



Prifysgol Cymru

Y Drindod Dewi Sant

University of Wales

Trinity Saint David

Wales Institute for Science and Art (WISA)

BEng (Hons) Mechanical Engineering

**Analysis of Fouling in Industrial Shell
and Tube Heat Exchangers**

Joshua Craig Thorngate

2008670

Executive Summary

Shell and Tube Heat Exchangers are essential to many industries, including power generation, Heating, Ventilation, and Air Conditioning systems, and the oil and gas sector. They have been used since early industrialisation. They have a shell that houses several tubes established based on the application requirements and fluid properties. These versatile devices help two fluids transfer heat effectively. However, fouling, the accumulation of unwanted substances, can impair their performance. Routine maintenance and cleaning using mechanical or chemical methods are necessary to prevent fouling and preserve effectiveness. Predictive maintenance is also utilised to avoid problems early.

Ebert and Panchal's fouling model has contributed to Shell and Tube Heat Exchanger Design. It mathematically predicts fouling rates and understanding of these rates allows for the balance of the deposition and mitigation terms, driving more effective heat exchanger designs to optimise fouling resistance. One outcome of this model is the design of Helical Baffles, which reduce the deposition term by providing more uniform fluid flow distribution, whilst increased shear stress increases the mitigation term; combined, this reduces fouling and improves heat transfer efficiency. Also, helical baffles are preferred in contemporary heat exchangers due to their enhanced thermal performance, reduced pressure drop, and simpler maintenance.

Analytical analysis of fouling in Shell and Tube Heat Exchangers indicates that fouling decreases the heat transfer rates. Furthermore, the increase in fouling thickness has a greater effect on heat transfer rates than the fouling materials' thermal conductivity. Therefore, as a fouling substance increases in thickness within a heat exchanger, the effective area for heat transfer decreases; thus, as the total area decreases, heat transfer rates decrease at a linear rate.

Table of Contents

1.0. Introduction.....	1
2.0. Shell and Tube Heat Exchangers: Overview.....	2
2.1. History.....	2
2.2. Industrial Applications.....	3
2.3. Design	5
2.3.1. Tubes.....	8
2.3.2. Shells.....	9
2.3.3. Baffles	9
2.3.4. Tube Sheets	10
2.3.5. Nozzles.....	11
2.3.6. Specific Application and Summary	11
2.4. Fouling	11
2.4.1. Principles of Fouling.....	12
2.4.2. Cleaning and Maintenance.....	13
3.0. Ebert and Panchal's Fouling Model.....	14
3.1. Fouling Model Explanation	14
3.2. Helical Baffles	15
3.3. Helical Baffle Application Justification.....	16
4.0. Mathematical Analysis of Fouling's Impact on Heat Transfer	20
4.1. Heat Transfer Rate for the 'New' Condition (No Fouling Present).....	20
4.2. Heat Transfer Rate for the 'Fouled' Condition	22
4.3. Model of Increasing ZnS Deposit	23
5.0. Conclusion	27
References.....	28
Figure References.....	31
Graph References.....	32

Table References	33
-------------------------------	-----------

Table of Figures

Figure 1. Heat Exchanger Development History (Mehta, 2022)	2
Figure 2. Shell and Tube Heat Exchanger (Cavallo, 2023)	6
Figure 3. STHE Design – Component Reference Numbers (Brogan, 2011).....	7
Figure 4. Shell Construction (Heat Exchanger: Materials & Construction - Shell & Tube, 2023)	9
Figure 5. Baffle Arrangements (Heat Exchanger: Materials & Construction - Shell & Tube, 2023)	10
Figure 6. Tube Sheets (Heat Exchanger: Materials & Construction - Shell & Tube, 2023) ...	11
Figure 7. STHE with Helical Baffles (De et al., 2017).....	15

Table of Graphs

Graph 1. Pressure Drop for given Helix Angles (De et al., 2017).....	17
Graph 2. Heat Transfer Coefficient for given Helix Angles (De et al., 2017).....	18
Graph 3. Segmental vs Helical Baffles for Pressure Drop (Kunwer et al., 2020)	19
Graph 4. Heat Transfer Rate Vs Internal Area Reduction due to Fouling.....	24
Graph 5. Heat Transfer Rate Vs Fouling Thickness	25
Graph 6. Percentage of Heat Transfer Rate Reduction Vs Percentage of Internal Area Reduction	26

List of Tables

Table 1. STHes - Industrial Applications.....	4
Table 2. STHes Advantages and Disadvantages (Shell and Tube Type Heat Exchangers, 2023)	5
Table 3. STHE Design - Bill of Materials for Reference Numbers (Brogan, 2011)	8
Table 4. Fouling Principles (Kazi, 2012).....	12
Table 5. Helix Angle's Affect on Pressure and Heat Transfer (De et al., 2017)	18
Table 6. Parameters.....	20
Table 7. Analysis Assumptions	26

1.0. Introduction

Due to their versatile heat transfer capabilities, Shell and Tube Heat Exchangers are vital in various industries. This report delves into their history, design, and applications, emphasising the importance of analysis for optimising thermal performance, minimising fouling, and creating efficient, adaptable heat exchangers to satisfy diverse industrial demands.

2.0. Shell and Tube Heat Exchangers: Overview

In heat exchangers, heat is transferred without the fluids being mixed. Many industries have used Shell and Tube Heat Exchangers (STHEs) for over a century. They are used in processes like heating, cooling, and condensation.

STHEs have many benefits and are easy to use, versatile, and effective for various applications. However, STHEs are easily fouled, mainly when segmented baffle geometry is employed. As a result, this section comprehends the history, uses, and design of these heat exchangers, discusses the fouling mechanisms, and provides a list of the necessary upkeep and cleaning techniques.

2.1. History

Heat exchangers as a concept have been around for centuries. The development and understanding of heat exchangers have evolved with contributions from many scientists and engineers. One of which is that of Sir Benjamin Thompson, whereby in the early 18th century, made many contributions to heat exchanger devices, which led to modern heat exchangers. The development of heat exchangers regarding STHEs is shown in Figure 1 (Wisniak, 2016).

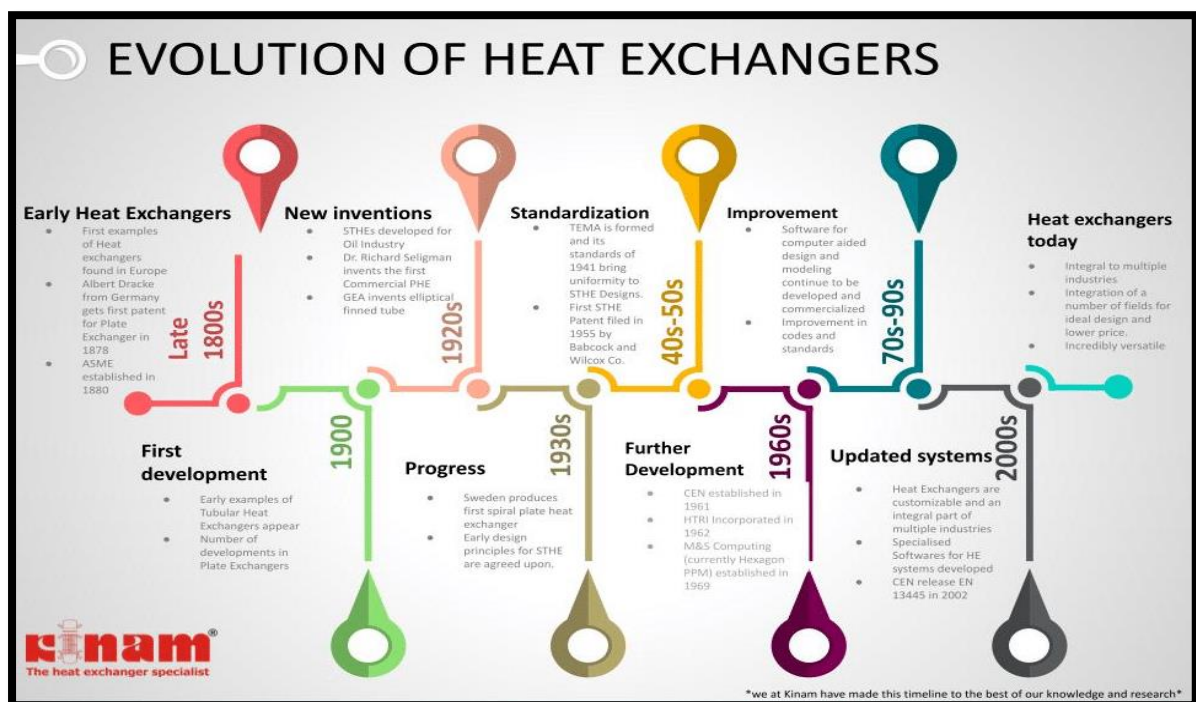


Figure 1. Heat Exchanger Development History (Mehta, 2022)

In the early 1900s, the basic design of STHes emerged to meet the demands of power plants and the growing oil industry. The methods focused on material strength and manufacturing techniques. The oil industry expanded in the 1920s, and early STHE designs were created to serve as reboilers, condensers, and oil heaters/coolers in crude oil plants. They were made for extreme conditions and high pressure. Initially, designs prioritised material strength with rudimentary estimates of heat transfer (Mehta, 2022)

In the 1930s, as new information on ideal tube banks emerged, designers established sound design principles using their intuition. Exchangers that use water-steam and water-water were created with fouling resistances in mind. Since shell-side pressure drop was not mentioned in literature until the late 1940s, viscous flow remained a challenging issue for shell-side flow until the 1960s (Mehta, 2022).

Modern STHes feature improved materials such as corrosion resistance, optimised tube arrangements, and enhanced heat transfer performance. Ongoing research and development continue to refine STHE design and performance (Taborek, 2023).

2.2. Industrial Applications

Due to their adaptability and durability, STHes are versatile and frequently used in various industries. Typical industrial applications are shown in Table 1. The advantages and disadvantages of using STHes are shown in Table 2.

Table 1. STHes - Industrial Applications

Industrial Application	Description
Power Generation	In power plants, STHes pre-heat boiler feedwater, condense steam in surface condensers, and cool turbine lubrication oil (<i>Application and Advantages of Shell and Tube Heat Exchanger</i> , 2023).
Chemical and Petrochemical Industry	In procedures like distillation, reaction, and separation, these heat exchangers are essential for heating, cooling, or condensing different chemicals and hydrocarbons (<i>Application and Advantages of Shell and Tube Heat Exchanger</i> , 2023).
Oil and Gas Industry	STHes are employed in oil and gas applications for pre-heating crude oil, cooling natural gas, and regasifying Liquefied Natural Gas (LNG) (<i>Application and Advantages of Shell and Tube Heat Exchanger</i> , 2023).
HVAC and Refrigeration	STHes are used in Heating, Ventilation, and Air Conditioning (HVAC) systems and Refrigeration systems to transfer heat between fluids (Evans, 2018).
Food and Beverage Industry	STHes are used in the food and beverage industry in procedures and processes such as pasteurisation, sterilisation, cooking and cooling (<i>The Benefits of heat exchangers in Process and Clean in Place</i> , 2020).
Pharmaceutical Industry	STHes are used in the pharmaceutical industry to heat or cool different process fluids, maintain temperature control during manufacturing, and guarantee product quality (<i>The Benefits of heat exchangers in Process and Clean in Place</i> , 2020).
Pulp and Paper Industry	STHes are used in pulp and paper mills to heat or cool process fluids, recover heat from waste streams, and regulate the temperature throughout various manufacturing processes (<i>Why BEPeterson is the Best Option for Custom Shell and Tube Heat Exchanger Manufacturing</i> , 2023).
Marine and Shipbuilding Industry	In marine applications, STHes are used to cool engines, condense steam, and control temperature in shipboard systems (Anish, 2021).

Table 2. STHEs Advantages and Disadvantages (Shell and Tube Type Heat Exchangers, 2023)

Advantages	Disadvantages
Less expensive than plate heat exchangers.	Less effective heat exchanger compared to a plate heat exchanger.
Relatively easy to maintain with a simple design.	More room is needed in order to open and remove tubes.
Superior to plate heat exchangers in that it can withstand higher pressures and temperatures.	In contrast to a plate heat exchanger, cooling capacity cannot be increased.
It has a lower pressure drop than a plate heat exchanger.	
Leaking tubes are simple to locate and isolate.	
To lessen the possibility of the fluid from the shell side leaking into the tube side fluid, tubes can be "double-walled" (or vice versa).	
Sacrifice anode installation is simple.	
They are not as susceptible to fouling compared with plate heat exchangers.	

2.3. Design

A STHEs design (see Figure 2) includes several essential elements that can be altered depending on the application to optimise performance and guarantee compatibility with the fluids and operating conditions.

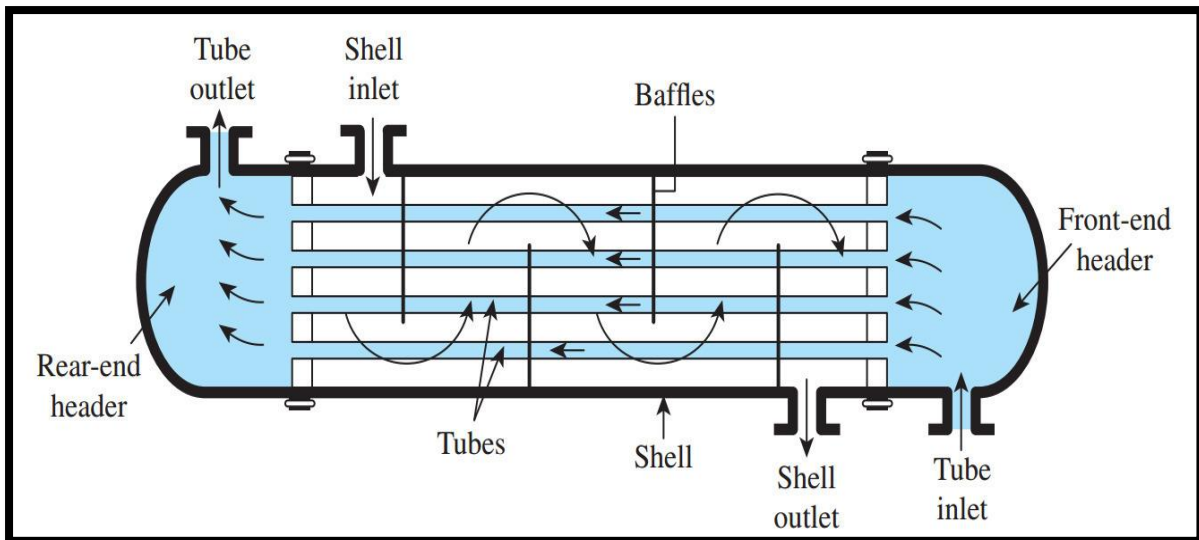


Figure 2. Shell and Tube Heat Exchanger (Cavallo, 2023)

The Tubular Exchangers Manufacturers Association, or TEMA, governs heat exchangers using shell and tube technology. The designs can be sorted into three main categories: Front-end Header, Shell, and Rear-end Header. Each category is identified by a letter. This report only focuses on the three most prevalent TEMA standard heat exchangers, despite each component being available in a wide range of variations. U-tube, fixed tube sheet, and floating head heat exchangers are the three types of these devices (Cavallo, 2023).

Fixed Tube Sheet Heat Exchangers have their tube sheets permanently welded to the exchanger's shell. Due to their simplicity, affordability, and low maintenance requirements, they are suitable for applications with moderate fluid temperature differences. Common applications include HVAC systems, water heating, and oil cooling (Brogan, 2011).

U-Tube Heat Exchangers have U-shaped tubes, accommodating large temperature differences or thermal cycling. Heat recovery systems, cryogenic cooling, and steam condensation are examples of applications involving high-temperature variations or aggressive fluids that are ideal for this design (Cavallo, 2023).

Floating Head Heat Exchangers can handle differential thermal expansion because their tube sheet is free to move. They are frequently used in the petrochemical and chemical industries, where regular cleaning and inspection are required to avoid corrosion and fouling. They are appropriate for applications requiring simple access for upkeep and cleaning (Cavallo, 2023).

There are many components in the design of STHes, as shown in Figure 3, with Table 3 describing the components. However, the main components are discussed in section 2.3.1. to 2.3.5.

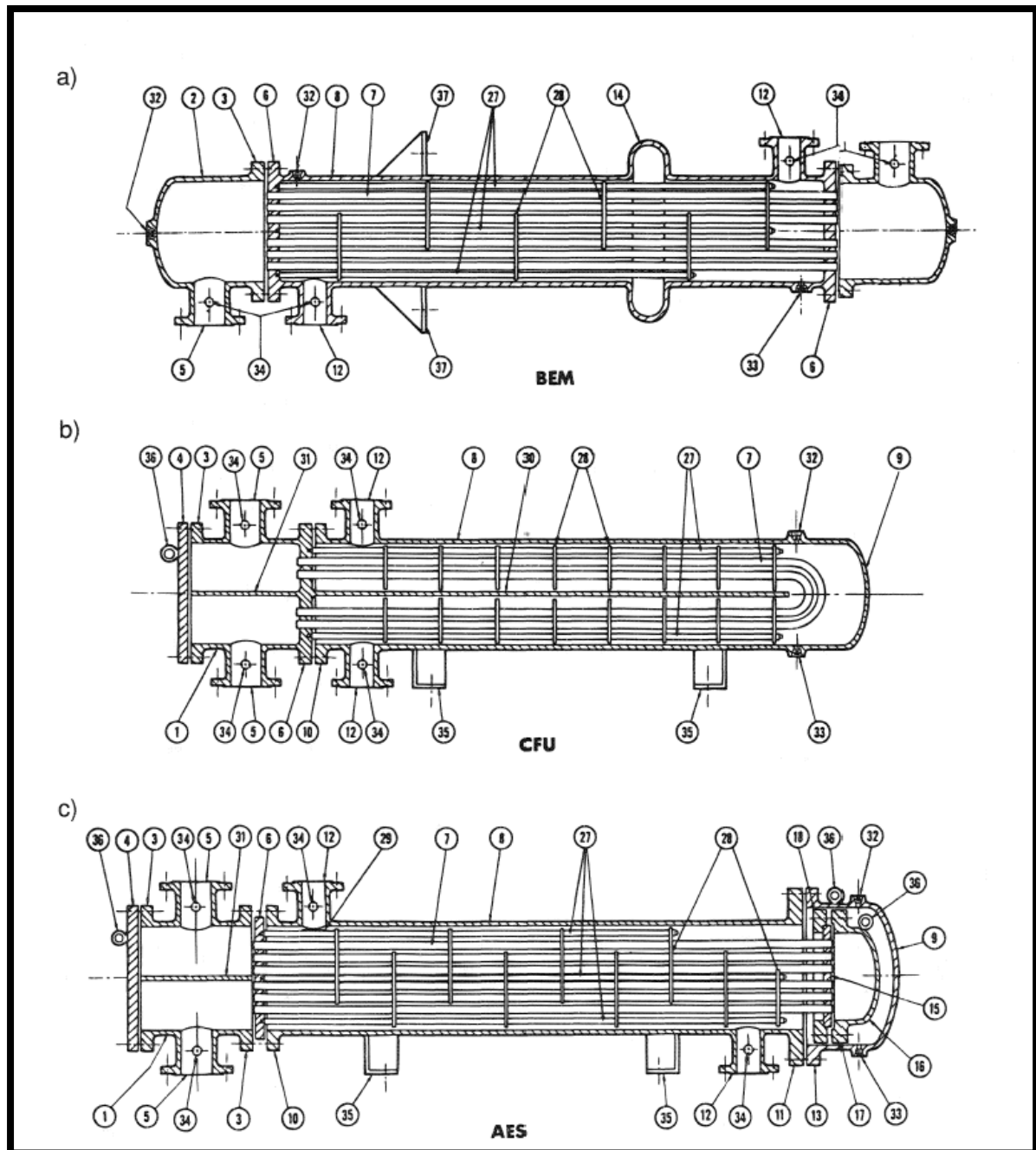


Figure 3. STH Design – Component Reference Numbers (Brogan, 2011)

Table 3. *STHE Design - Bill of Materials for Reference Numbers (Brogan, 2011)*

1	Stationary (Front) Head—Channel	20	Slip-on Backing Flange
2	Stationary (Front) Head—Bonnet	21	Floating Tubesheet Skirt
3	Stationary (Front) Head Flange	22	Floating Tubesheet Skirt
4	Channel Cover	23	Packing Box Flange
5	Stationary Head Nozzle	24	Packing
6	Stationary Tubesheet	25	Packing Follower Ring
7	Tubes	26	Lantern Ring
8	Shell	27	Tie Rods and Spacers
9	Shell Cover	28	Transverse Baffles or Support Plates
10	Shell Flange—Stationary Head End	29	Impingement Baffle or Plate
11	Shell Flange—Rear Head End	30	Longitudinal Baffle
12	Shell Nozzle	31	Pass Partition
13	Shell Cover Flange	32	Vent Connection
14	Expansion Joint	33	Drain Connection
15	Floating Tubesheet	34	Instrument Connection
16	Floating Head Cover	35	Support Saddle
17	Floating Head Flange	36	Lifting Lug
18	Floating Head Backing Device	37	Support Bracket
19	Split Shear Ring		

2.3.1. Tubes

Copper, Brass or Stainless Steel are typical material choices for the Tubes due to their high thermal conductivity. The choice of material is influenced by the temperature requirements, required corrosion resistance, and fluid properties. For instance, copper tubes are appropriate for HVAC systems, while stainless steel tubes are ideal for chemical processing.

Tubes can be corrugated, finned, or left plain to improve heat transfer. Designs are based on desired heat transfer rate, fouling potential, and pressure drop restrictions. For example, Finned Tubes are best suited for applications involving highly viscous fluids with low heat transfer coefficients to improve heat transfer efficiency due to the increased surface area whilst increasing turbulence, thus, disrupting the boundary layer to expose the bulk fluid to more of the tube (*Shell and Tube Type Heat Exchangers*, 2023).

2.3.2. Shells

Corrosion Resistance and strength requirements affect the design of the shells (Figure 4). However, they are typically made of carbon steel, stainless steel, or other suitable materials. Depending on the application's space restrictions and necessary fluid flow patterns, shells can have a variety of shapes, such as cylindrical, square, or rectangular (*Heat Exchanger: Materials & Construction - Shell & Tube*, 2023).

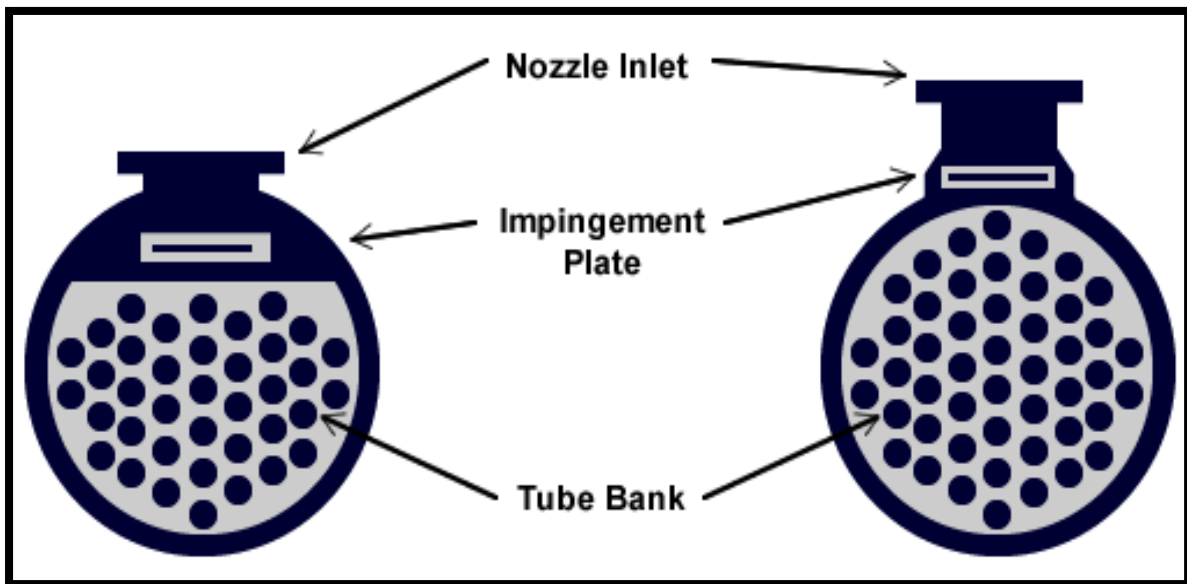


Figure 4. Shell Construction (*Heat Exchanger: Materials & Construction - Shell & Tube*, 2023)

2.3.3. Baffles

Single-segmental, double-segmental (Figure 5), and rod baffles are examples of various types of baffles which can be utilised. They are all manufactured with the same material as the shell. By directing the fluid flow from the shell across the tubes, baffles increase heat transfer efficiency. The required heat transfer rate, fluid properties on the shell side, and pressure drop restrictions all affect baffle design (De *et al.*, 2017, p.379).

Tie rods and spacers maintain the chosen baffle spacing and hold the baffle assembly together (Smith, 2023).

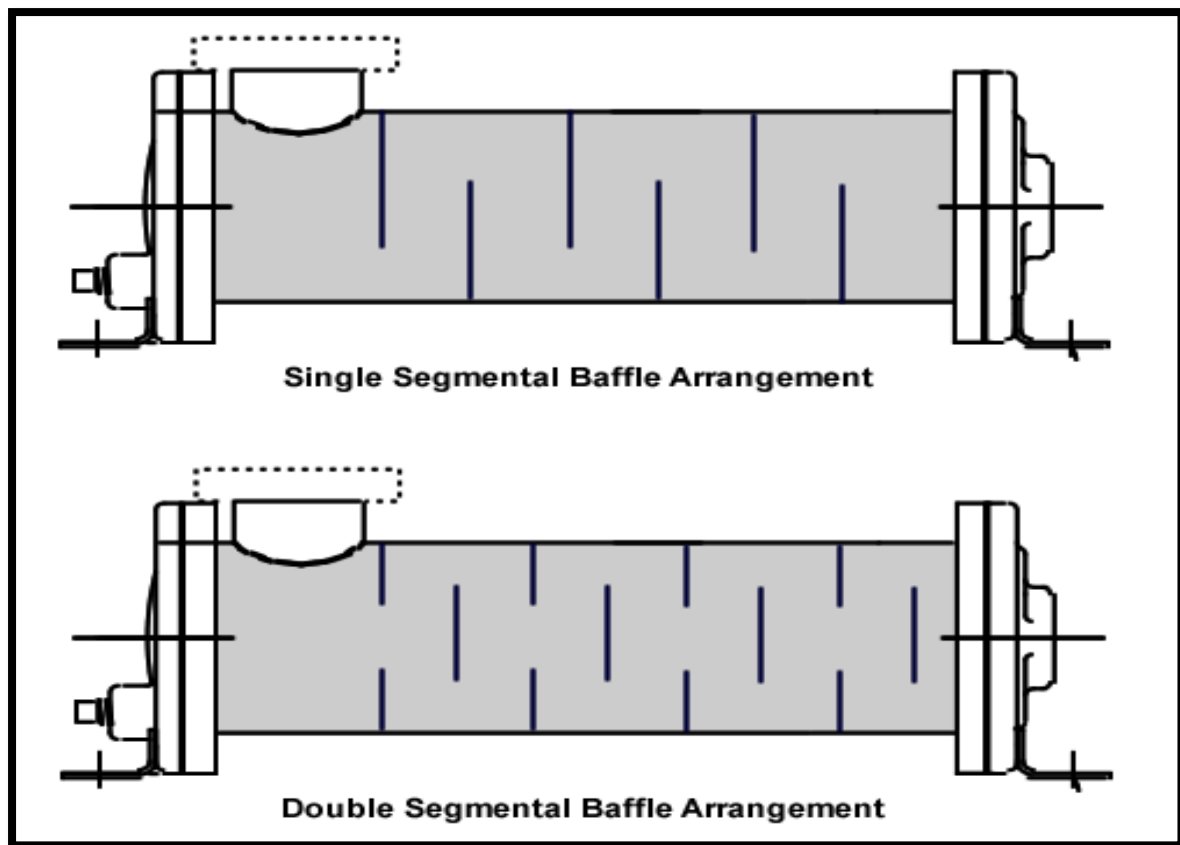


Figure 5. Baffle Arrangements (*Heat Exchanger: Materials & Construction - Shell & Tube*, 2023)

2.3.4. Tube Sheets

Tube sheets (Figure 6) are made from a flat, round metal sheet with holes drilled through the centre for the tube ends. They are attached using tube expansion methods using tools such as a pressure roller. Tube sheets are also constructed from the same material as the tubes.

Tube sheets in heat exchangers are made from corrosion-resistant materials due to their contact with both fluids in the system. The arrangement of tube holes can be modified for better heat transfer. Tubes and tube sheets are joined using weldable metals and reinforced with additional strength welds or seal welds. To prevent fluid mixing, a second tube sheet may be used (*Heat Exchanger: Materials & Construction - Shell & Tube*, 2023).

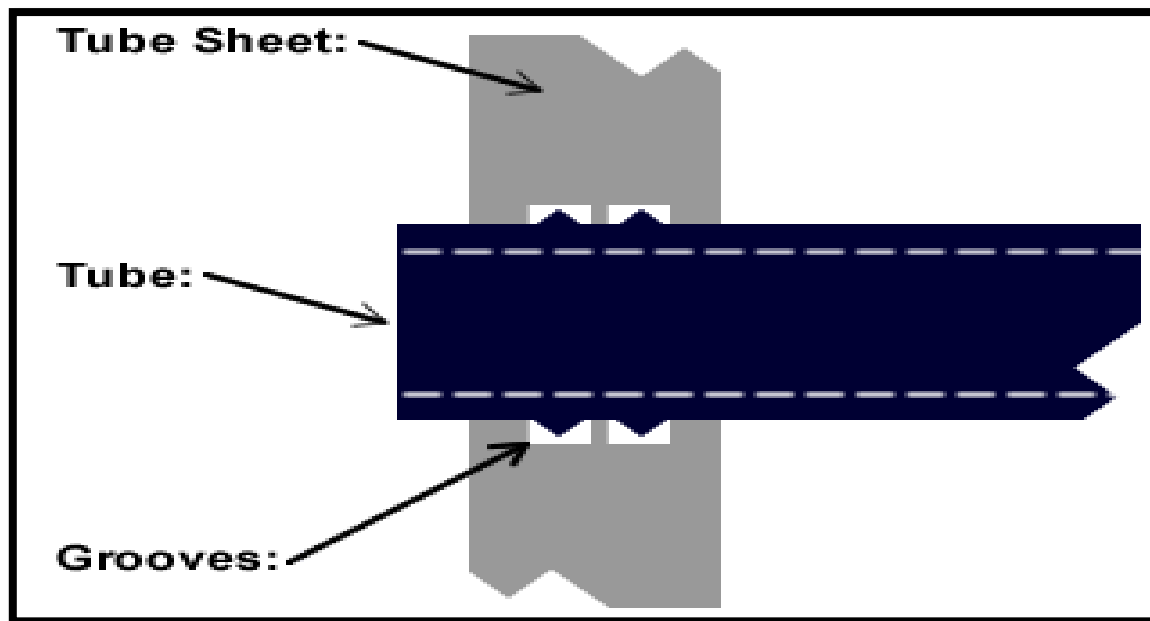


Figure 6. Tube Sheets (Heat Exchanger: Materials & Construction - Shell & Tube, 2023)

2.3.5. Nozzles

Nozzles are the inlets and outlets; their size and position ensure effective heat transfer and fluid flow. The required flow rates, operating pressures, and fluid characteristics affect nozzle design. Nozzles may be constructed from stronger or more corrosion-resistant materials in applications involving high-pressure or corrosive fluids. The tube and shell have inlet and outlet nozzles (Smith, 2023).

2.3.6. Specific Application and Summary

By choosing the appropriate materials, configurations, and component dimensions, STHes' designs can be made to fit a variety of applications. The design decisions are influenced by fluid properties, operating temperatures, pressures, and space limitations to ensure effective heat transfer and compatibility with the application's requirements.

2.4. Fouling

In STHes, segmental baffles are typically used to direct fluid flow from the shell side across the tubes, causing turbulence and enhancing heat transfer. However, these baffles can also promote and exacerbate shell-side fouling, which has a negative impact on the effectiveness of heat transfer. The primary fouling mechanisms, as well as the necessary upkeep and cleaning methods, are covered in this section (Kazi, 2012).

2.4.1. Principles of Fouling

Table 4 shows typical principles of fouling whilst describing them in detail.

Table 4. Fouling Principles (Kazi, 2012)

Fouling Principle	Description
Precipitation Fouling	Also referred to as Scaling , this is the build-up of solid deposits on heat transfer surfaces as a result of the fluid being oversaturated with dissolved salts. The solubility of these salts decreases as the fluid temperature rises, causing precipitation and deposition on the heat exchanger surfaces. Due to the salts in the fluids, this is also known as Crystallisation Fouling (Kazi, 2012).
Chemical Reaction Fouling	Occurs when chemical reactions that are frequently started by high temperatures, high fluid concentrations, or contact with reactive surfaces lead to solid deposits forming on heat transfer surfaces. This kind of fouling, like the development of carbonaceous material deposits from the thermal gradation of process stream components, can be very tenacious and necessitate special cleaning procedures to ensure satisfactory operation life (Kazi, 2012).
Corrosion Fouling	When heat transfer surfaces and fluid interact, corrosion and other deposits like oxide layers are created. These deposits have the potential to reduce heat exchanger efficiency, compromise structural integrity, and even lead to deposition further down the process loop. Corrosion, which occurs more frequently on the liquid side of heat exchangers, can be influenced by variables, including the pH value and the amount of sulphur in the fuel (Kazi, 2012).
Biofouling	When microorganisms like bacteria, algae, and fungi develop on heat transfer surfaces, they create biofilms that impede heat transfer and encourage corrosion. This process is sometimes known as Biological Fouling . In heat exchanger operations across various industries, such as food processing and power plants using seawater for cooling, this growth of biological materials, including seaweeds, waterweeds, and barnacles, can result in microbial fouling and is a prevalent issue. The growth of connected organisms on these surfaces can lead to serious operating difficulties and a loss of efficiency (Kazi, 2012).
Particulate Fouling	Solid particles suspended in the process stream create Particulate Fouling, thus, a build-up on the heat transfer surface. Gravity causes heavy particles to settle on a horizontal surface, and suction force or other mechanisms cause fine particles to settle onto heat transfer surfaces at various angles. Particulate Fouling includes unburned fuel or ash build-up on boiler tubes, dust build-up on air-cooled condensers, and so on (Kazi, 2012).

2.4.2. Cleaning and Maintenance

Kazi (2012) highlights the importance of cleaning and maintaining heat exchangers to minimise fouling-related degradation. **Online Cleaning** techniques allow for maintenance without disassembly. **Mechanical methods** are used, such as pulsating water jets to remove fouling, cavitation-based ultrasonic cleaning, sponge-ball systems to wipe tubes clean and brush systems to remove deposits are common methods. With these techniques, efficiency is maintained while interference is reduced. However, these can be costly and may not provide thorough cleaning.

Disassembly and process interruption are necessary for **Offline Cleaning** techniques to provide thorough cleaning. Among them are **Manual Cleaning** with hand tools, **Mechanical Cleaning** with high-pressure water or steam and lances or water guns, and **Chemical Cleaning** using agents such as acids or alkaline solutions, which dissolve or disperse the fouling deposits, which are useful to access tight spaces without endangering mechanical components. Even though they are efficient, offline methods demand downtime and careful handling, with the additional risk of chemical corrosion (Kazi, 2012).

Fryer (2021) recommends **Preventative Maintenance** based on routine inspections, using detection methods like physical inspections or measuring heat transfer rates and pressure drops. Fouling factors affecting the maintenance schedule include fluid velocity, temperature, chemistry, and fabrication materials. The fluids' propensity to foul, the working environment, and the heat exchanger design are a few variables that affect how frequently maintenance is required.

Design Changes, such as alternative baffle designs such as helical or rod baffles or corrosion-resistant materials, can help reduce fouling potential. Surface coatings also effectively mitigate corrosion fouling (Fryer, 2021).

3.0. Ebert and Panchal's Fouling Model

Fouling is a major concern in STHes, as it reduces thermal efficiency and increases pressure drop, leading to higher operating costs and maintenance requirements. Ebert and Panchal (1997) proposed a fouling model that has significantly influenced the design of heat exchangers, particularly concerning the implementation of Helical Baffles.

3.1. Fouling Model Explanation

The fouling model proposed by Ebert and Panchal (1997) is a mathematical representation of the fouling process in heat exchangers. Master *et al.* (2003, p.3) states the fouling model is:

$$\frac{dR_f}{dt} = \alpha \cdot Re^\beta \cdot Pr^\delta \cdot \exp\left(\frac{-E}{RT_f}\right) - \gamma\tau$$

This equation predicts the fouling rate $\left(\frac{dR_f}{dt}\right)$ in a heat exchanger as a function of the Reynolds number (Re), the Prandtl number (Pr), the fluid temperature (T_f), and the time elapsed since the last cleaning or the start of the fouling process (τ). The constants $\alpha, \beta, \delta, \gamma$, and E depend on the specific heat exchanger system and the fluid being processed. The model implies that it is possible to successfully maintain circumstances lower than the threshold conditions in a particular heat exchanger by exploiting its geometry, as this can influence the film and surface temperatures, shear stresses, and fluid velocities (Master *et al.*, 2003 p.3).

A simple explanation of the model is that the average linear fouling rate (R_f) within defined parameters is the outcome of two antagonistic terms: a deposition term (R_d) and a mitigation term (R_m) (Ibrahim, 2012). The following equation can represent the fouling rate:

$$R_f = R_d - R_m$$

The deposition term (R_d), which affects how deposits build up on heat transfer surfaces, is influenced by fluid properties, flow velocity, and heat transfer surface characteristics. The term "mitigation" (R_m) refers to the process of removing deposits using different mechanisms, such as shear stress brought on by fluid flow, thermal cycling, or chemical cleaning (Master *et al.*, 2003, p.3).

The fouling model suggests that minimising fouling requires balancing the terms by reducing deposition and enhancing mitigation. The aim is to design more effective heat exchangers, experience less fouling, and sustain superior thermal performance over time. This can be

achieved by understanding and addressing the factors that cause fouling during the design stage of heat exchangers. One significant advancement in this area is the incorporation of helical baffles in STHes, demonstrating how this approach has greatly improved heat exchanger design. However, using the simplified model is limited to simple fouling and cannot be utilised for complex fouling such as biofouling.

Helical baffles address the thermodynamics of shell side flow by lowering the flow dispersion that is principally responsible for decreasing heat exchanger efficiency. The helical baffle designs achieve the least dispersion (high Peclet numbers) closer to a plug flow condition, increasing the heat exchanger's thermal efficiency (Master *et al.*, 2003, p.3).

3.2. Helical Baffles

A helical baffle, shown in Figure 7, is used in STHes to guide fluid flow and improve heat transfer efficiency. Unlike traditional segmental baffles consisting of flat, circular plates with segments removed, helical baffles are continuous, with curved surfaces that spiral around the tube bundle within the heat exchanger.

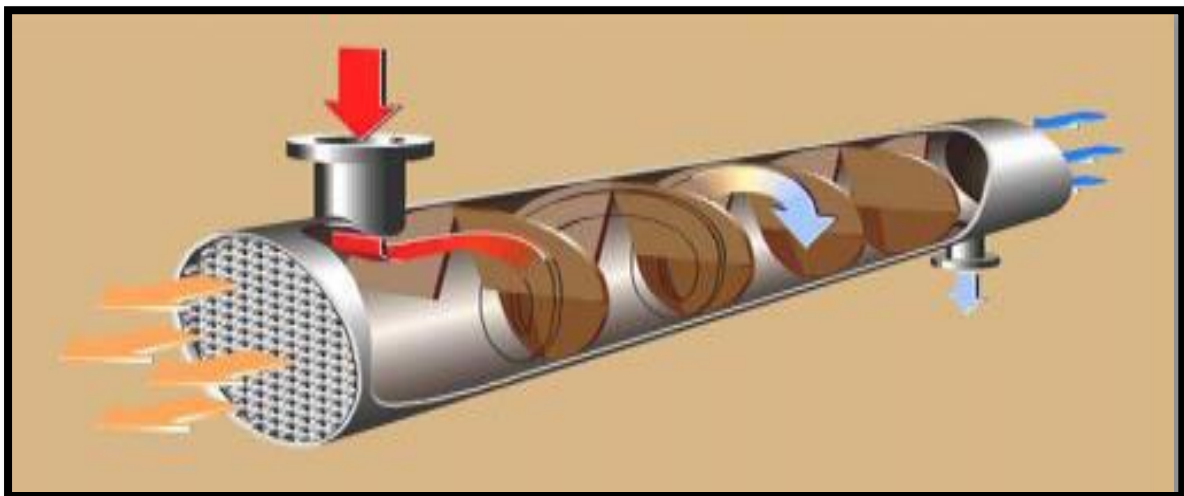


Figure 7. STHE with Helical Baffles (De *et al.*, 2017)

A baffle in a heat exchanger directs fluid flow across the tube bundle, thereby enhancing heat transfer and preventing fluid bypass. Helical baffles achieve this by guiding the fluid in a helical or spiral flow pattern along the tube bundle, promoting turbulence and flow distribution.

Ebert and Panchal's fouling model has led to the development of helical baffles by providing a clearer understanding of the fouling process and emphasising the need to balance deposition and mitigation factors.

Engineers and researchers, inspired by the model, sought innovative design solutions to minimise fouling and improve the overall performance of heat exchangers. Helical baffles were developed as a result of these efforts.

The connection between Ebert and Panchal's fouling model and helical baffles lies in the way the baffles address the model's key components:

- **Reduction of the deposition term (R_d):** Helical baffles create a more uniform flow distribution, reducing dead zones and stagnation points where particles can deposit on the heat transfer surfaces. This helps to minimise the deposition term in the fouling model.
- **Enhancement of the mitigation term (R_m):** The helical flow pattern created by helical baffles increases wall shear stress, which helps remove deposits from the heat transfer surfaces. This contributes to the mitigation term in the fouling model.

By addressing both components of the fouling model (R_d and R_m), helical baffles offer an effective solution to minimise fouling and improve heat transfer performance. This direct link between the fouling model and the development of helical baffles showcases how the model has shaped the design and innovation of STHs (Master *et al.*, 2003, pp.1-7).

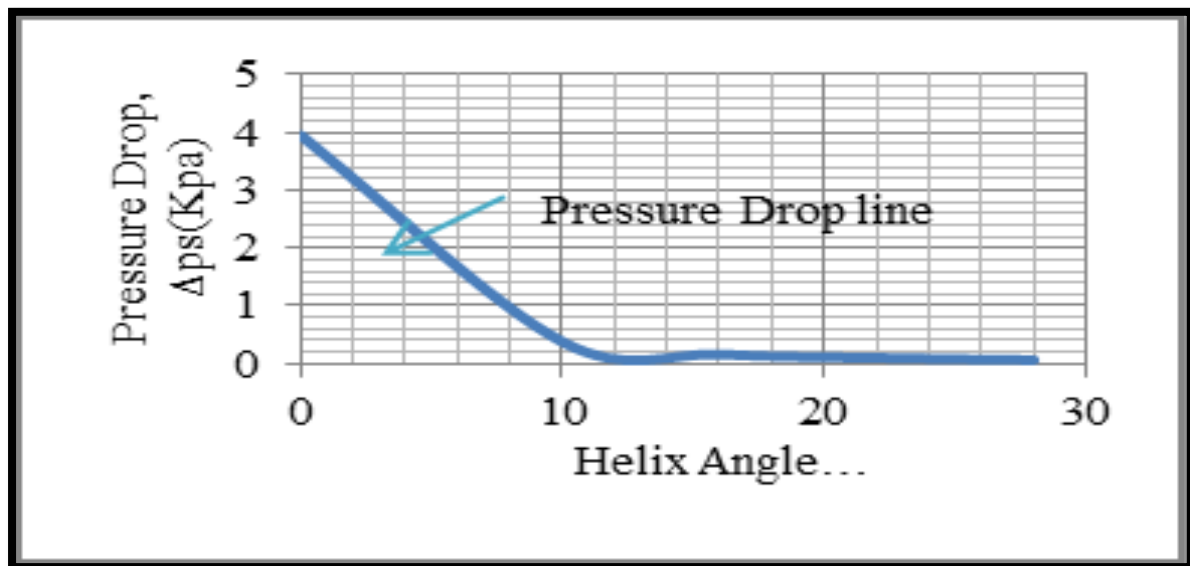
3.3. Helical Baffle Application Justification

Segmental baffles, commonly used in conventional STHs, may be ineffective at preventing fouling. Researchers have found that helical baffles provide a more potent remedy. The heat exchanger's helical baffles have the following benefits:

- **Improved Heat Transfer:** Because of the increased turbulence and improved fluid distribution produced by the helical flow pattern created by these baffles, heat transfer is more effectively facilitated. As a result, the thermal performance is enhanced, and the overall heat transfer coefficient (U) is raised (Master *et al.*, 2003, p.4).
- **Reduced Fouling:** As a result of reducing dead zones and stagnation points, where fouling is more likely to occur, helical baffles produce a more uniform flow distribution. The continuous flow pattern also maintains a higher wall shear stress, which can reduce fouling and prevent particle deposition (Master *et al.*, 2003, p.4).

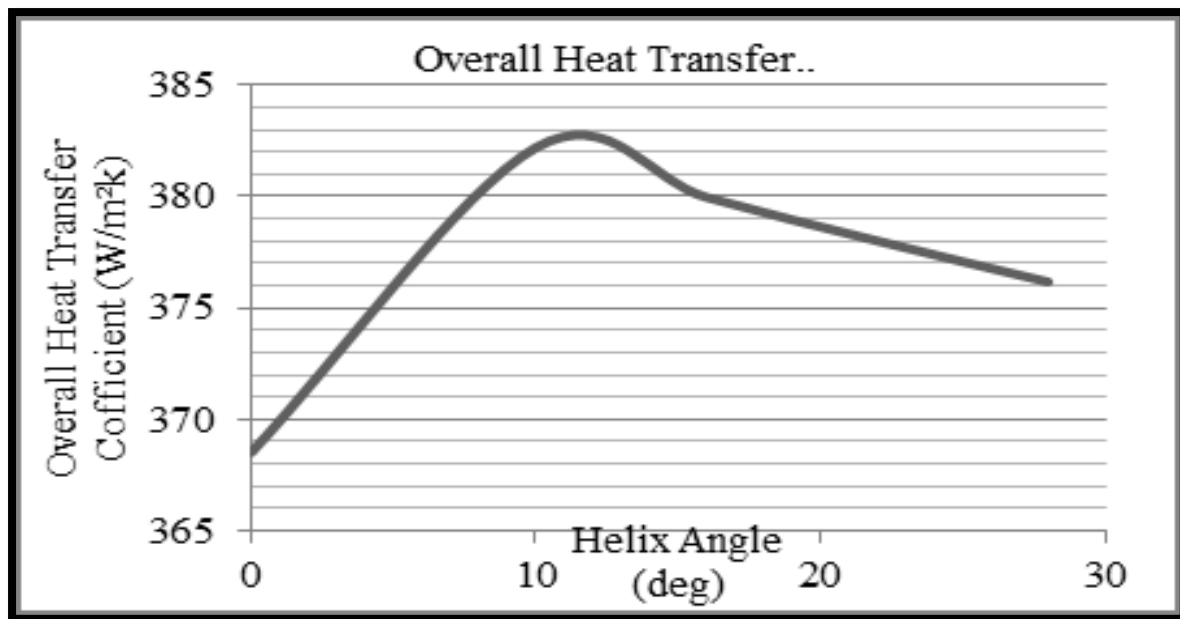
- **Lower Pressure Drop:** Compared to segmental baffles, the helical flow pattern has fewer abrupt changes in the flow direction, which lowers the pressure drop across the heat exchanger. Therefore, less energy is needed to pump fluid through the exchanger (De *et al.*, 2017, p. 379).
- **Easier Maintenance:** Cleaning and maintaining the heat exchanger is easier as helical baffles can be removed and replaced without requiring complete disassembly (De *et al.*, 2017, p. 379).

Helical baffles in STHes have been shown to be effective in numerous studies. De *et al.* (2017, p. 379) state that a helix angle controls the angle between a tangent line drawn on the helical surface and the helical baffle's rotation axis. The helix angle affects the heat exchanger's parameters for pressure drop and heat transmission. Tests are performed for these baffles, whereby the helix angle can directly affect pressure drop, as Graph 1 shows. It can be seen there is an optimal angle whereby there is no longer a pressure drop, and thus, smoother flow paths reduce flow-induced vibrations and noise.



Graph 1. Pressure Drop for given Helix Angles (De *et al.*, 2017)

The helix angle also affects the heat transfer coefficient, as Graph 2 shows. It can be seen there is an optimal angle before negative returns occur. These results are shown clearly in Table 5. It can be seen that the optimal angle is between 10-16 degrees.

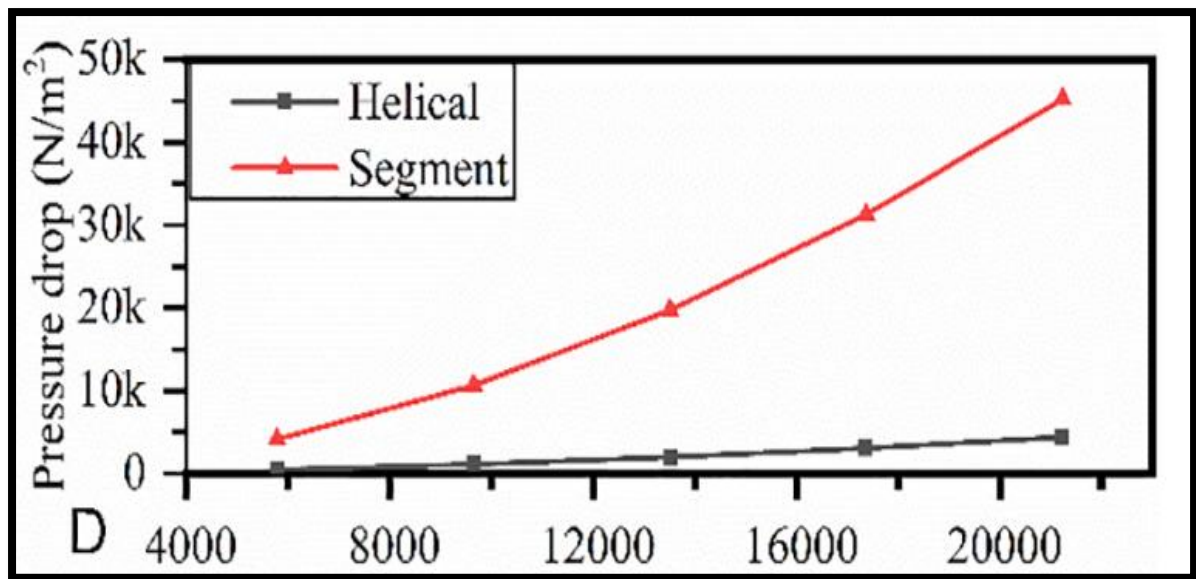


Graph 2. Heat Transfer Coefficient for given Helix Angles (De et al., 2017)

Table 5. Helix Angle's Affect on Pressure and Heat Transfer (De et al., 2017)

Helix Angle (deg)	Heat transfer Coefficient, h_s W/m²k	Over All Heat Transfer Coefficient W/m²k	Pressure Drop Δ_{ps} (Kpa)
Straight	6789.786	368.514	3.9545
10	19938.1529	382.196	0.3795
16	15259.0253	379.963	0.1634
22	12638.72	378.012	0.0994
28	10866.616	376.17	0.0629

Kunwer *et al.* (2020, p.5) support these statements whilst comparing segmental baffles with helical baffles for pressure drop, as Graph 3 shows.



Graph 3. Segmental vs Helical Baffles for Pressure Drop (Kunwer *et al.*, 2020)

Wang *et al.* (2011) state throughout their report that STHs with helical baffles, compared to segmental baffles, have an average of a 7% increase in heat transfer coefficient, with the helical baffle enhancing shell-side condensation coefficients by 13% compared to segmental baffles. However, it must be noted that the majority of the report is centred around Helixchangers, which have additional features other than helical baffles.

These performance improvements due to helical baffles can be due to the previously stated advantages, such as improved fluid distribution, which reduces stagnant zones and is often responsible for fouling. Enhanced turbulence in the shell-side fluid increases the heat transfer coefficients whilst increasing the uniform distribution of shear forces on the tube side surfaces. Increased turbulence reduces particle deposition formation of fouling layers. Furthermore, helical baffles are designed to be removed, thus, allowing for easier cleaning and maintenance procedures to mitigate fouling (Master *et al.*, 2003, p.4).

4.0. Mathematical Analysis of Fouling's Impact on Heat Transfer

This section is used to understand the effects of internal pipe fouling. Calculations are carried out, analysing the Heat Transfer Rate (Q) in an STHE counterflow experimental setup for 'new' and 'fouled' conditions using the parameters shown in Table 6. A model for an increasing thickness of ZnS deposit is created, analysing its effect on heat transfer rate.

Table 6. Parameters

Parameter	Symbol	Value	Unit
Inner Pipe			
Thermal Conductivity	k	54	W/m·K
Length	L	3.05	m
Internal Diameter	d_i	0.0254	m
External Diameter	d_o	0.0381	m
Mineral Oil			
Convective Heat Transfer	h_i	100	W/m ² ·K
Fouling Factor	R_{fi}	$1.0578 \cdot 10^{-3}$	m ² K/W
Water			
Convective Heat Transfer	h_o	7300	W/m ² ·K
Fouling Factor	R_{fo}	$35.22 \cdot 10^{-6}$	m ² K/W
Temperatures			
Inlet Temperature (Oil)	T_{inOil}	160	°C
Outlet Temperature (Oil)	T_{outOil}	100	°C
Inlet Temperature (Water)	$T_{inWater}$	15	°C
Outlet Temperature (Water)	$T_{outWater}$	85	°C
Other			
Correction Factor	F	0.96	Unitless

4.1. Heat Transfer Rate for the 'New' Condition (No Fouling Present)

Heat transfer rate can be calculated using:

$$Q = U \cdot A \cdot F \cdot \Delta T$$

Note: The analysis documents answers with decimals rounded to significant places for report simplicity. However, actual calculations utilise full decimal places to ensure the most accurate answers.

First, the Inner and Outer areas (A) are calculated:

$$A_i = \pi \cdot d_i \cdot L$$

$$A_i = \pi \cdot 0.0254 \cdot 3.05$$

$$A_i = \mathbf{0.243 \, m^2 (Three Decimal Places)}$$

$$A_o = \pi \cdot d_o \cdot L$$

$$A_o = \pi \cdot 0.0381 \cdot 3.05$$

$$A_o = \mathbf{0.365 \, m^2 (Three Decimal Places)}$$

To calculate thermal resistance without fouling, the Overall Heat Transfer Coefficient (U) is used:

$$\frac{1}{U_{new}} = \frac{1}{h_o \cdot A_o} + \frac{\ln\left(\frac{d_o}{d_i}\right)}{2\pi \cdot k \cdot L} + \frac{1}{h_i \cdot A_i}$$

$$\frac{1}{U_{new}} = \frac{1}{7300 \cdot 0.365} + \frac{\ln\left(\frac{0.0381}{0.0254}\right)}{2\pi \cdot 54 \cdot 3.05} + \frac{1}{100 \cdot 0.243}$$

$$\frac{1}{U_{new}} = 0.042 \, (Three Decimal Places)$$

$$\therefore U_{new} = \mathbf{23.89 \, W/m^2K (Two Decimal Places)}$$

The Logarithmic Mean Temperature Difference (ΔT_{LM}) method is used in place of the local temperature difference. In a counterflow configuration, it is defined as:

$$\Delta T_{LM} = \frac{\Delta T_2 - \Delta T_1}{\ln\left(\frac{\Delta T_2}{\Delta T_1}\right)}$$

Whereby:

$$\Delta T_1 = T_{H,in} - T_{C,out}$$

$$\Delta T_2 = T_{H,out} - T_{C,in}$$

$$\therefore \Delta T_1 = (160 - 85) ^\circ C = 75^\circ C$$

$$\Delta T_2 = (100 - 15) ^\circ C = 85^\circ C$$

$$\therefore \Delta T_{LM} = \frac{85 - 75}{\ln\left(\frac{85}{75}\right)}$$

$$\Delta T_{Lm} = 79.9^\circ C \text{ (One Decimal Place)}$$

Therefore, the heat transfer rate can now be found using the following:

$$Q = U \cdot A \cdot F \cdot \Delta T_{LM}$$

However, the area is calculated within the overall heat transfer coefficient, therefore:

$$Q_{new} = U_{new} * F * \Delta T_{LM}$$

$$Q_{new} = 23.89 * 0.96 * 79.9$$

$$Q_{new} = 1832.51 \text{ W (Two Decimal Places)}$$

$$Q_{new} = 1.83 \text{ kW (Two Decimal Places)}$$

4.2. Heat Transfer Rate for the 'Fouled' Condition

Now the fouled condition can be calculated utilising the fouling factors for oil and water; therefore, the overall heat transfer coefficient is determined:

$$\frac{1}{U_{fouled}} = \frac{1}{h_o \cdot A_o} + \frac{R_{fo}}{A_o} + \frac{\ln\left(\frac{d_o}{d_i}\right)}{2\pi \cdot k \cdot L} + \frac{1}{h_i \cdot A_i} + \frac{R_{fi}}{A_i}$$

$$\begin{aligned} \frac{1}{U_{fouled}} &= \frac{1}{7300 \cdot 0.365} + \frac{35.22 \cdot 10^{-6}}{0.365} + \frac{\ln\left(\frac{0.0381}{0.0254}\right)}{2\pi \cdot 54 \cdot 3.05} + \frac{1}{100 \cdot 0.243} \\ &\quad + \frac{1.0578 \cdot 10^{-3}}{0.243} \end{aligned}$$

$$\frac{1}{U_{fouled}} = 0.046 \text{ (Three Decimal Places)}$$

$$\therefore U_{fouled} = 21.6 \text{ W/m}^2\text{K (One Decimal Place)}$$

Using the new overall heat transfer coefficient:

$$Q_{fouled} = U_{fouled} \cdot F \cdot \Delta T_{LM}$$

$$Q_{fouled} = 21.6 \cdot 0.96 \cdot 79.9$$

$$Q_{fouled} = 1656.66 \text{ W (Two Decimal Places)}$$

$$Q_{fouled} = \mathbf{1.66 \text{ kW (Two Decimal Places)}}$$

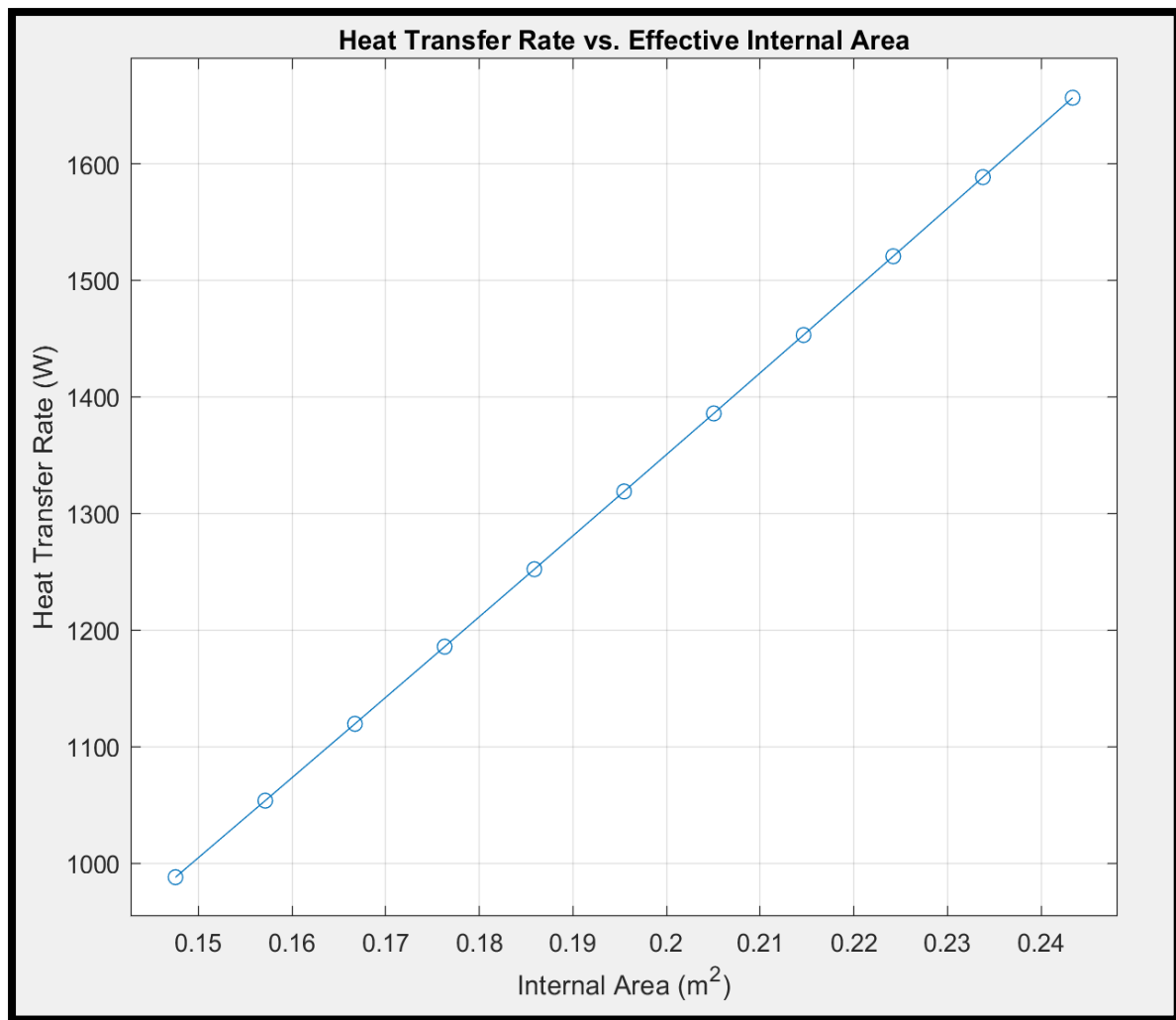
4.3. Model of Increasing ZnS Deposit

An additional fouling term (R_{fz}) is now introduced into the equation due to the Zinc Sulfide (ZnS) deposit. The thickness of ZnS deposit (t_{znS}) will increase from 0.5 mm to 5.0 mm in increments of 0.5 mm. For each thickness value, the new heat transfer rate will be calculated and plotted against the reducing internal area of the oil pipe using the Thermal Conductivity of the Zinc Sulfide (k_{znS}), which is 25.1 W/m K . The additional fouling term is included in the overall heat transfer coefficient:

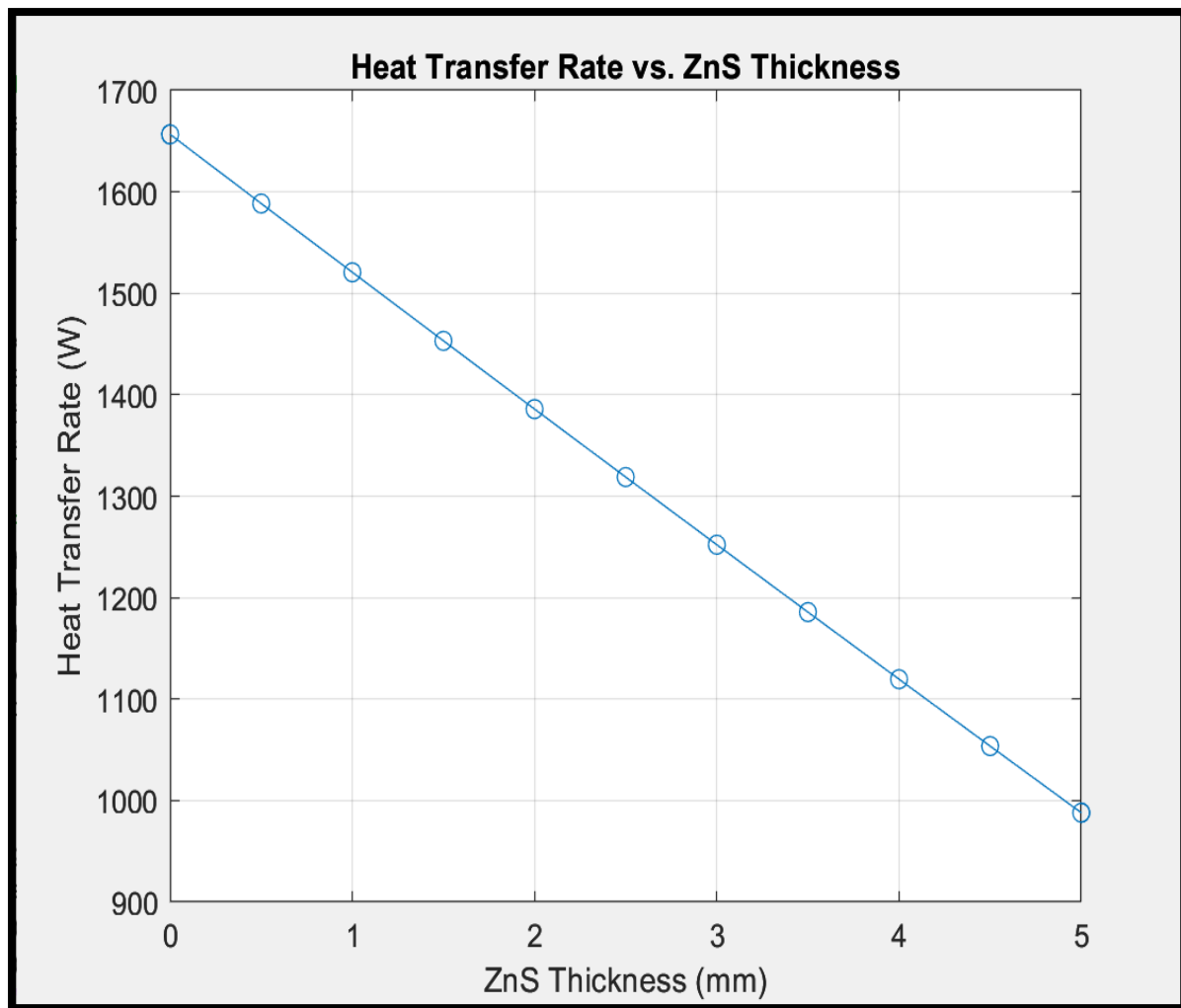
$$R_{fz} = \frac{t_{znS}}{k_{znS} \cdot A_i}$$

$$\therefore U_{znS} = \frac{1}{\frac{1}{h_o \cdot A_o} + \frac{R_{fo}}{A_o} + \frac{\ln\left(\frac{d_o}{d_{i_{new}}}\right)}{2\pi \cdot k \cdot L} + \frac{t_{znS}}{k_{znS} \cdot A_{i_{new}}} + \frac{1}{h_i \cdot A_{i_{new}}} + \frac{R_{fi}}{A_{i_{new}}}}$$

Therefore, Graph 4 shows the heat transfer rate with a reducing area of the inner pipe. Graph 5 further shows this, depicting the heat transfer rate with increasing ZnS deposit thickness.



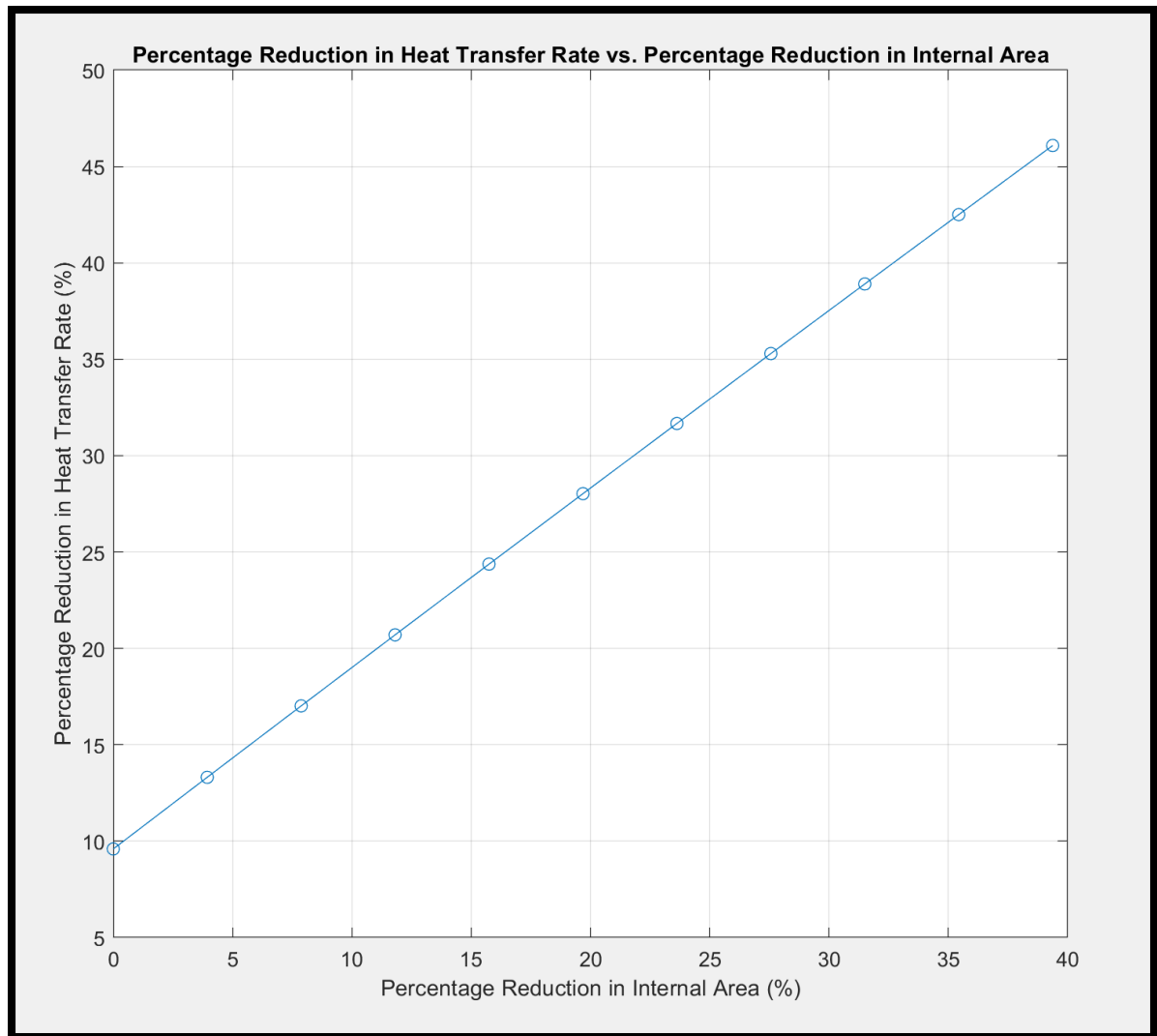
Graph 4. Heat Transfer Rate Vs Internal Area Reduction due to Fouling



Graph 5. Heat Transfer Rate Vs Fouling Thickness

Increasing ZnS deposit thickness in heat exchangers linearly reduces heat transfer rates due to increased thermal resistance and diminished internal area, thereby reducing efficiency. This direct correlation is illustrated in Graphs 4 and 5, where a thicker deposit corresponds to a reduced effective area and consequently lower heat transfer rates.

If ZnS had an increased Thermal Conductivity, this would elevate the heat transfer rate; however, this effect plateaus as the area becomes more impactful. As Graph 6 demonstrates, fouling initially reduces the heat transfer rate by approximately 10%, as supported by section 4.1. and 4.2. Subsequent percentage decreases in the internal area directly correlate with percentage decreases in heat transfer rates. The assumptions underlying this analysis are shown in Table 7.



Graph 6. Percentage of Heat Transfer Rate Reduction Vs Percentage of Internal Area Reduction

Table 7. Analysis Assumptions

Assumptions
The system is in steady-state conditions.
The properties of the fluids and materials remain constant.
The ZnS deposit layer is uniform in thickness and evenly distributed over the internal surface of the pipe.
The analytical methods assume that the heat transfer coefficient (U) is constant throughout the heat exchanger.
It is also assumed that this is a perfectly isolated system, with no heat losses with the surroundings.

5.0. Conclusion

Fouling significantly affects STHE performance, necessitating an understanding of fouling processes and proper maintenance measures.

Ebert and Panchal's model highlights the balance of deposition and mitigation factors in heat exchanger design. Helical baffles, an alternative to segmental baffles, provide improved heat transfer, less fouling, and easier maintenance. Numerous studies have confirmed their benefits, increasing adoption in various industries.

Analysis shows that an increase in deposit layer thickness from fouling proportionally reduces heat transfer rates; however, this proportionality depends on several factors and assumptions.

References

Anish (2021) *Types of heat exchangers used on ship, Marine Insight*. Available at: <https://www.marineinsight.com/refrigeration-air-conditioning/types-of-heat-exchangers-on-a-ship/#:~:text=Shell%20and%20tube%20type%20heat%20exchanger%20is%20extremely%20economical%20to,commonly%20known%20as%20the%20shell>. (Accessed: May 7, 2023).

Application and Advantages of Shell and Tube Heat Exchanger (2023) *LinkedIn*. Sungov. Available at: <https://www.linkedin.com/pulse/application-advantages-shell-tube-heat/> (Accessed: April 30, 2023).

Brogan, R. (2011) "Shell and tube heat exchangers," *A-to-Z Guide to Thermodynamics, Heat and Mass Transfer, and Fluids Engineering* [Preprint]. Available at: https://doi.org/10.1615/atoz.s.shell_and_tube_heat_exchangers.

Cavallo, C. (2023) *All about shell and tube heat exchangers - what you need to know, Thomasnet*. Available at: <https://www.thomasnet.com/articles/process-equipment/shell-and-tube-heat-exchangers/> (Accessed: March 25, 2023).

De, D., Pal, T. and Bandyopadhyay, S. (2017) "Helical baffle design in shell and tube type heat exchanger with CFD analysis," *International Journal of Heat and Technology*, 35(2), pp. 378–383. Available at: <https://doi.org/10.18280/ijht.350221>.

Ebert, W.A. and Panchal, C.B. (1997) "Analysis of Exxon crude-oil slip stream coking data" In: T.R. Bott et al., eds. *Fouling Mitigation of Industrial Heat-Exchange Equipment*. New York: Begell House, pp.451-460.

Evans, P. (2018) *HVAC Heat Exchangers Explained - How heat exchangers work, The Engineering Mindset*. Available at: <https://theengineeringmindset.com/hvac-heat-exchangers-explained/#:~:text=For%20example%20an%20air%20cooled,the%20chiller%20to%20the%20central> (Accessed: April 30, 2023).

Fryer, M. (2021) *Fouling in heat exchangers: Learn causes, detection, and prevention, Central States Industrial*. Available at: <https://www.csidesigns.com/blog/articles/fouling-in-heat-exchangers> (Accessed: April 30, 2023).

Heat Exchanger: Materials & Construction - Shell & Tube (2023) *Heat X*. Available at: <https://www.shell-tube.com/Materials-and-Construction.html#:~:text=Shell%20%26%20Tube&text=Heat%20exchangers%20with%20s>

hell%20diameters,Hastelloy%2C%20Inconel%2C%20or%20titanium. (Accessed: April 30, 2023).

Ibrahim, H.A.-H. (2012) *Fouling in heat exchangers*, IntechOpen. Available at: <https://www.intechopen.com/chapters/39353> (Accessed: 27 May 2023).

Kazi, S.N. (2012) "Fouling and fouling mitigation on heat exchanger surfaces," *Heat Exchangers - Basics Design Applications* [Preprint]. Available at: <https://doi.org/10.5772/32990>.

Kunwer, R., Pandey, S. and Sureshchandra Bhurat, S. (2020) "Comparison of selected shell and tube heat exchangers with segmental and helical baffles," *Thermal Science and Engineering Progress*, 20, p. 5. Available at: <https://doi.org/10.1016/j.tsep.2020.100712>.

Master, B.I., Chunangad, K.S. and Pushpanathan, V. (2003) "Heat Exchanger Fouling and Cleaning: Fundamentals and Applications," in *Fouling Mitigation Using Helixchanger Heat Exchangers*, pp. 1–6. Available at: <https://dc.engconfintl.org/cgi/viewcontent.cgi?article=1042&context=heatexchanger> (Accessed: April 2023).

Mehta, M.K. (2022) *Evolution Of Heat Exchangers: How Heat Exchangers have evolved through time*, Kinam Engineering Industries. Available at: <https://kinam.in/evolution-of-heat-exchangers-2/#:~:text=The%20recorded%20history%20of%20Heat,Dracke%20of%20Germany%20in%201878>. (Accessed: April 30, 2023).

Shell and Tube Type Heat Exchangers (2023) saVRee. savree.com. Available at: https://savree.com/en/encyclopedia/shell-and-tube-type-heat-exchanger#:~:text=A%20shell%20and%20tube%20heat,as%20'tube%20stacks'). (Accessed: April 30, 2023).

Smith, J.W. (2023) *Components of Shell-and-Tube Heat Exchangers, Volume XXIII: Components of Shell & Tube Heat Exchangers | Boardman LLC*. Available at: <https://www.boardmaninc.com/news.html/2017/12/28/volume-xxiii-asme-pressure-vessels/> (Accessed: April 30, 2023).

Taborek, J. (2023) "Shell-and-tube heat exchanger design: Objectives and background," *HEDH Multimedia* [Preprint]. Available at: <https://doi.org/10.1615/hedhme.a.000247>.

The benefits of heat exchangers in Process and Clean in Place (2020) *Central States Industrial*. Available at: <https://www.csidesigns.com/blog/articles/the-benefits-of-heat-exchangers> (Accessed: April 30, 2023).

Why BEPeterson is the Best Option for Custom Shell and Tube Heat Exchanger Manufacturing? (2023) *BEPeterson*. Available at: <https://www.bepeterson.com/why-bepeterson-is-the-best-option-for-custom-shell-and-tube-heat-exchanger-manufacturing> (Accessed: May 7, 2023).

Wisniak, J. (2016) "Benjamín Thomson, Count Rumford," *CENIC Magazine. chemical sciences*, 47, pp. 109–121.

Figure References

Figure 1 - Mehta, M.K. (2022) *Evolution Of Heat Exchangers: How Heat Exchangers have evolved through time*, Kinam Engineering Industries. Available at: <https://kinam.in/evolution-of-heat-exchangers-2/#:~:text=The%20recorded%20history%20of%20Heat,Dracke%20of%20Germany%20in%201878.> (Accessed: April 30, 2023).

Figure 2 - Cavallo, C. (2023) *All about shell and tube heat exchangers - what you need to know*, Thomasnet. Available at: <https://www.thomasnet.com/articles/process-equipment/shell-and-tube-heat-exchangers/> (Accessed: March 25, 2023).

Figure 3 - Brogan, R. (2011) "Shell and tube heat exchangers," *A-to-Z Guide to Thermodynamics, Heat and Mass Transfer, and Fluids Engineering* [Preprint]. Available at: https://doi.org/10.1615/atoz.s.shell_and_tube_heat_exchangers.

Figure 4 – *Heat Exchanger: Materials & Construction - Shell & Tube* (2023) Heat X. Available at: <https://www.shell-tube.com/Materials-and-Construction.html#:~:text=Shell%20%26%20Tube&text=Heat%20exchangers%20with%20shell%20diameters,Hastelloy%2C%20Inconel%2C%20or%20titanium.> (Accessed: April 30, 2023).

Figure 5 – *Heat Exchanger: Materials & Construction - Shell & Tube* (2023) Heat X. Available at: <https://www.shell-tube.com/Materials-and-Construction.html#:~:text=Shell%20%26%20Tube&text=Heat%20exchangers%20with%20shell%20diameters,Hastelloy%2C%20Inconel%2C%20or%20titanium.> (Accessed: April 30, 2023).

Figure 6 – *Heat Exchanger: Materials & Construction - Shell & Tube* (2023) Heat X. Available at: <https://www.shell-tube.com/Materials-and-Construction.html#:~:text=Shell%20%26%20Tube&text=Heat%20exchangers%20with%20shell%20diameters,Hastelloy%2C%20Inconel%2C%20or%20titanium.> (Accessed: April 30, 2023).

Figure 7 - De, D., Pal, T. and Bandyopadhyay, S. (2017) "Helical baffle design in shell and tube type heat exchanger with CFD analysis," *International Journal of Heat and Technology*, 35(2), pp. 378–383. Available at: <https://doi.org/10.18280/ijht.350221>.

Graph References

Graph 1 - De, D., Pal, T. and Bandyopadhyay, S. (2017) "Helical baffle design in shell and tube type heat exchanger with CFD analysis," *International Journal of Heat and Technology*, 35(2), pp. 378–383. Available at: <https://doi.org/10.18280/ijht.350221>.

Graph 2 - De, D., Pal, T. and Bandyopadhyay, S. (2017) "Helical baffle design in shell and tube type heat exchanger with CFD analysis," *International Journal of Heat and Technology*, 35(2), pp. 378–383. Available at: <https://doi.org/10.18280/ijht.350221>.

Graph 3 - Kunwer, R., Pandey, S. and Sureshchandra Bhurat, S. (2020) "Comparison of selected shell and tube heat exchangers with segmental and helical baffles," *Thermal Science and Engineering Progress*, 20, p. 5. Available at: <https://doi.org/10.1016/j.tsep.2020.100712>.

Table References

Table 2 - *Shell and Tube Type Heat Exchangers* (2023) saVRee. savree.com. Available at: [https://savree.com/en/encyclopedia/shell-and-tube-type-heat-exchanger#:~:text=A%20shell%20and%20tube%20heat,as%20'tube%20stacks'\)](https://savree.com/en/encyclopedia/shell-and-tube-type-heat-exchanger#:~:text=A%20shell%20and%20tube%20heat,as%20'tube%20stacks')). (Accessed: April 30, 2023).

Table 3 - Brogan, R. (2011) "Shell and tube heat exchangers," *A-to-Z Guide to Thermodynamics, Heat and Mass Transfer, and Fluids Engineering* [Preprint]. Available at: https://doi.org/10.1615/atoz.s.shell_and_tube_heat_exchangers.

Table 4 - Kazi, S.N. (2012) "Fouling and fouling mitigation on heat exchanger surfaces," *Heat Exchangers - Basics Design Applications* [Preprint]. Available at: <https://doi.org/10.5772/32990>.

Table 5 - De, D., Pal, T. and Bandyopadhyay, S. (2017) "Helical baffle design in shell and tube type heat exchanger with CFD analysis," *International Journal of Heat and Technology*, 35(2), pp. 378–383. Available at: <https://doi.org/10.18280/ijht.350221>.