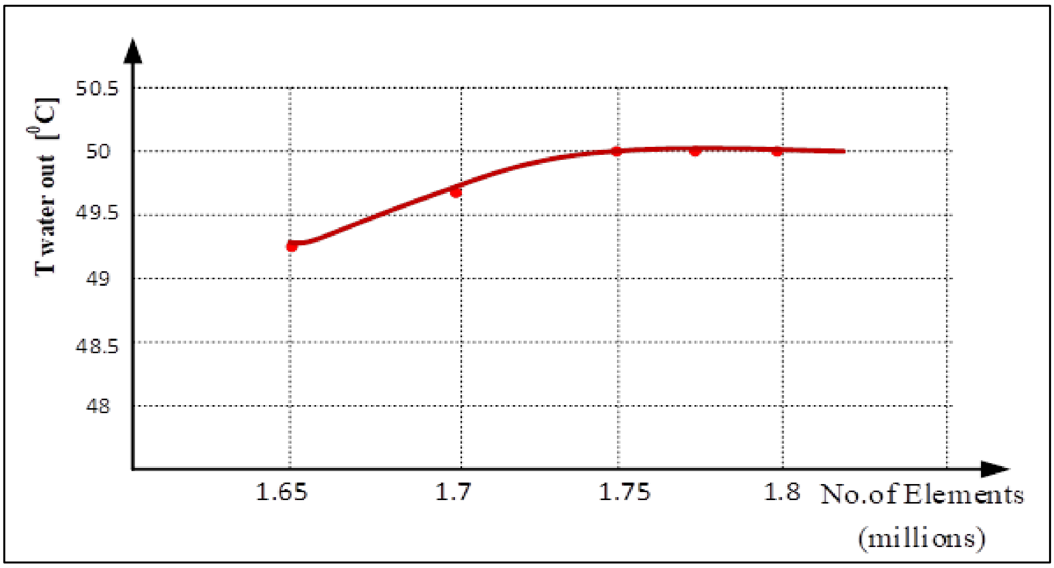


Figure 3.10: Grid Independence Test for Exchanger Model Case 1.

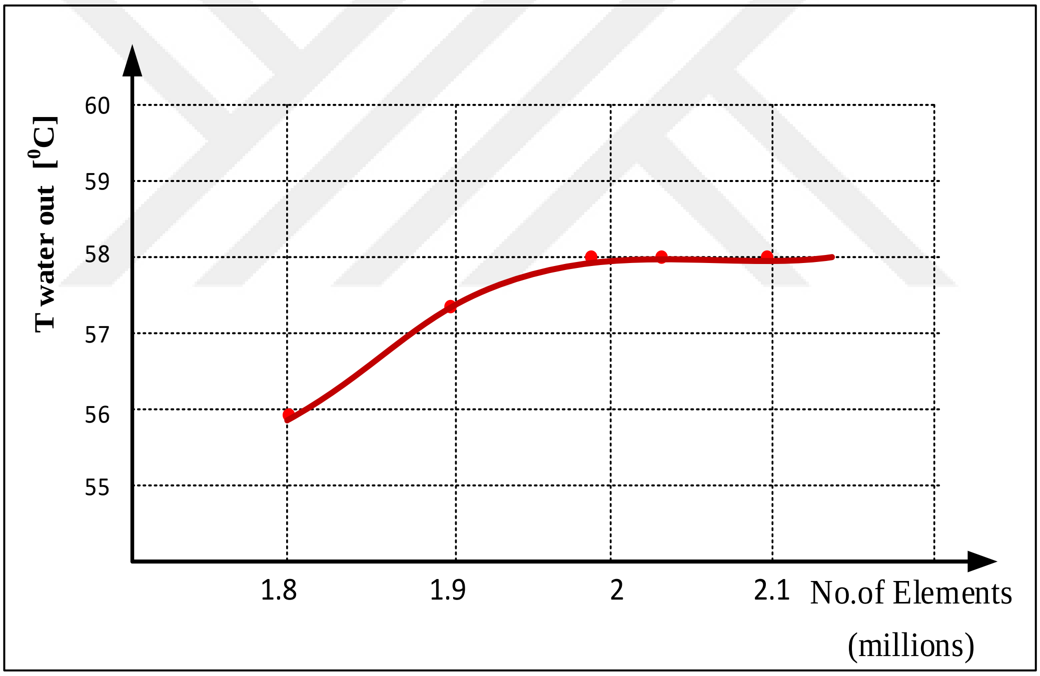


Figure 3.19: Grid Independence Test for Exchanger Model Case 2.

The number of elements represents the total number of discrete elements that make up the computational mesh in the simulation. This line is crucial, as it indicates the level of detail or fineness of the mesh used in the numerical analysis. A finer mesh, with a higher number of elements, generally provides more detailed and accurate results. However, there is a point where increasing the number of elements further does not significantly change the simulation results. This point of stability, where further refinement of the mesh does not lead to substantial changes in results, is essential for ensuring that the simulation is both accurate and computationally efficient. The horizontal line of the number of elements in the graph shows how the results of the simulation stabilize or converge as the mesh becomes finer. This is a key aspect of validation, indicating that the model's predictions are reliable and not unduly influenced by the mesh size.

3.7 STHE CAD MODEL

The 3D geometric model of a STHE is depicted in Figures 3.20 and 3.21

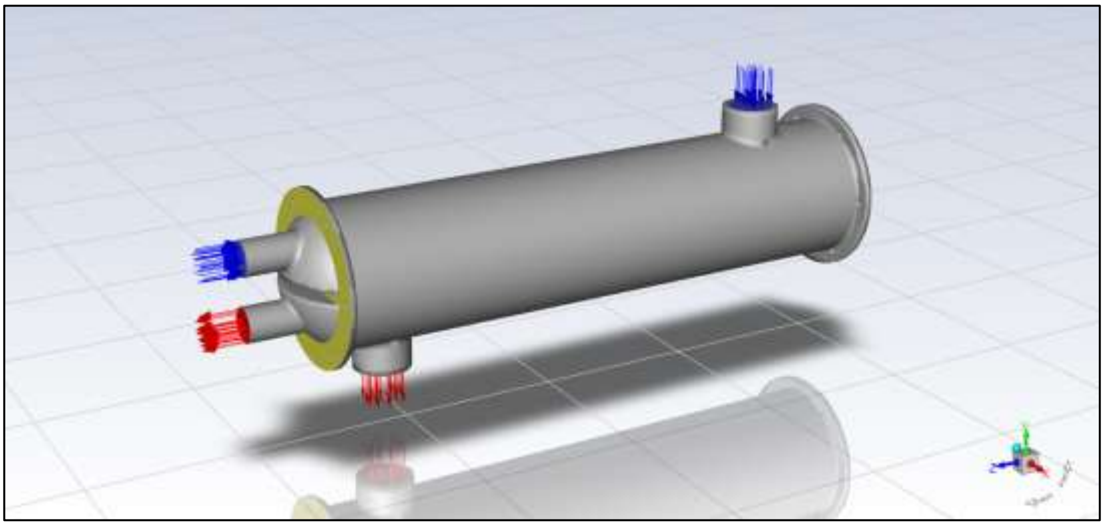


Figure 3.11: 3D Geometric Model and Boundary Condition of the First Case.

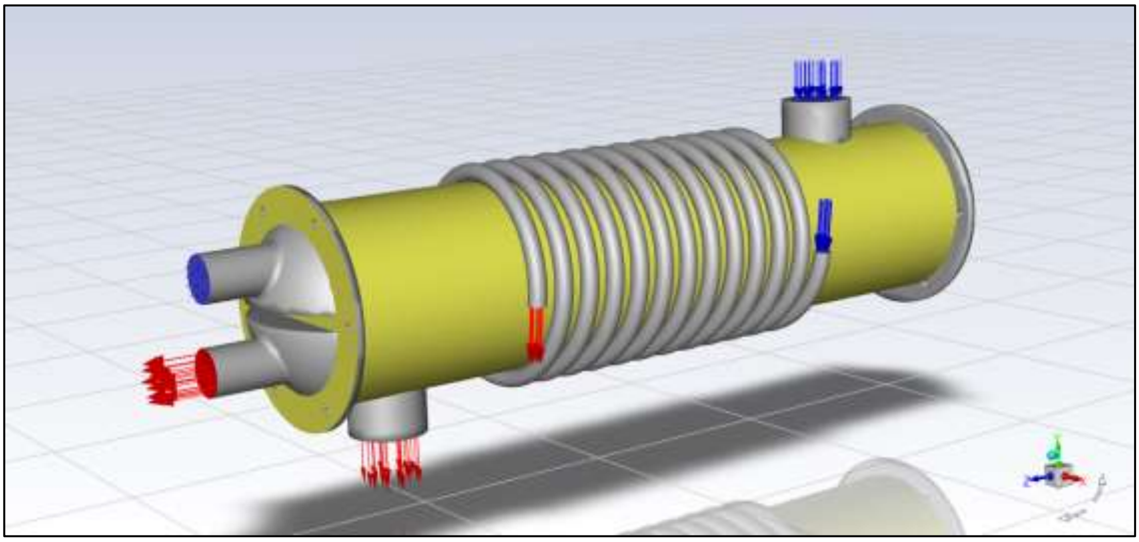


Figure 3.12: 3D Geometric Model and Boundary Condition of the Second Case.

4. RESULT AND DISCUSSIONS

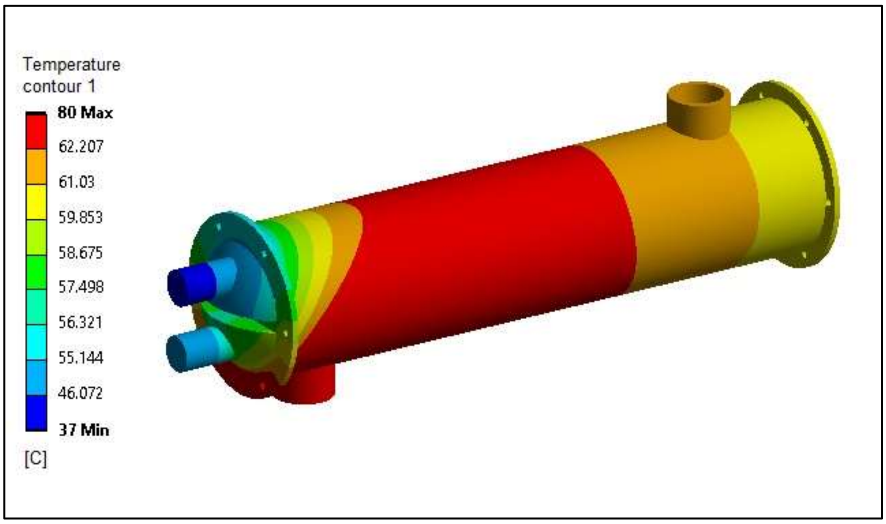
4.1 INTRODUCTION

In this chapter, the focus is on summarizing and analyzing the results from the numerical simulations of the HE conducted using ANSYS software. The chapter aims to evaluate how the heat exchange between the different layers of the exchanger and the fluids that pass through it changes with variations in the flow rates of water and oil. Additionally, it examines the impact of adding a spiral coil to the exchanger's outer surface on its thermal performance. The chapter provides a comparative analysis between two studied cases: the standard configuration and the modified configuration with the helical coil, highlighting the enhancements or changes in thermal efficiency due to this modification.

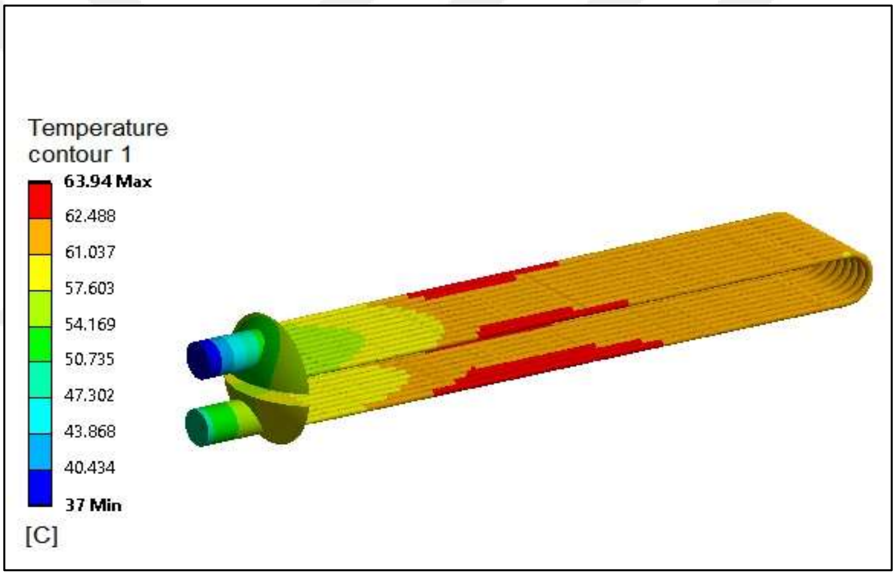
4.2 NUMERICAL RESULTS

4.2.1 Temperature Distribution on the Front Surface of the Heat Exchanger

The numerical study of the engineering model was conducted using four flow values of oil and water (2, 2.5, 3, and 3.5 kg/s) and two case studies of the exchanger. The temperature of the water inlet was 38 °C, and the temperature of the oil inlet was 80 °C Figures 4.1 depict the TD across the HEs tubes and surface (in the two cases, the water and oil mass flow rate were 2.0 kg/s).



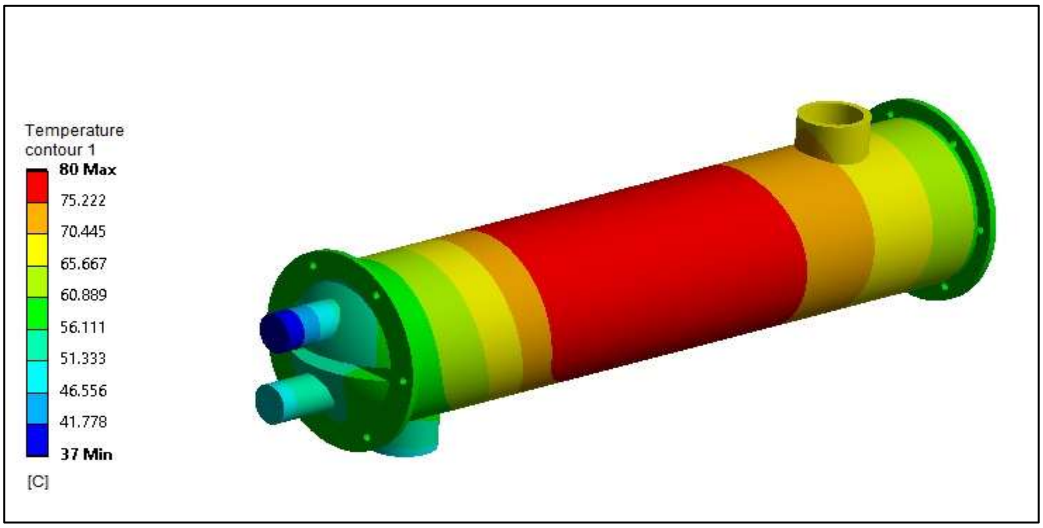
(a)



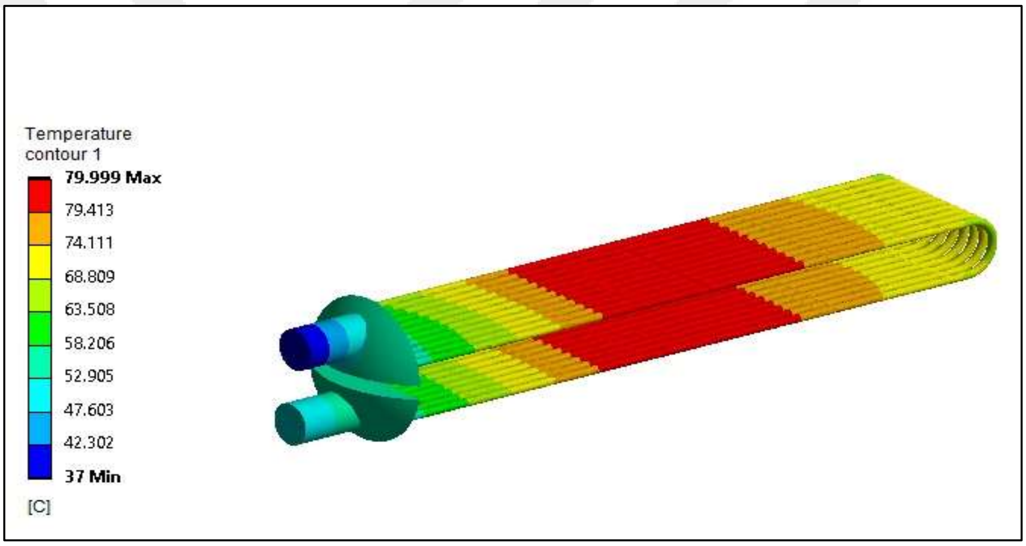
(b)

Figure 4.1: Average TD on (a) the Shell And (B) The Tubes, Case 1 (at 2 kg/s).

For the first case, which is the STHE, the mass flow rate was 2 kg/s and the temperature of the water outlet was 48 °C, while the temperature of the oil outlet was 67 °C. Figures 4.2 show the TD on the surface of the HE and tubes (in the two cases, the water and oil mass flow rate was 2.5 kg/s).



(a)

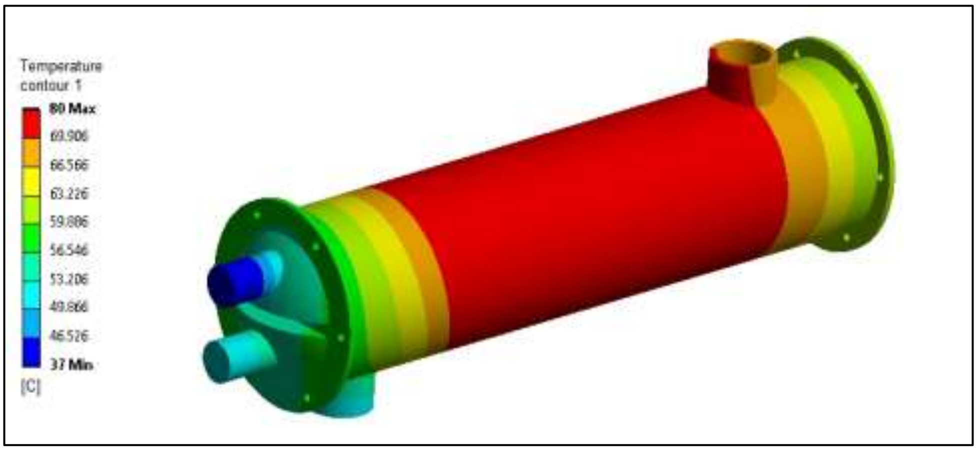


(b)

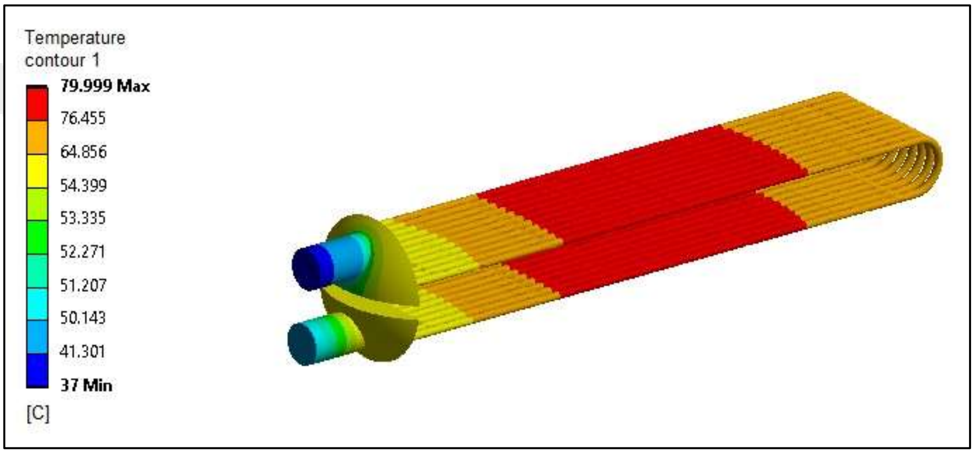
Figure 4.2: Average TD on (a) The Shell And (B) The Tubes, Case 1 (at 2.5 kg/s).

For the first case, which is the STHE the mass flow rate was 2.5 kg/s and the temperature of the water outlet was 50 °C, while the temperature of the oil outlet was 65 °C.

Figures 4.3 show the TD on the surface of the HE and tubes (in the two cases, the water and oil mass flow rate was 3 kg/s).



(a)

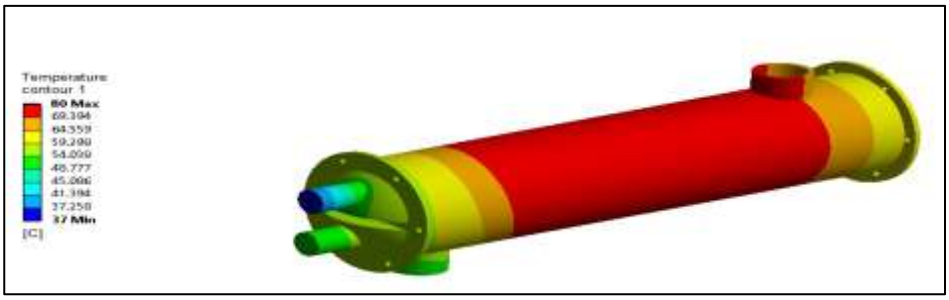


(b)

Figure 4.3: Average TD on (a) The Shell And (B) The Tubes, Case 1 (at 3 kg/s).

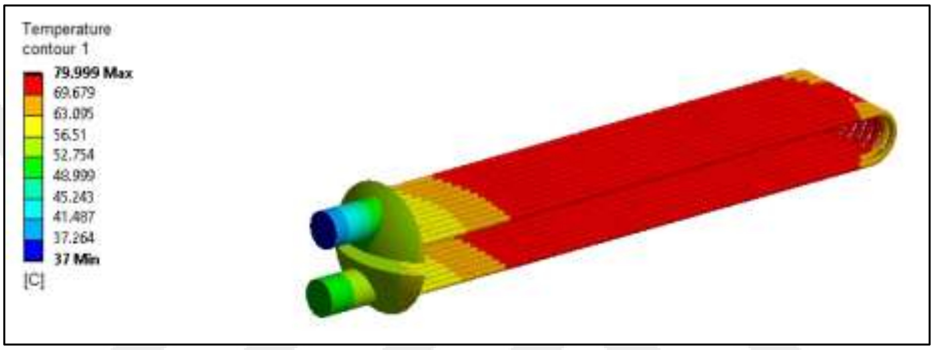
For the first case, which is the STHT, the mass flow rate was 3 kg/s, and the temperature of the water outlet was 52 °C, while the temperature of the oil outlet was 64 °C.

Figures 4.4 show the TD on the surface of the HT and tubes (in the two cases, the water and oil mass flow rate were 3.5 kg/s).



(a)

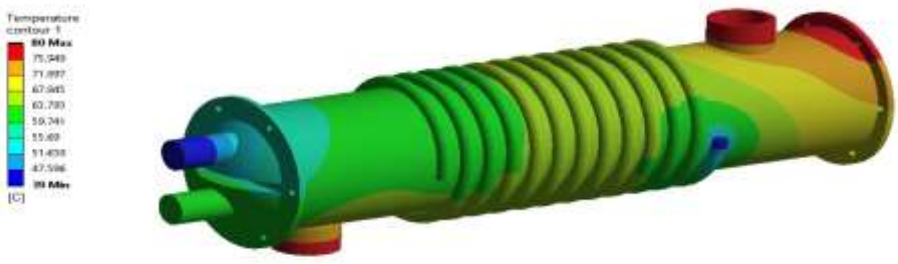
Figure 4.4: Average TD On (A) The Shell And (B) The Tubes, Case 1 (at 3.5 kg/s).



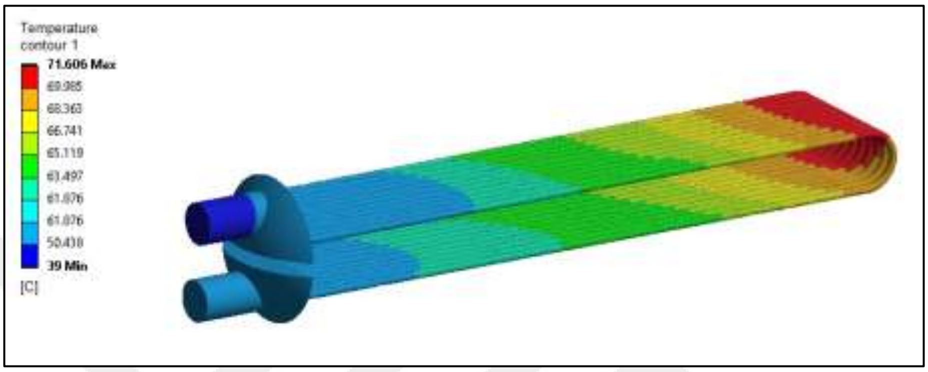
(b)

Figure 4.5: Average TD On (A) The Shell And (B) The Tubes, Case 1 (at 3.5 kg/s).

For the first case, which is the STHE, the mass flow rate was 3.5 kg/s, and the temperature of the water outlet was 53 °C, while the temperature of the oil outlet was 65 °C. Figures 4.5 show the TD on the surface of the HE and tubes (in the two cases, the water and oil mass flow rate was 2.0 kg/s).



(a)

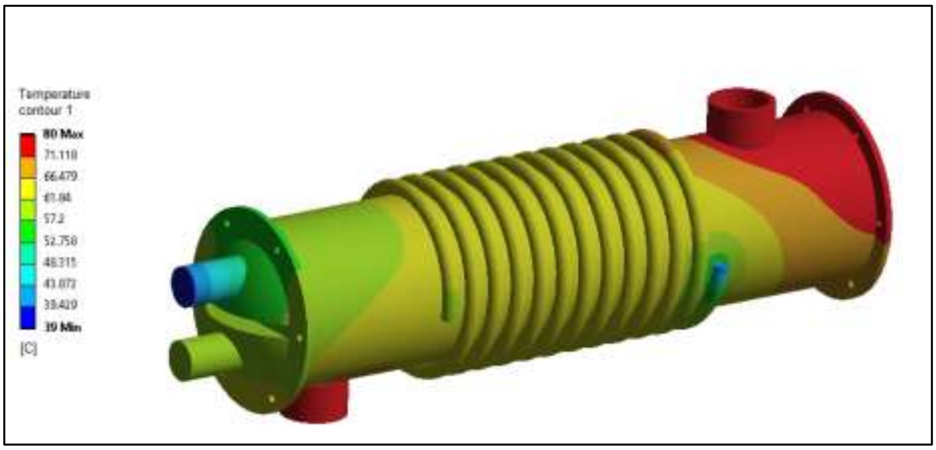


(b)

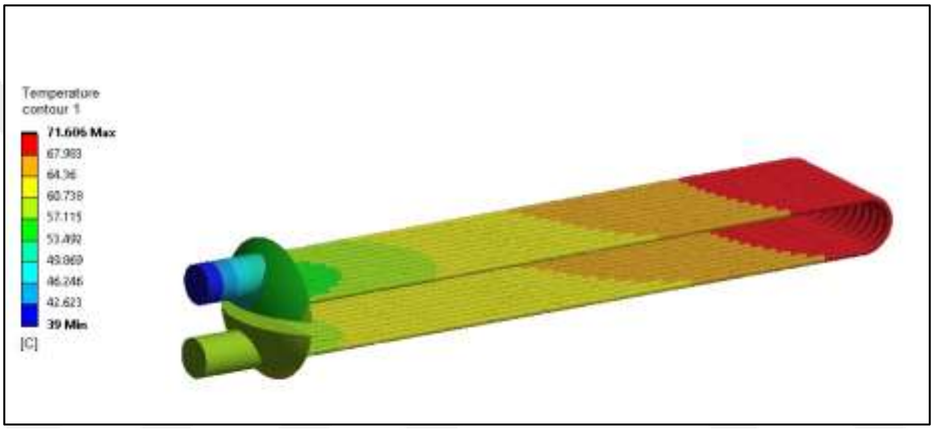
Figure 4.6: Average TD on (a) The Shell And (B) The Tubes, Case 2 (at 2 kg/s).

For the second case, which is the exchanger with the helical coil, it was 53 °C for the water outlet and 63 °C for the oil outlet.

Figures 4.6 show the TD on the surface of the HE and tubes (in the two cases, the water and oil mass flow rate were 2.5 kg/s).



(a)

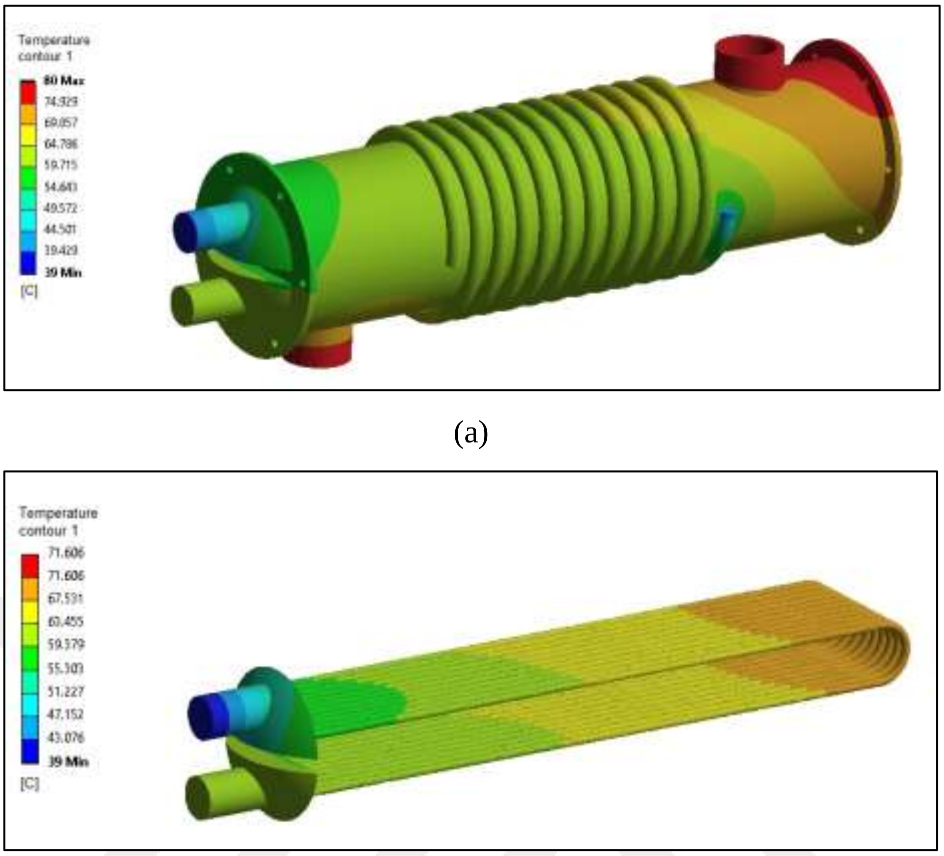


(b)

Figure 4.7: Average TD on (a) The Shell And (B) The Tubes, Case 2 (at 2.5 kg/s).

For the second case, which is the exchanger with the helical spring coil, the temperature was 60 °C for the water outlet and 63 °C for the oil outlet.

Moreover, Figures 4.7 show the TD on the surface of the HE and tubes (in the two cases, the water and oil mass flow rate were 3 kg/s).



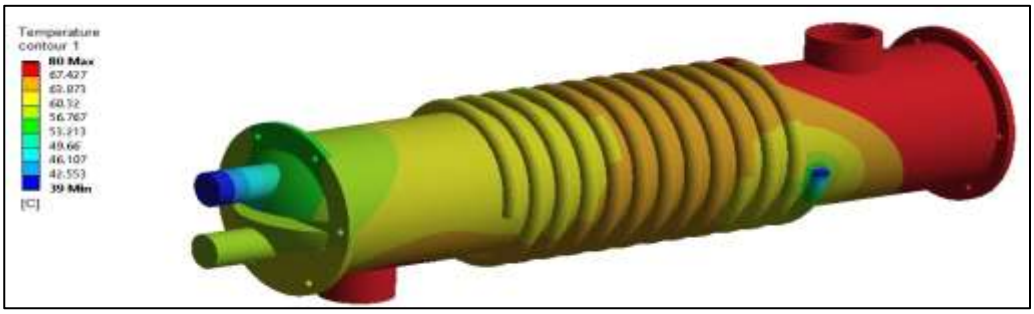
(a)

(b)

Figure 4.8: Average TD on (a) The Shell And (B) The Tubes, Case 2 (at 3 kg/s).

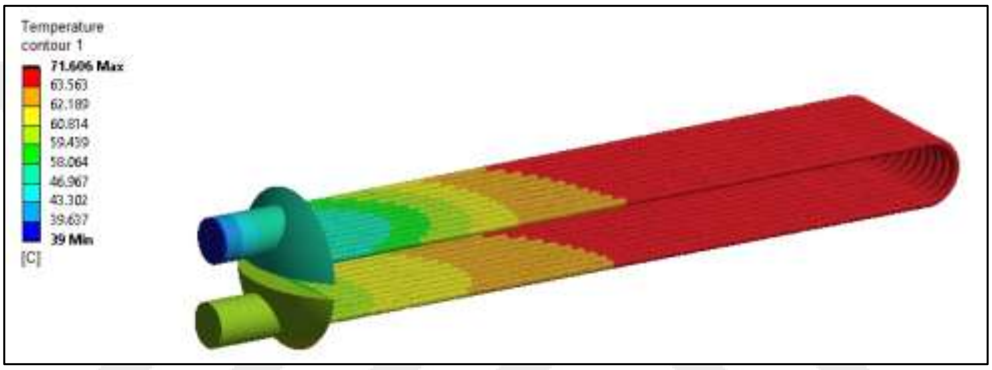
For the second case, which is the exchanger with the helical spring coil, the temperature was 60 °C for the water outlet and 63 °C for the oil outlet.

Figures 4.8 show the TD on the surface of the HE and tubes (in the two cases, the water and oil mass flow rate were 3.5 kg/s).



(a)

Figure 4.9: Average TD on (a) The Shell And (B) The Tubes, Case 2 (at 3.5 kg/s).

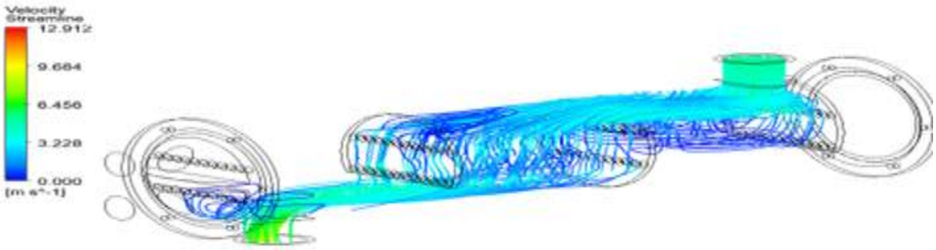


(b)

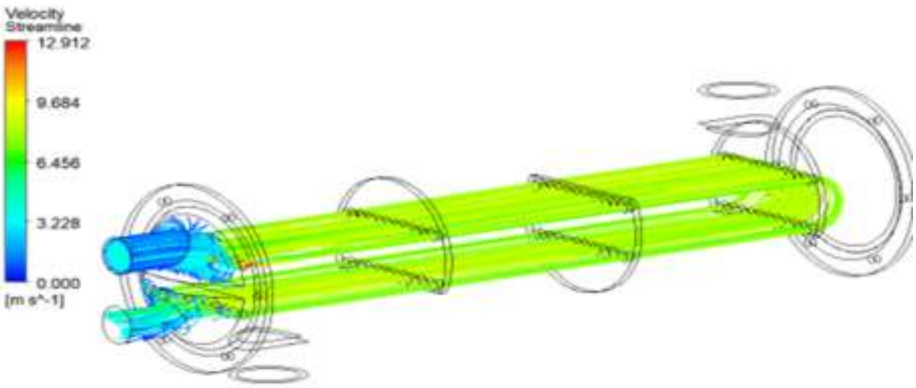
Figure 4.10: Average TD on (a) The Shell And (B) The Tubes, Case 2 (at 3.5 kg/s).

For the second case, which is the exchanger with the helical spring coil, the temperature was 60.5 °C for the water outlet and 60 °C for the oil outlet.

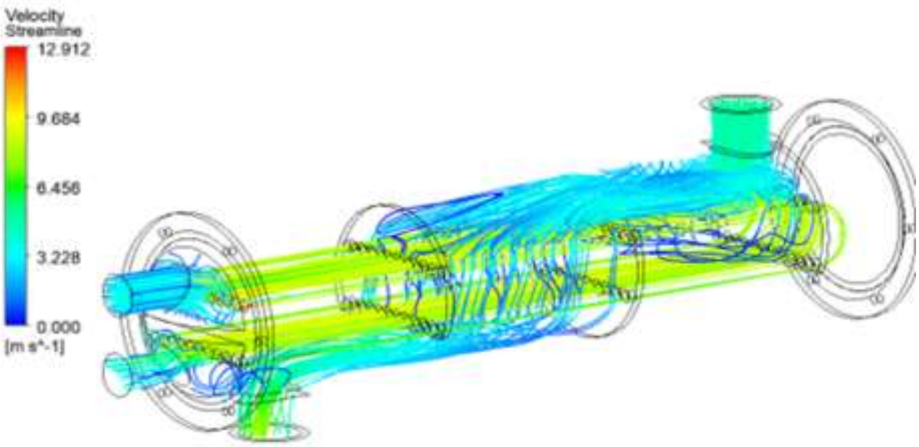
Streamlines are a fundamental concept in fluid dynamics, providing a visual representation of the flow field within a fluid. The imaginary lines represent the fluid particles' immediate trajectories as they navigate through the system. Understanding streamlines is crucial in the analysis of HEs, as they offer insights into the patterns and efficiency of HT. In the context of your project, comparing the streamline patterns between Case 1 (normal configuration) as shown in Figures 4.9 and Case 2 (coil addition) Figures 4.10 becomes significant. Streamlines help reveal how the introduction of a spiral element alters the fluid flow, influencing factors such as velocity, pressure, and TD. By examining and interpreting these streamlines, you can gain valuable information about the impact of the spiral on HT characteristics within the HE, aiding in the optimization and design of such systems for enhanced thermal performance.



(a)

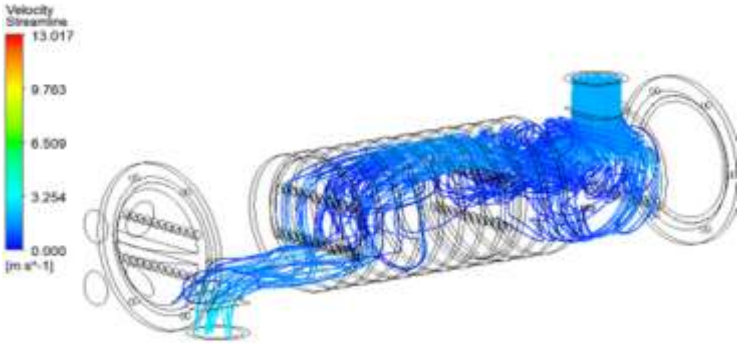


(b)

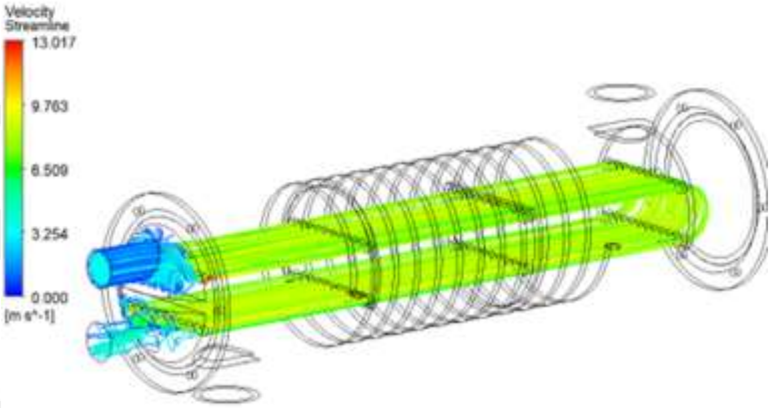


(c)

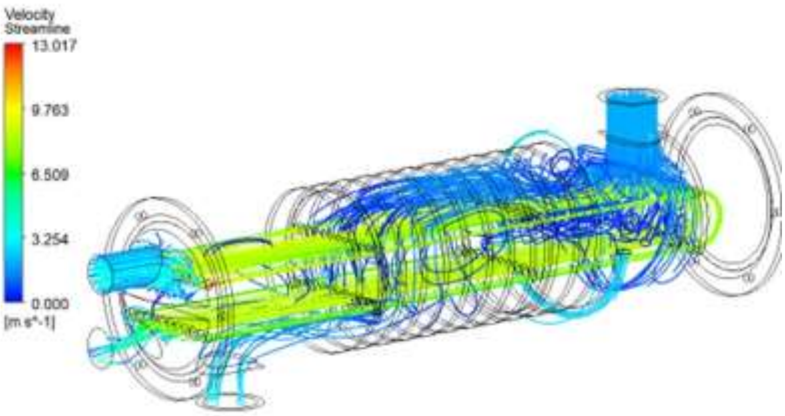
Figure 4.11: Average Velocity SD for Case 1 On (A) The Shell And (B) The Tubes, (C): Shell and Tubes.



(a)



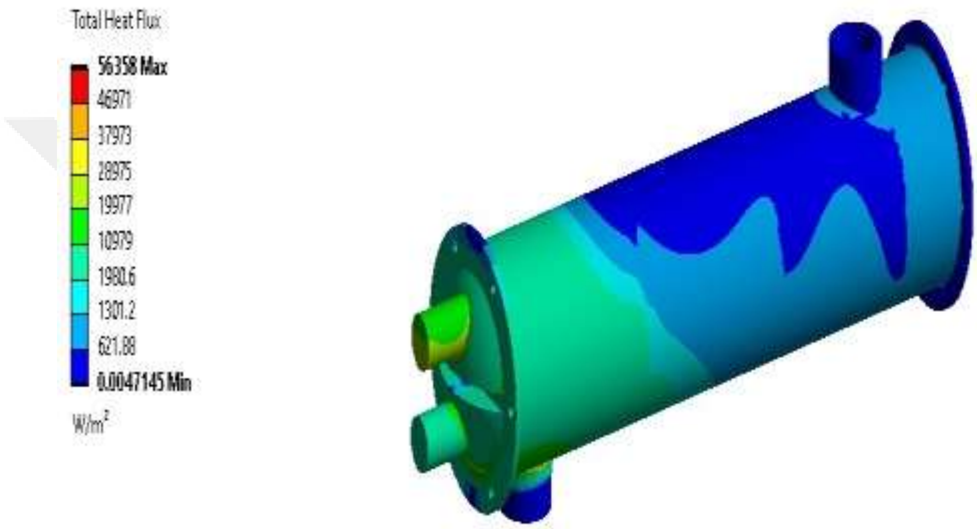
(b)



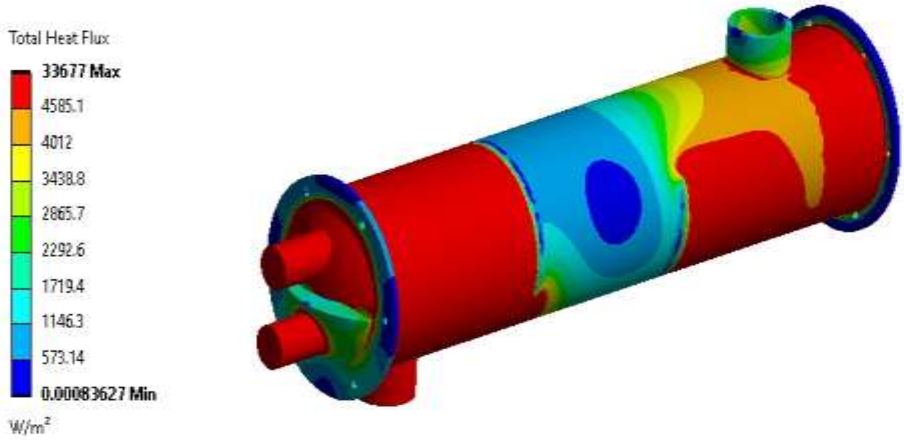
(c)

Figure 4.12: Average Velocity SD for Case 2 On (A) The Shell And (B) The Tubes, (C): Shell, Tubes, And Coil.

Heat flow is a pivotal factor in HT, indicating the rate at which thermal energy moves through a given area. It represents a vector quantity that includes both the magnitude and direction of HT. Within the scope of a HE project; the analysis of heat flow patterns holds great importance in understanding how thermal HEs occur between the liquid and solid components of the system. Examining the heat flow distribution on the surface of the HE gives valuable insights into areas of intense HT and potential thermal inefficiency. By understanding the dynamics of heat flow, it becomes possible to optimize the design and operation of the HE, ensuring efficient and uniform heat distribution. Ultimately, this improvement leads to improved overall performance and increased energy efficiency. Figures 4.11- 4.12 illustrate the heat flux for case 1 and case 2 at 2.0 kg/s and 3.5 kg/s).

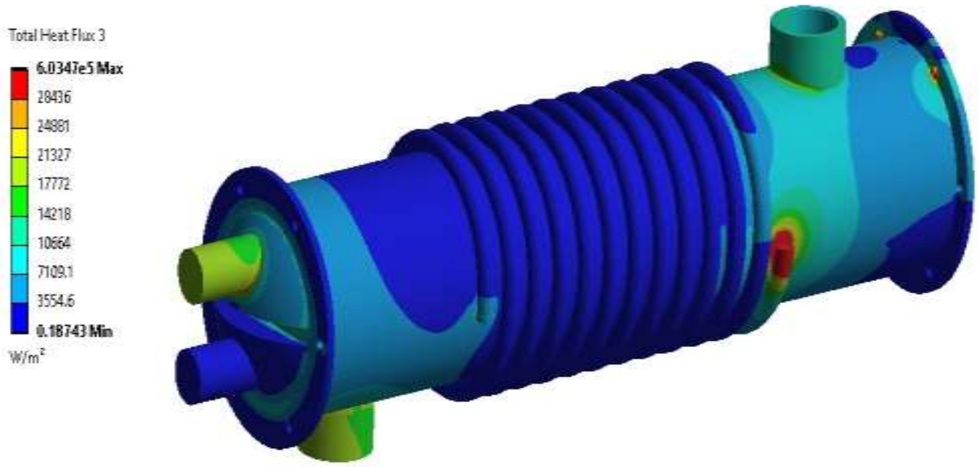


(a)

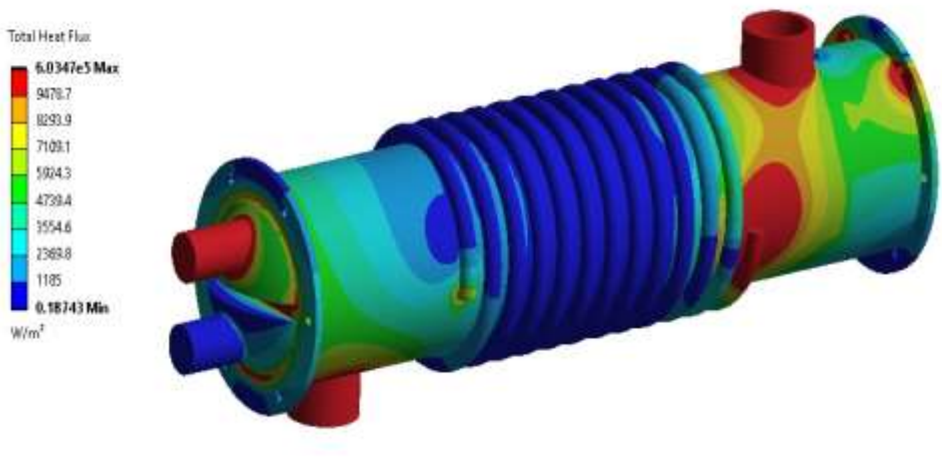


(b)

Figure 4.13: The Total Heat Flux For Case 1 at (a): 2. kg/s, (b): 3.5. kg/s.



(a)



(b)

Figure 4.14: The Total Heat Flux For Case 2 At (A): 2. kg/s, (b): 3.5. kg/s.

4.2.2 Analysis of Heat Convection

It was noted that the convective HT coefficient increases as the fluid velocity increases, leading to an increase in the Reynolds number. A graph was created showing the convection coefficient for different values of the water and oil flows (if the two fluids flow at the same value), as shown in Figure 4.13.

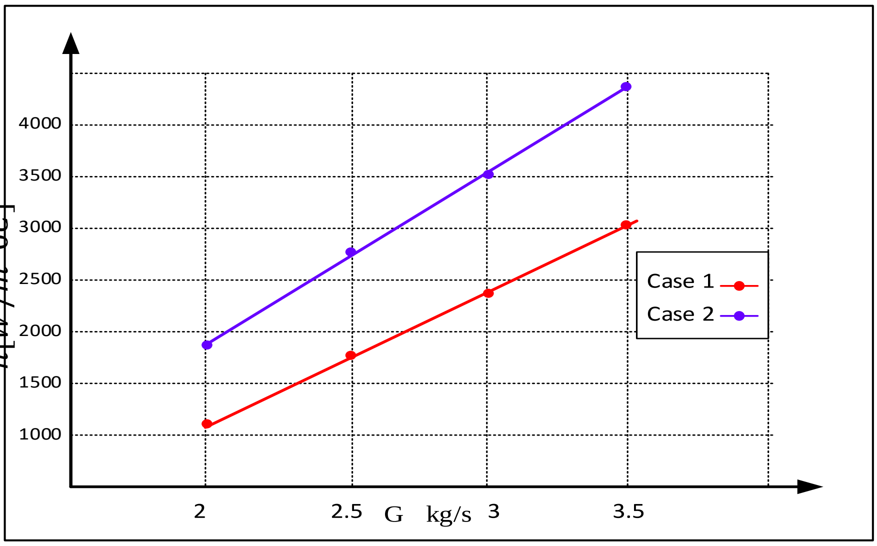


Figure 4.15: The Convection HT Coefficient For The Two Cases With Different Flow Rates.

In addition, a graph was created showing the convection coefficient for different values of the Reynolds coefficient, as shown in Figure 4.14.

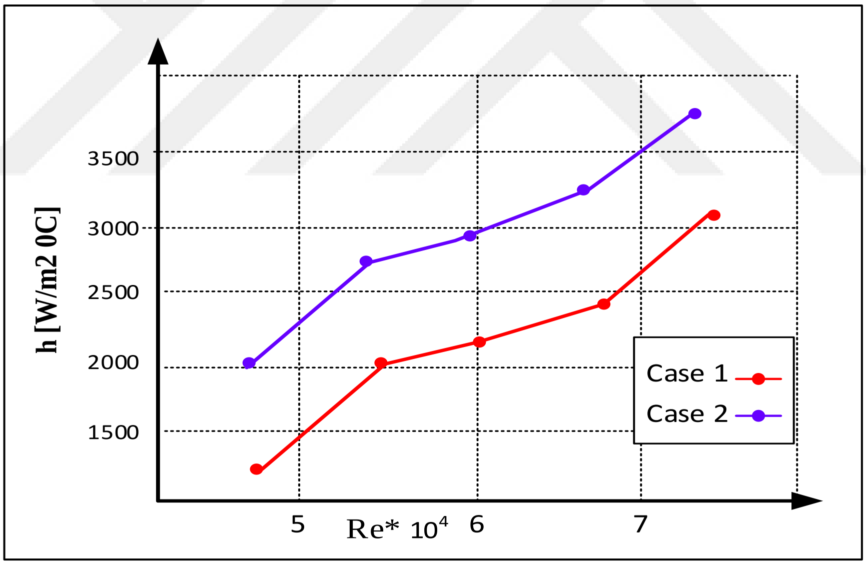


Figure 4.16: The Convection HT Coefficient For The Two Cases With Different Reynolds Numbers.

4.2.3 Analysis of Temperature

Temperature profiles were generated along the thermometer reciprocating and on different sectional surfaces to stress on temperature. The distribution of the steady-state flow of water and oil is shown in figure 4.15.

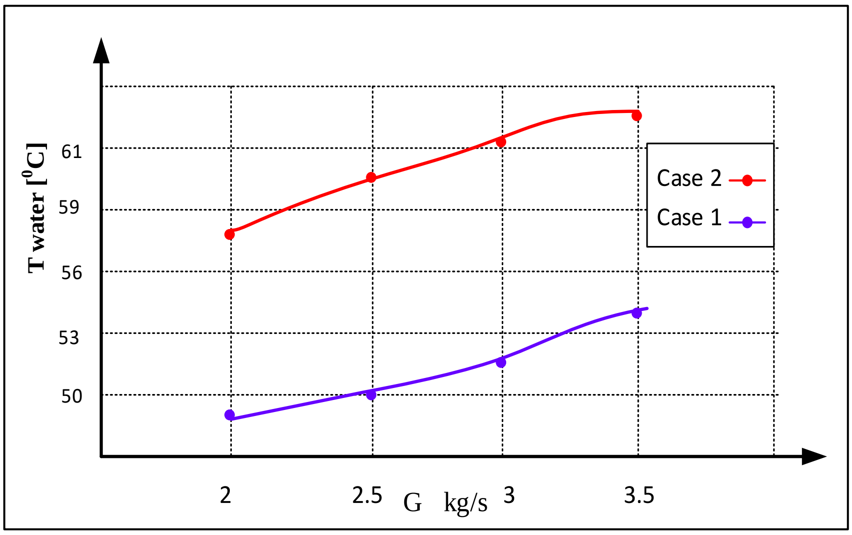


Figure 4.17: The Outlet Water Temperature For The Two Cases With Different Flow Rates.

4.2.4 Analysis of Pressure Drop

Pressure drop is a critical aspect in thermal studies, as it directly impacts the net power gained by causing a decrease in frictional pressure. Decreased pressure results in a reduction in the overall efficiency of the system. In the present investigation, the introduction of a spiral coil results in a decrease in pressure in the second scenario. The reduction in frictional pressure, known as pressure, drop, is a critical element in thermal assessments as it directly impacts the net power obtained.

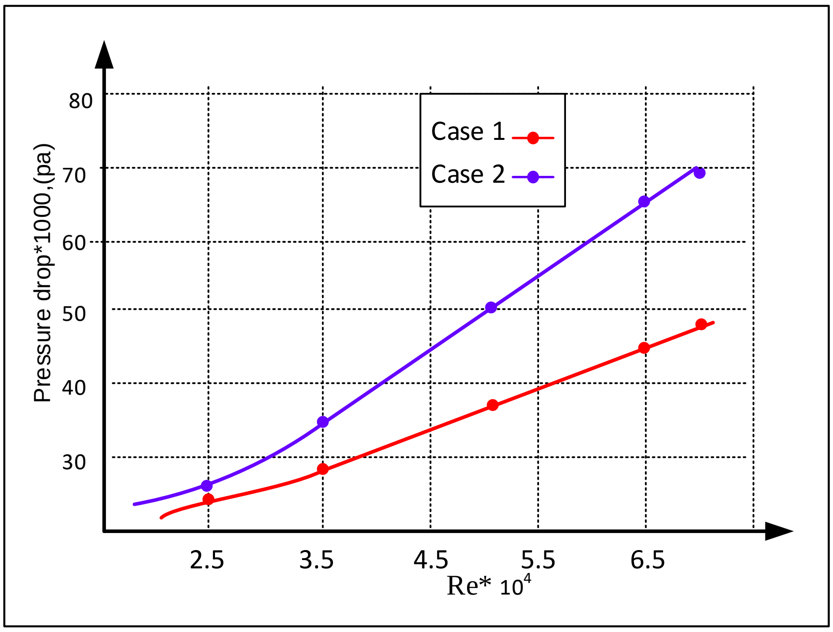


Figure 4.18: Pressure Drop For The Two Cases With Different Flow Rates.

The detailed examination of the numerical simulation results in this study reveals significant advantages of adding a helical coil to the HE. The analysis particularly focuses on comparing thermal performance between two configurations: Case 1 being the standard shell-and-tube HE, and Case 2 featuring the addition of the helical coil. In the temperature distribution analysis, a marked improvement in HT efficiency is evident for Case 2. The distribution of temperature across the exchanger's surface and tubes shows that the modified configuration with the helical coil provides a more efficient heat exchange. This enhancement is attributed to the altered fluid dynamics and increased surface area for HT due to the coil. The study of streamline patterns further substantiates these findings. In Case 2, the introduction of the spiral element creates more turbulent and effective flow patterns, which contribute to enhanced heat exchange efficiency. This alteration in fluid dynamics is a key factor in achieving a higher HT rate. Additionally, the analysis of heat flow and convective HT coefficients across different flow rates of water and oil reinforces the superiority of Case 2. The graphical representations show a consistent increase in HT efficiency with the helical coil in place. The examination of pressure drop and temperature profiles across the system further underlines the improved operational efficiency in Case 2. Despite potential concerns of increased pressure drop due to the coil addition, the study finds that the overall efficiency of the HE remains significantly higher in the modified configuration. In conclusion, the comprehensive analysis clearly demonstrates that the integration of a helical coil in Case 2 notably enhances the thermal efficiency of the HE. This modification not only improves HT rates but also contributes to the overall performance and energy efficiency of the system, making it a valuable consideration in HE design and optimization.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Heat exchangers continue to be a pivotal component in various industrial applications, demanding ongoing advancements in their design and efficiency. This study focused on enhancing the HT efficiency of a STHE by exploring two distinct configurations: a standard STHE and a modified version with an added helical coil on the outer shell. The findings from this study demonstrate the significant improvements achieved with the addition of the spiral coil, particularly in terms of HT efficiency and operational performance. Key conclusions from this research are:

a. Altering fluid flow rates significantly impacts heat exchange processes, with the added helical coil facilitating better conductivity, load factor, and heat transfer efficiency.

b. The second case model, featuring the added helical coil, exhibited remarkably high efficiency and superior performance compared to the standard configuration.

c. Notable enhancement in heat transfer was observed in areas with lower turbulence, indicating the effectiveness of the coil in optimizing fluid dynamics.

d. There was a clear correlation observed between the increased volume of water, elevated heat transmission, and the associated pressure drops.

e. A nonlinear drop in pressure was proportional to the heat transfer rate with increasing Reynolds number, highlighting the coil's role in maintaining system efficiency.

f. Overall, the study achieved satisfactory results in terms of heat transfer enhancement and operational efficiency.

g. The introduction of the coil on the outer shell led to a remarkable efficiency increase of over 10%, implying significant energy savings in pump consumption.

5.2 RECOMMENDATIONS

Based on the findings of this study, future research in the field of heat exchangers can be guided in several key directions:

a. Further theoretical, experimental, and numerical studies are recommended using different fluids in STHE to generalize the findings.
b. Conducting experimental studies to validate and compare with the results of this research, thereby determining optimal configurations for thermal performance.
c. Exploring the effects of internal fins in HEs through both numerical and experimental studies, focusing on optimizing parameters like fin shape, dimensions, number, and spacing.
d. Numerical and experimental analysis of HEs with varying tube parameters, such as tube number and material, to understand their impact on overall efficiency.

REFERENCE

[1] A. P. Fraas, *Heat exchanger design*. John Wiley & Sons, 1991.

[2] M. . L. Brusseau, “Sustainable development and other solutions to pollution and global change,” in *Sustainable development goals*, Elsevier, 2019, pp. 585–604.

[3] T. Li *et al.*, “Developing fibrillated cellulose as a sustainable technological material,” *Nature*, vol. 591, no. 7845, pp. 47–57, 2021, doi: https://doi.org/10.1038/s41586-020-03167-7.

[4] J. Yue, J. C. Schouten, and T. A. Nijhuis, “Integration of microreactors with spectroscopic detection for online reaction monitoring and catalyst characterization,” *Ind Eng Chem Res*, vol. 51, no. ,45, pp. 14583–14609.

[5] B. Zohuri and B. Zohuri, “Heat exchanger types and classifications,” *Compact Heat Exchangers: Selection, Application, Design and Evaluation*, pp. 19–56, 2017.

[6] A. Kalair, N. Abas, M. S. Saleem, A. R. Kalair, and N. Khan, “Role of energy storage systems in energy transition from fossil fuels to renewables,” *Energy Storage*, vol. 3, no. 1, p. e135, 2021.

[7] K. Huang, Y. Yan, B. Li, Y. Li, K. Li, and J. Li, “A novel design of thermoelectric generator for automotive waste heat recovery,” *Automotive Innovation*, vol. 1, pp. 54–61, 2018.

[8] H. Lee, *Other research projects looked into thermal devices that worked better, like refrigerators and heating exchangers*. John Wiley & Sons, 2022.

[9] A. G. Olabi, T. Wilberforce, E. T. Sayed, K. Elsaid, S. M. A. Rahman, and M. A. Abdelkareem, “Geometrical effect coupled with nanofluid on heat transfer enhancement in heat exchangers,” *International Journal of Thermofluids*, vol. 10, p. 100072, 2021.

[10] R. Kumar *et al.*, “Convective heat transfer enhancement using impingement jets in channels and tubes: A comprehensive review,” *Alexandria Engineering Journal*, vol. 70, pp. 349–376, 2023.

[11] S. A. Marzouk, M. M. Abou Al-Sood, E. M. S. El-Said, M. M. Younes, and M. K. El-Fakharany, “A comprehensive review of methods of heat transfer enhancement in shell and tube heat exchangers,” *J Therm Anal Calorim*, pp. 1–40, 2023.

[12] N. A. and S. MUSEUM, “Gyrodyne QH-50C Drone Anti-Submarine Helicopter (DASH) | National Air and Space Museum,” National Air and Space MUSEUM. [Online]. Available: https://airandspace.si.edu/collection-objects/gyrodyne-qh-50c-drone-anti-submarine-helicopter-dash/nasm_A20090023000

[13] P. C. Sarker, K. Islam, M. S. Reza, H. Mobarak, and M. M. Rahaman, “Performance Test Of Heat Exchanger by Using Different Material Tubes.” Sonargoan University (SU), 2023.

[14] C.-C. Lee and İ. A. Taştemir, “Direct heat exchangers in the food industry,” in *Thermal Processing of Food Products by Steam and Hot Water*, Elsevier, 2023, pp. 181–208.

[15] J. Yue, J. C. Schouten, and T. A. Nijhuis, “Integration of microreactors with spectroscopic detection for online reaction monitoring and catalyst characterization,” *Ind Eng Chem Res*, vol. 51, no. ,45, pp. 14583–14609.

[16] C. Castán-Fernández, G. Marcos-Robredo, M. P. Castro-García, M. A. Rey-Ronco, and T. Alonso-Sánchez, “Development of a dry mortar with nanosilica and different types of industrial waste for the application in borehole heat exchangers,” *Constr Build Mater*, vol. 359, p. 129511, 2022.

[17] M. Omidi, M. Farhadi, and M. Jafari, “A comprehensive review on double pipe heat exchangers,” *Appl Therm Eng*, vol. 110, pp. 1075–1090, 2017.

[18] B. I. Master, K. S. Chunangad, A. J. Boxma, D. Kral, and P. Stehlik, “Most frequently used heat exchangers from pioneering research to worldwide applications,” *Heat Transfer Engineering*, vol. 27, no. 6, pp. 4–11, 2006.

[19] A. A. A. Arani and R. Moradi, “Shell and tube heat exchanger optimization using new baffle and tube configuration,” *Appl Therm Eng*, vol. 157, p. 113736, 2019.

[20] R. Mukherjee, “Effectively design shell-and-tube heat exchangers,” *Chem Eng Prog*, vol. 94, no. 2, pp. 21–37, 1998.

[21] A. N. Meshram, R. Shaikh, A. Lalchadi, P. Dudhane, and S. Khan, “Design and analysis of heat exchanger trolley to cool the radar system of fighter jet Sukhoi-30,” 2019.

[22] B. Koçak, A. I. Fernandez, and H. Paksoy, “Review on sensible thermal energy storage for industrial solar applications and sustainability aspects,” *Solar Energy*, vol. 209, pp. 135–169, 2020.

[23] R. Niroomand, M. H. Saidi, and S. K. Hannani, “A general multi-scale modeling framework for two-phase simulation of multi-stream plate-fin heat exchangers,” *Int J Heat Mass Transf*, vol. 156, p. 119730, 2020.

[24] J. Zhang, X. Zhu, M. E. Mondejar, and F. Haglind, “A review of heat transfer enhancement techniques in plate heat exchangers,” *Renewable and Sustainable Energy Reviews*, vol. 101, pp. 305–328, 2019.

[25] Z. Wang and Y. Li, “Layer pattern thermal design and optimization for multistream plate-fin heat exchangers—A review,” *Renewable and Sustainable Energy Reviews*, vol. 53, pp. 500–514, 2016.

[26] J. E. Hesselgreaves, R. Law, and D. Reay, *Compact heat exchangers: selection, design and operation*. Butterworth-Heinemann, 2016.

[27] S. Qian, J. Yu, and G. Yan, “A review of regenerative heat exchange methods for various cooling technologies,” *Renewable and Sustainable Energy Reviews*, vol. 69, pp. 535–550, 2017.

[28] W. Zhang, X. Xue, F. Liu, and S. Mei, “Modelling and experimental validation of advanced adiabatic compressed air energy storage with off-design heat exchanger,” *IET Renewable Power Generation*, vol. 14, no. 3, pp. 389–398, 2020.

[29] M. Esapour, M. J. Hosseini, A. A. Ranjbar, Y. Pahamli, and R. Bahrampoury, “Phase change in multi-tube heat exchangers,” *Renew Energy*, vol. 85, pp. 1017–1025, 2016.

[30] Y. Lee and A. Bedrossian, “The characteristics of heat exchangers using heat pipes or thermosyphons,” *Int J Heat Mass Transf*, vol. 21, no. 2, pp. 221–229, 1978.

[31] C. K. Mangrulkar, A. S. Dhoble, S. Chamoli, A. Gupta, and V. B. Gawande, “Recent advancement in heat transfer and fluid flow characteristics in cross flow heat exchangers,” *Renewable and Sustainable Energy Reviews*, vol. 113, p. 109220, 2019.

[32] D. H. Nguyen and H. S. Ahn, “A comprehensive review on micro/nanoscale surface modification techniques for heat transfer enhancement in heat exchanger,” *Int J Heat Mass Transf*, vol. 178, p. 121601, 2021.

[33] L. Hua, H. Zhao, J. Li, Q. Zhu, and J. Wang, “Solid residence time distribution in a cross-flow dense fluidized bed with baffles,” *Chem Eng Sci*, vol. 200, pp. 320–335, 2019.

[34] G. Heidarinejad and S. Moshari, “Novel modeling of an indirect evaporative cooling system with cross-flow configuration,” *Energy Build*, vol. 92, pp. 351–362, 2015.

[35] T. N. Tien, Q. K. Vu, and V. N. Duy, “Novel designs of thermoelectric generator for automotive waste heat recovery: A review,” *AIMS Energy*, vol. 10, no. 4, pp. 922–942, 2022.

[36] I. Kaur and P. Singh, “State-of-the-art in heat exchanger additive manufacturing,” *Int J Heat Mass Transf*, vol. 178, p. 121600, 2021.

[37] M. Abdelmagid Abdelmagid, “Heat transfer enhancement in horizontal double tube concentric/eccentric heat exchanger by using nanofluid,” 2022.

[38] “Application of multipass heat exchanger,” electricalworkbook. [Online]. Available: https://electricalworkbook.com/multipass-heat-exchanger/

[39] C. A. Frissell, W. J. Liss, C. E. Warren, and M. D. Hurley, “A hierarchical framework for stream habitat classification: viewing streams in a watershed context,” *Environ Manage*, vol. 10, pp. 199–214, 1986.

[40] F. Pra, P. Tochon, C. Mauget, J. Fokkens, and S. Willemsen, “Promising designs of compact heat exchangers for modular HTRs using the Brayton cycle,” *Nuclear Engineering and Design*, vol. 238, no. 11, pp. 3160–3173, 2008.

[41] V. Pandiyarajan, M. C. Pandian, E. Malan, R. Velraj, and R. V Seeniraj, “Experimental investigation on heat recovery from diesel engine exhaust using finned shell and tube heat exchanger and thermal storage system,” *Appl Energy*, vol. 88, no. 1, pp. 77–87, 2011.

[42] M. Vollmer, “Newton’s law of cooling revisited,” *Eur J Phys*, vol. 30, no. 5, p. 1063, 2009.

[43] R. E. Hollon and C. W. Anderson, “Heat and Temperature: A Teaching Module. Occasional Paper No. 93.,” 1986.

[44] R. Das, “Forward and inverse solutions of a conductive, convective and radiative cylindrical porous fin,” *Energy Convers Manag*, vol. 87, pp. 96–106, 2014.

[45] A. Cossins, *Temperature biology of animals*. Springer Science & Business Media, 2012.

[46] S. Lee, S.-S. Choi, S. Li and, and J. A. Eastman, “Measuring thermal conductivity of fluids containing oxide nanoparticles,” 1999.

[47] theodore L. Bergman and A. S. Lavine, *Fundamentals of Heat and Mass Transfer*, 8th ed. New York: Wiley & Sons, Inc., 2017. [Online]. Available: http://repositorio.unan.edu.ni/2986/1/5624.pdf

[48] J. Newman and J. Newman, “Thermal Energy,” *Physics of the Life Sciences*, pp. 1–33, 2008.

[49] Y. Li *et al.*, “Transforming heat transfer with thermal metamaterials and devices,” *Nat Rev Mater*, vol. 6, no. 6, pp. 488–507, 2021.

[50] K. Mohammadi, “Investigation of the effects of baffle orientation, baffle cut and fluid viscosity on shell side pressure drop and heat transfer coefficient in an e-type shell and tube heat exchanger,” 2011.

[51] P. Breeze, *Combined heat and power*. Academic Press, 2017.

[52] A. Fragnito, N. Bianco, M. Iasiello, G. M. Mauro, and L. Mongibello, "Experimental and numerical analysis of a phase change material-based shell-and-tube heat exchanger for cold thermal energy storage," *J Energy Storage*, vol. 56, p. 105975, 2022.

[53] A. H. N. Al-Mudhafar, A. F. Nowakowski, and F. C. G. A. Nicolleau, "Enhancing the thermal performance of PCM in a shell and tube latent heat energy storage system by utilizing innovative fins," *Energy Reports*, vol. 7, pp. 120–126, 2021.

[54] N. Bianco, A. Fragnito, M. Iasiello, G. M. Mauro, and L. Mongibello, "Multi-objective optimization of a phase change material-based shell-and-tube heat exchanger for cold thermal energy storage: Experiments and numerical modeling," *Appl Therm Eng*, vol. 215, p. 119047, 2022.

[55] D. Patel and P. Parikh, "Numerical Simulation and Experiment Performance for Comparison of Shell and Tube Heat Exchanger with Plain Tube and Corrugated Tube," *IJISET) ISSN*, pp. 2348–7968.

[56] J. Kazi and M. Shaikh, "Standardization of tube expansion system in shell and tube type heat exchanger," 2017.

[57] F. Rößler *et al.*, "Hazard Analysis of Fixed-Tube-Sheet Shell-and-Tube Heat Exchangers," *Chemie Ingenieur Technik*, vol. 94, no. 5, pp. 727–737, 2022.

[58] S. K. Prasad and M. K. Sinha, "Thermal performance evaluation of Shell and U-tube heat exchanger fitted with helical baffles".

[59] R. J. Brogan, "Shell and tube heat exchangers," in *Thermopedia*, Begel House Inc., 2011.

[60] S. Chen, J. Mao, X. Han, C. Li, and L. Liu, "Numerical analysis of the factors influencing a vertical U-tube ground heat exchanger," *Sustainability*, vol. 8, no. 9, p. 882, 2016.

[61] P. K. Gupta, S. P. Asthana, and N. Gupta, "INTERNATIONAL JOURNAL OF RESEARCH IN AERONAUTICAL AND MECHANICAL ENGINEERING," 2013.

[62] S. Rungla, K. F. Fazal, K. S. Moazzam, and K. N. A. A. Ahmed, "Design and Analysis of Floating Head Heat Exchanger," *Available at SSRN 4285106*, 2022.

[63] S. K. Raman, "Effect of Tubesheet Weight on Shell Stresses in Heat Exchanger Saddle Support Analysis." Tennessee Technological University, 2018.

[64] F. N. Taher, S. Z. Movassag, K. Razmi, and R. T. Azar, "Baffle space impact on the performance of helical baffle shell and tube heat exchangers," *Appl Therm Eng*, vol. 44, pp. 143–149, 2012.

[65] M. M. Joybari, H. Selvnes, E. Vingelsgård, A. Sevault, and A. Hafner, "Parametric study of low-temperature thermal energy storage using carbon dioxide as the phase change material in pillow plate heat exchangers," *Appl Therm Eng*, vol. 221, p. 119796, 2023.

[66] S. Rafi, C. Sivarajan, and M. Ch, "Optimization of helical coil tube heat exchanger: a systematic review," in *IOP Conference Series: Materials Science and Engineering*, IOP Publishing, 2020, p. 12056.

[67] J. S. Jayakumar and R. B. Grover, "Two phase natural circulation residual heat removal," in *Proc. 3rd ISHMT-ASME Heat and Mass Transfer Conference*, 1997.

[68] H. F. Elattar, A. Fouda, S. A. Nada, H. A. Refaey, and A. Al-Zahrani, "Thermal and hydraulic numerical study for a novel multi tubes in tube helically coiled heat exchangers: Effects of operating/geometric parameters," *International Journal of Thermal Sciences*, vol. 128, pp. 70–83, 2018.

[69] J. S. Jayakumar, "Helically coiled heat exchangers," *Book: Heat Exchangers–Basics Design Applications*, pp. 311–342, 2012.

[70] S. Li *et al.*, "A state-of-the-art overview on the developing trend of heat transfer enhancement by single-phase flow at micro scale," *Int J Heat Mass Transf*, vol. 143, p. 118476, 2019.

[71] K. Yamamoto, T. Akita, H. Ikeuchi, and Y. Kita, “Experimental study of the flow in a helical circular tube,” *Fluid Dyn Res*, vol. 16, no. 4, pp. 237–249, 1995.

[72] L. Zabielski and A. J. Mestel, “Unsteady blood flow in a helically symmetric pipe,” *J Fluid Mech*, vol. 370, pp. 321–345, 1998.

[73] A. JOHNNY and E. S. OBIKA, “MODIFICATION OF THE COOLING CHAMBER OF A WATER COOLER”.

[74] A. H. Pordanjani, S. Aghakhani, M. Afrand, B. Mahmoudi, O. Mahian, and S. Wongwises, “An updated review on application of nanofluids in heat exchangers for saving energy,” *Energy Convers Manag*, vol. 198, p. 111886, 2019.

[75] A. Sarrami Foroushani and M. Nasr Esfahany, “CFD simulation of gas-solid two-phase flow in pneumatic conveying of wheat,” *Iranian Journal of Chemistry and Chemical Engineering*, vol. 34, no. 4, pp. 123–140, 2015.

[76] J. Bonilla, A. de la Calle, M. M. Rodríguez-García, L. Roca, and L. Valenzuela, “Study on shell-and-tube heat exchanger models with different degree of complexity for process simulation and control design,” *Appl Therm Eng*, vol. 124, pp. 1425–1440, 2017.

[77] H. Bütün, I. Kantor, and F. Maréchal, “A heat integration method with multiple heat exchange interfaces,” *Energy*, vol. 152, pp. 476–488, 2018.

[78] F. Zaversky, M. Sánchez, and D. Astrain, “Object-oriented modeling for the transient response simulation of multi-pass shell-and-tube heat exchangers as applied in active indirect thermal energy storage systems for concentrated solar power,” *Energy*, vol. 65, pp. 647–664, 2014.

[79] K. Boukhadia, H. Ameur, D. Sahel, and M. Bozit, “Effect of the perforation design on the fluid flow and heat transfer characteristics of a plate fin heat exchanger,” *International Journal of Thermal Sciences*, vol. 126, pp. 172–180, 2018.

[80] S. Xie, Z. Liang, L. Zhang, and Y. Wang, “A numerical study on heat transfer enhancement and flow structure in enhanced tube with cross ellipsoidal dimples,” *Int J Heat Mass Transf*, vol. 125, pp. 434–444, 2018.

[81] R. S. Matos, T. A. Laursen, J. V. C. Vargas, and A. Bejan, "Three-dimensional optimization of staggered finned circular and elliptic tubes in forced convection," *International Journal of Thermal Sciences*, vol. 43, no. 5, pp. 477–487, 2004.

[82] S. Abolfathi, A. M. Lavasani, P. Mobedi, and K. S. Afshar, "Experimental study on flow around a tube in mixed tube bundles comprising cam-shaped and circular cylinders in in-line arrangement," *International Journal of Thermal Sciences*, vol. 163, p. 106812, 2021.

[83] M. Moawed, "Experimental study of forced convection from helical coiled tubes with different parameters," *Energy Convers Manag*, vol. 52, no. 2, pp. 1150–1156, 2011.

[84] H. Mroue, "Numerical and experimental investigation of a multi-pass heat-pipe-based heat exchanger." Brunel University London, 2018.

[85] P. Debnath and M. Pradhan, "A recent state of art review on heat transfer enhanced characteristics and material selection of SCTHX," *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, vol. 237, no. 3, pp. 1005–1013, 2023.

[86] S. S. Pawar and V. K. Sunnapwar, "Experimental studies on heat transfer to Newtonian and non-Newtonian fluids in helical coils with laminar and turbulent flow," *Exp Therm Fluid Sci*, vol. 44, pp. 792–804, 2013.

[87] S. A. Nada, H. F. Elattar, A. Fouda, and H. A. Refaey, "Numerical investigation of heat transfer in annulus laminar flow of multi tubes-in-tube helical coil," *Heat and Mass Transfer*, vol. 54, pp. 715–726, 2018.

[88] R. Kumar, M. S. Deshmukh, and K. K. Ghosh, "A Review on Investigation of Performance of Pipe in Pipe Helically Coil Heat Exchanger".

[89] G. Wang, D. Wang, X. Peng, L. Han, S. Xiang, and F. Ma, "Experimental and numerical study on heat transfer and flow characteristics in the shell side of helically coiled trilobal tube heat exchanger," *Appl Therm Eng*, vol. 149, pp. 772–787, 2019.

[90] H. Mirgolbabaei, H. Taherian, G. Domairry, and N. Ghorbani, “Numerical estimation of mixed convection heat transfer in vertical helically coiled tube heat exchangers,” *Int J Numer Methods Fluids*, vol. 66, no. 7, pp. 805–819, 2011.

[91] Anusha A, D. Sathya Narayana Rao, and G. D Saxena, “Enhancing the efficiency and speed of heat transfer using shell and tube heat exchanger design,” *International Journal of Scientific Methods in Engineering and Management*, vol. 01, no. 02, pp. 01–12, 2023, doi: 10.58599/ijsmem.2023.1201.

[92] S. Anantha *et al.*, “A CFD investigation and heat transfer augmentation of double pipe heat exchanger by employing helical baffles on shell and tube side,” *Thermal Science*, vol. 26, no. 2 Part A, pp. 991–998, 2022.

[93] T. D. PRASAD, “CFD ANALYSIS ON VARIOUS FINNED TUBE HEAT EXCHANGER.” Andhra University, 2018.

[94] M. R. Salimpour, “Heat transfer coefficients of shell and coiled tube heat exchangers,” *Exp Therm Fluid Sci*, vol. 33, no. 2, pp. 203–207, 2009.

[95] H. Kücük, M. Ünverdi, and M. S. Yılmaz, “Experimental investigation of shell side heat transfer and pressure drop in a mini-channel shell and tube heat exchanger,” *Int J Heat Mass Transf*, vol. 143, p. 118493, 2019.

[96] M. R. Salem, K. M. Elshazly, R. Y. Sakr, and R. K. Ali, “Effect of coil torsion on heat transfer and pressure drop characteristics of shell and coil heat exchanger,” *J Therm Sci Eng Appl*, vol. 8, no. 1, 2016.

[97] S. Wongwises and P. Naphon, “Heat transfer characteristics and performance of a spirally coiled heat exchanger under sensible cooling conditions,” *JSME International Journal Series B Fluids and Thermal Engineering*, vol. 48, no. 4, pp. 810–819, 2005.

[98] M. N. Kuvadiya, G. K. Deshmukh, R. A. Patel, and R. H. Bhoi, “Parametric analysis of tube in tube helical coil heat exchanger at constant wall temperature,” *International Journal of Engineering Research & Technology*, vol. 1, no. 10, pp. 279–285, 2015.

[99] C. Ononogbo *et al.*, “Opportunities of waste heat recovery from various sources: Review of technologies and implementation,” *Heliyon*, 2023.

[100] M. S. Bretado-de los Rios, C. I. Rivera-Solorio, and K. D. P. Nigam, "An overview of sustainability of heat exchangers and solar thermal applications with nanofluids: A review," *Renewable and Sustainable Energy Reviews*, vol. 142, p. 110855, 2021.

[101] M. C. Barma, R. Saidur, S. M. A. Rahman, A. Allouhi, B. A. Akash, and S. M. Sait, "A review on boilers energy use, energy savings, and emissions reductions," *Renewable and Sustainable Energy Reviews*, vol. 79, pp. 970–983, 2017.

[102] K. Balaji, S. Iniyan, and V. Muthusamyswami, "Experimental investigation on heat transfer and pumping power of forced circulation flat plate solar collector using heat transfer enhancer in absorber tube," *Appl Therm Eng*, vol. 112, pp. 237–247, 2017.

[103] A. Hobbi and K. Siddiqui, "A. Hobbi and K. Siddiqui, 'Experimental study on the effect of heat transfer enhancement devices in flat-plate solar collectors,' Int. J. Heat Mass Transf., vol. 52, no. 19–20, pp. 4650–4658, 2009.," *Int J Heat Mass Transf*, vol. 52, no. 19–20, pp. 4650–4658, 2009.

[104] A. El Maakoul, A. Laknizi, S. Saadeddine, A. Ben Abdellah, M. Meziane, and M. El Metoui, "Numerical design and investigation of heat transfer enhancement and performance for an annulus with continuous helical baffles in a double-pipe heat exchanger," *Energy Convers Manag*, vol. 133, pp. 76–86, 2017.

[105] A. A. Lokhande, D. R. Waghole, and S. A. Dayane, "Heat transfer augmentation in shell and tube heat exchangers using copper oxide nanofluid with modified geometry: A numerical investigation," *Mater Today Proc*, vol. 72, pp. 1240–1245, 2023.

[106] O. Keklikcioglu and V. Ozceyhan, "Experimental investigation on heat transfer enhancement in a circular tube with equilateral triangle cross sectioned coiled-wire inserts," *Appl Therm Eng*, vol. 131, pp. 686–695, 2018.

[107] M. Bahiraei, N. Mazaheri, and M. Hanooni, "Performance enhancement of a triple-tube heat exchanger through heat transfer intensification using novel crimped-spiral ribs and nanofluid: A two-phase analysis," *Chemical Engineering and Processing-Process Intensification*, vol. 160, p. 108289, 2021.

[108] E. Tavousi, N. Perera, D. Flynn, and R. Hasan, “Heat transfer and fluid flow characteristics of the passive method in double tube heat exchangers: a critical review,” *International Journal of Thermofluids*, p. 100282, 2023.

[109] K. Boomsma, D. Poulikakos, and F. Zwick, “Metal foams as compact high performance heat exchangers,” *Mechanics of materials*, vol. 35, no. 12, pp. 1161–1176, 2003.

[110] N. Sahiti, F. Durst, and A. Dewan, “Heat transfer enhancement by pin elements,” *Int J Heat Mass Transf*, vol. 48, no. 23–24, pp. 4738–4747, 2005.

[111] S. Wang, J. Wen, and Y. Li, “An experimental investigation of heat transfer enhancement for a shell-and-tube heat exchanger,” *Appl Therm Eng*, vol. 29, no. 11–12, pp. 2433–2438, 2009.

[112] Q. J. M. Slaiman and A. N. Znad, “Enhancement of Heat Transfer in The Tube-Sid of A Double Pipe Heat Exchanger by Wire Coils,” *Al-Nahrain Journal for Engineering Sciences*, vol. 16, no. 1, pp. 51–57, 2013.

[113] A. Ghozatloo, A. Rashidi, and M. Shariaty-Niassar, “Convective heat transfer enhancement of graphene nanofluids in shell and tube heat exchanger,” *Exp Therm Fluid Sci*, vol. 53, pp. 136–141, 2014.

[114] S. V Patil and P. V Vijay Babu, “Laminar heat transfer augmentation through a square duct and circular tube fitted with twisted tapes,” *Experimental Heat Transfer*, vol. 27, no. 2, pp. 124–143, 2014.

[115] S. Guccione, A. Fontalvo, R. Guedez, J. Pye, L. Savoldi, and R. Zanino, “Techno-economic optimisation of a sodium–chloride salt heat exchanger for concentrating solar power applications,” *Solar Energy*, vol. 239, pp. 252–267, 2022.

[116] A. Tyagi and A. Kumar, “Thermal Analysis of Double Pipe Heat Exchanger,” *International Journal of Applied Engineering Research*, vol. 13, no. 6, pp. 299–302, 2018.

[117] B. C. Sekhar, D. Krishnaiah, and F. A. Raju, “Thermal analysis of multi tube pass shell and tube heat exchanger,” *Int J Innov Res Sci Eng Technol*, vol. 3, no. 11, pp. 17605–17612, 2014.

[118] K. Nawaz and M. Sultan, “Thermal-Hydraulic Performance of Wavy-Fin Heat Exchanger Under Dehumidifying Condition,” Oak Ridge National Lab.(ORNL), Oak Ridge, TN (United States), 2018.

[119] D. Shinde Digvijay and H. M. Dange, “Heat transfer analysis of a cone shaped helical coil heat exchanger,” *International Journal of Innovations in Engineering and Technology (IJIET)*, vol. 3, no. 1, pp. 1058–2319, 2013.

[120] P. Date and V. W. Khond, “Heat transfer enhancement in fin and tube heat exchanger-a review,” *ARPN Journal of Engineering and Applied Sciences*, vol. 8, no. 3, pp. 241–245, 2013.

[121] S. Perumal, R. Mohan, S. Sasidharan, and K. Venkatesh, “Study On Concentric Tube Heat Exchanger With Different Nano Fluids For Enhancing The Heat Transfer: A Review,” *Imperial Journal of Interdisciplinary Research*, vol. 3, no. 9, pp. 682–688, 2017.

[122] N. Ghorbani, H. Taherian, M. Gorji, and H. Mirgolbabaei, “Experimental study of mixed convection heat transfer in vertical helically coiled tube heat exchangers,” *Exp Therm Fluid Sci*, vol. 34, no. 7, pp. 900–905, 2010.

[123] C.-N. Chen, J.-T. Han, T.-C. Jen, and L. Shao, “Thermo-chemical characteristics of R134a flow boiling in helically coiled tubes at low mass flux and low pressure,” *Thermochim Acta*, vol. 512, no. 1–2, pp. 163–169, 2011.

[124] Fernandes, Erica Jacqueline, and Sachidananda Hassan Krishanmurthy. "Design and analysis of shell and tube heat exchanger." International Journal for Simulation and Multidisciplinary Design Optimization 13 (2022): 15.

[125]Yousufuddin, Syed, et al. "Design and Optimization of a Shell and Tube Heat Exchanger with Different Baffle Spacing Arrangement for Cooling Lean Diethanolamine." SF J Chem Res 2.1 (2018): 2.