



3544 MeOH Column Overhead Condenser

DISSERTATION

Declaration of Authenticity

This Thesis is the result of the Author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed: *L. Knight* **L. Knight**

Date: 19/05/20

Table of Contents

Section 1: Abstract	4
Section 2: Introduction	5
Section 3: Corrosion	6
Corrosion Methods	6
Oxidation:.....	6
Electrolytic:	7
Chemistry:	7
Corrosion Groups	8
Group 1	8
Group 2	10
Group 3	12
Dow Specific Corrosion Types	14
Electrochemical Corrosion	14
Erosion	15
Microbiological Corrosion	16
Section 4: Standards	18
Health and Safety	18
COSHH	18
RIDDOR.....	19
ASTM	19
API/ISO Standards	19
ASME Standards	20
BSI (British Standards).....	20
Section 5: The Condenser Unit	21
Types of Heat Exchanger Units:	21
Shell and Tube	21
Plate and Frame	22
Plate and Fin.....	24
Flow Types	26
Parallel Flow	26
Counter Flow	27
Cross Flow	28
The 3544 MeOH Condenser.....	29
Section 6: Inspections	33

Types Of Inspections	33
Visual Inspections	33
Eddy Current	34
Inspection Reports	34
Tubular Inspection data 29 th -30 th September 2020	36
Tubular Inspection data 3 rd -4 th September 2021	37
Section 7: Materials	38
Tubing Material Options	38
Section 8: Condenser Design	39
Baffle Design	39
Segmental Baffles	39
Disk and Doughnut Baffle	40
Grid/Rod Baffles	41
Helical Baffles	42
Section 9: Conclusion and Recommendations	44
Section 10: References	45

Section 1: Abstract

In this dissertation I have been looking into the frequency and cost efficiency in which a condenser is being maintained and repaired. I have investigated the current faults the system has and have researched methods in ways to reduce the frequency of the maintenance activities whilst also keeping maintenance costs to a minimum. Although the initial costs are the greatest, the helical baffle design gives the most benefits and keeps maintenance frequency low enough to balance the costs. Carbon steel tubing would remain preferable if the design is changes to helical. However, if the design is kept the same as current, the titanium material would become preferable.

Section 2: Introduction

The company I work for is Dow Silicones UK LTD. The Barry site I am based in, previously known as Dow Corning, has been producing silicone-based products since 1971. The company takes raw silicone and put it through one of many processes to produce products such as gels and other by-products.

The reason for this project is that one of our condenser units on site (3544 MeOH) has been dealing with a corrosion issue for the past 5 years. The tubes that run through the inside of the condenser have been experiencing increasing levels of wall reduction. This has resulted in an increased frequency in down time and costs for replacement of the tubing.

The 3544 MeOH Column Overhead condenser is a piece of equipment with the primary function to reducing the temperature of the passing material, Methanol on this occasion, using heat transference. The equipment has multiple Carbon Steel tubes travelling up and down the length of the shell. Cooling water is injected into these tubes with the intention of absorbing the heat away from the Methanol material.

The tubing within the condenser is frequently getting eroded away from general wear and usage. The tubing replacement occurs every 12 months to prevent an unwanted event from occurring. Sometimes the maintenance activity of replacing the tubing is not enough and the condenser itself needs replacing. When inspection tests have been carried out on a select number of tubes, the percentage of wall loss can range from less than 10% up to the highest recorded figure of 40-49%. The cost of repairs can range from £70K-£80K on average per annum.

The main benefit of this project is that I hope to find a method of reducing the frequency of these maintenance activities and to make the system more reliable for the plant. This would save the company from having to shut down the plant so often and to also provide the company savings in manpower and other resource costs.

My **main goal** for this project is to provide an alternative material or design for the tubing of the condenser, this material must deliver an overall smaller net cost to purchase and maintain in comparison to the existing material.

Sub goals for the material include:

- To provide the best corrosion resistance to the environment it would need to endure.
- To be manageable when it comes to the production of the tubing.
- Meet the existing manufacturing standards set by governing bodies.

Section 3: Corrosion

The definition of corrosion according to (Collins Dictionary, 2023) is the process by which a metal is gradually degraded by an electrochemical process.

Materials such as metals are not technically in a natural state as they have had to be processed through manufacturing techniques. Corrosion is essentially the material attempting to revert into its more stable, natural state in the presence of oxygen, moisture, or other corrosive substances. (Dr.P.Holden, 2023)

Corrosion Methods

The main ways corrosion can react with a material is through one of the three following:

Oxidation:

Apart from gold, this is the process of oxygen in the atmosphere reacting with the metallic material to produce oxides. This process will typically involve the loss of electrons from the metal atoms, resulting in the increase in their oxidation state. Oxidation is commonly referred to as “rust” by the general public, however, oxidation does not always result in the orange-brown colour associated with rust (Example image shown below).

Some metals, such as copper will instead produce a greenish hue when going through the oxidation process. A famous example of this would be the statue of liberty.



Image of metallic gear experiencing oxidation (*Presto, 2023*)

Electrolytic:

This refers to electrolysis, where an electric current is put through an electrolyte to induce a chemical reaction to a material. The conducted electricity forms anodic and cathodic sites, producing corrosion.

The example below shows a method in which electrolysis is used to perform electroplating. In the example, the power produced by the battery travels through the electrolyte and reacts with the copper. The copper is corroded away from the anode, and the material then transfers over to the iron cathode, coating the material.

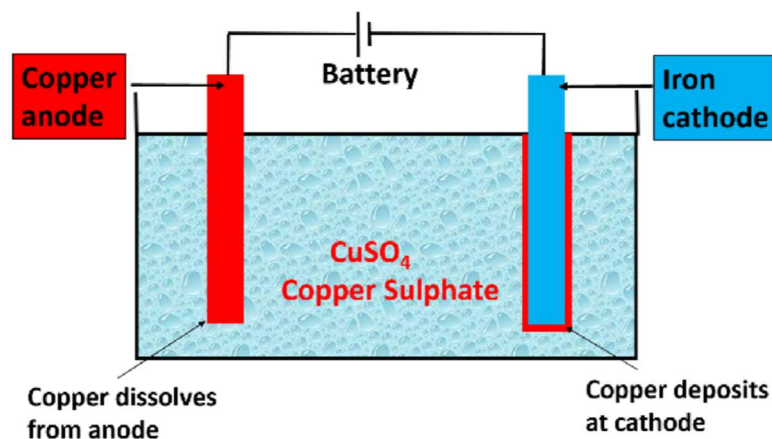


Diagram showing the electrolysis process (Dr.P.Holden, 2023)

Chemistry:

This is where metals have reactions with other elements in the atmosphere. Often, this leads to the materials deteriorating and breaking down due to the chemical reactions with their environments. Exposure to elements such as carbon, nitrogen and chlorine can all lead to inevitable destruction of the metallic material.

The image below shows a chain used out on a beach. The salt air and other elements in the environment have led the chain to become discoloured and corrosion has begun to eat away at it.



Image of metallic chains that have been exposed to the elements (RevisionOnline, 2023)

Corrosion Groups

Corrosion can occur due to multiple reasons including prolonged exposure to a corrosive environment, dissimilar materials making contact or by general wear and tear when forces have acted upon a material. Ampp.org (2023) explains that the forms of corrosion can be categorised into three groups with the defining factor being how the corrosion can be identified.

Group 1: Determined by visual inspection.

- **Uniform Corrosion**

- This type of corrosion occurs evenly across the surface of the material, resulting in a consistent loss of material thickness. The below example shows a chain, stud and nut that has all experienced a consistent level of corrosion across all the materials. This corrosion is often referred to as rust.



Image of a stud, nut and chain experiencing corrosion (*ExperimentosFaciles, 2016*)

- **Pitting**

- This type of corrosion is more localised/concentrated in smaller areas of a material. These areas are penetrated by external chemicals or environmental to create deep pits. The image below shows a steel pipe with multiple areas affected by pitting corrosion.



Image of metallic pipe with visible pitting (*ResearchGate.net, 2015*)

- **Crevice Corrosion**

- This occurs more specifically between two surfaces that are in close contact, such as joints or gaskets. Moisture can build up in these gaps and can become acidic when left to sit still for too long. This will begin to eat away at one or both materials. Example below shows corrosion occurring between the base plate of the support and the ground.



Photo of a piping support base plate (Corbett.N, 2021)

- **Galvanic Corrosion**

- This is where two dissimilar metals make contact in an electrolyte for a prolonged amount of time. When the metals are in an electrolyte such as a form of moisture, an electrochemical reaction occurs which leads to the less noble material experiencing increased levels of corrosion. The image below highlights how this can occur if fittings of dissimilar materials are used together. The nut on the right is made of a less noble material to that of the nut on the left and the stud, leading to the accelerated rate of galvanic corrosion.

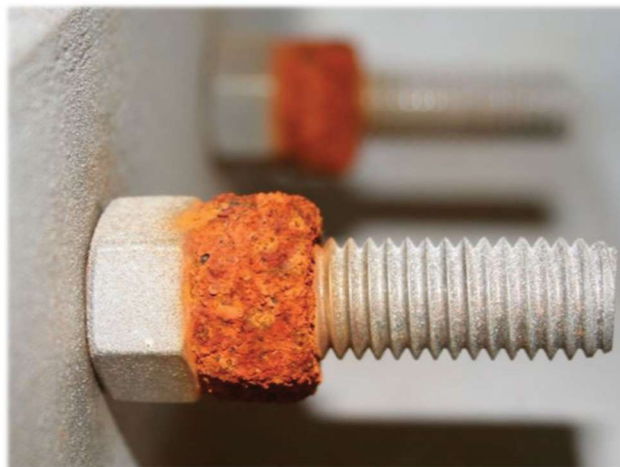


Image of two different metallic nuts. One is severely corroded. (Wilkison Coutts, 2021)

Group 2: Identified with special inspection tools.

- **Erosion**

- This form of corrosion refers to the progressive removal of material from the surface area of an object because of mechanical actions of abrasive particles or other environmental elements. A common example of this is which abrasive materials running through a pipe, this is especially prevalent at elbows and other fittings that cause the contents to need to change direction or flow velocity. The image below shows the cross section of a pipe elbow that has had a notable amount of wall thickness removed on the arc of the bend.



Section view of a metallic pipe that has experienced erosion. *ResearchGate.net, 2018*)

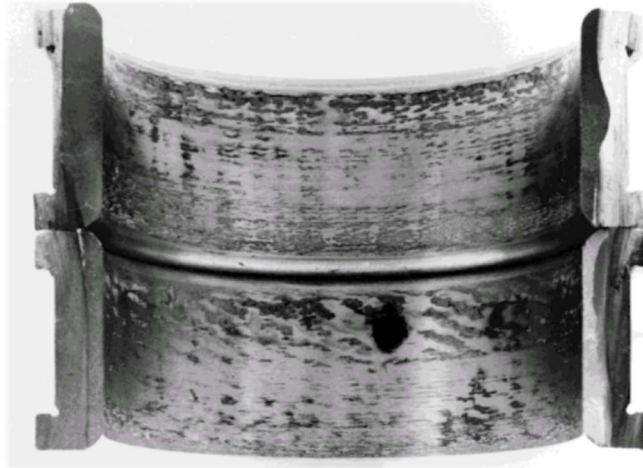
- **Cavitation**

- This is when a gas bubble forms within a liquid and the resultant pressure difference causes damage to the material. Over time, the damage will gradually worsen until the material fails. This is most prevalent in materials that are typically kept in a fluid, pump impellers for example. The below image (Rodelta, 2023) shows cavitation that has occurred to a pump impeller.



Image of an impeller that has suffered severe cavitation. *(Detloff.C, 2021)*

- Fretting
 - This form of corrosion will typically occur between layers of metal. A combination of oxides forming between the two surfaces and mechanical forces acting on the materials will create fretting fatigue. This will be more prevalent in mechanical items such as joints and bearings. The image below shows a bearing ring that is experiencing fretting corrosion due to the constant wear of the bearings.



Section view of the inner wall of a bearing ring. (Schaeffler, 2018)

- Intergranular
 - When an alloy goes through solidification, grain boundaries are produced. This form of corrosion is brought on by contaminants found in the material and will begin to develop along the grain boundaries of the metal. The example below shows a section of piping experiencing a form of intergranular corrosion.



Photo of a pipe that has experienced corrosion. (Corbett.N, 2021)

Group 3: Visible by microscopic verification.

- Stress Cracking Corrosion
 - The combination of a corrosive material and stress applied to a material can lead to stress corrosion cracking. This is a source of premature failures in materials such as alloys. Similar to the previously mentioned intergranular corrosion, the corrosive material gets between the grain boundaries of the metal and weakens the integrity of the metal. However, it's the applied stress that can lead to the cracking and failure of the material. The image below is an example of a pipe that has undergone stress cracking corrosion.



Photo of the outside of a pipe that has suffered stress cracking corrosion. (Azom.com, 2001)

- Microbiological Corrosion
 - This typically occurs in stagnant water. Where water does not flow, bacteria is able to thrive and produce hydrogen sulphide which reduces the PH levels of the water, making the water more acidic. The combination of the acidic water and the bacteria feeding on the metal will enable corrosion to accelerate on the submerged metal. Ships and structures built on or submerged in water are likely to come into contact with this type of corrosion. The image below shows a metal structure that is submerged in stagnant water. It clearly shows how the material is eaten away specifically where it meets the water.

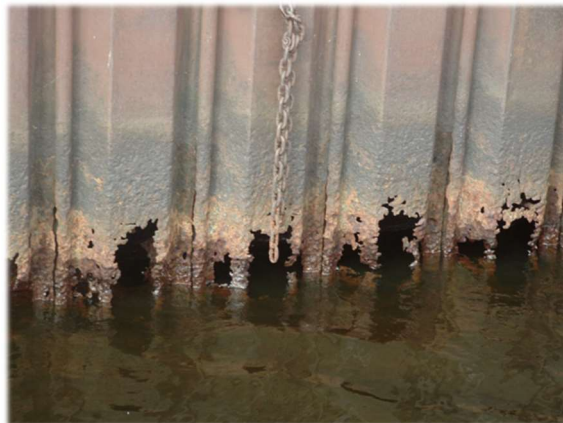
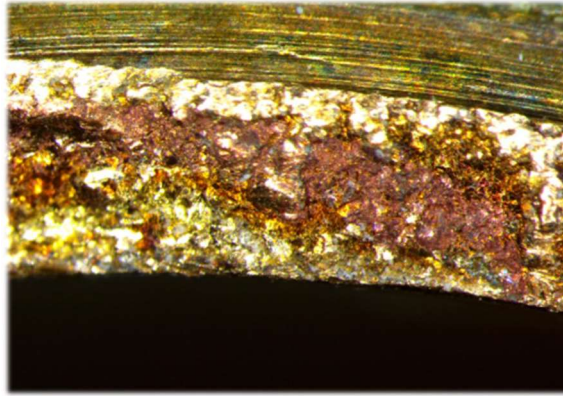


Image showing sheet metal that is being eaten away. (K.Larsen, 2020)

- De-Alloying

- Also known as selective leaching, this occurs when one or more elements have been targeted in an alloy and removed via corrosion. This will tend to leave behind a material that is less resistant to corrosion. This will be more likely to occur in alloys where the components have significantly different levels of corrosion resistance. The less noble of the two materials will be more likely to be eaten away. This can leave behind structure with a compromised mechanical integrity in comparison to the original alloy.

A common variation of Dealloying is with the dezincification of Brass materials. The image below (Technorm.ca, 2023) shows the surface from a damaged faucet. The material is yellow is how the brass should look, the darkened areas are where zinc has been removed from the alloy. The darkened area has had its structural integrity compromised.



Zoomed in image of a brass faucet. (TECHNORM.ca, 2022)

Dow Specific Corrosion Types

In Dow we have multiple opportunities for corrosion to occur on our plants. Whether its from the geographical locations, the operational environment, or the material we run through our equipment. The types of corrosion I want to investigate are those that would specifically affect the 3544-condenser equipment.

Electrochemical Corrosion

The Dow Barry site is located in a seaside town. Thus, we experience higher levels of exposure to saltwater in the atmosphere in comparison to areas more inland. This saltwater in the air acts as a conductor, which encourages electrolytic corrosion to occur between the moisture, oxygen, and salt with the material. This form of corrosion can eat away at the material anywhere between 5 to 10 times the rate it normally would in an environment with regular humidity levels (sciencing.com, 2023).

In relation to the condenser, this would primarily affect the outside of the equipment, the steelwork supporting it and the pipework attached to the equipment. The steel infrastructure holding the equipment and the pipework is given a coating to protect it from the environment. In some environments, painting the structural steel would be enough to keep the material safe for a length of time. However, as the conditions of the environment are harsher than the average location, it is preferable to hot dip galvanise the steel. This galvanised coating helps to protect the metal by acting as a sacrificial layer, keeping the integrity of the steel intact.

There are ways to test the corrosion rates of saltwater on a material. The first method of testing the corrosion rates of a material is through the use of the salt spray test. The image below (Tensiontestmachine.com, 2023) shows an example salt spray test chamber. By putting a sample piece of material within the chamber, you can expose it to high levels of salt spray in a controlled environment. This will make the material experience accelerated rates of electrochemical corrosion, providing insight into how the material would experience corrosion over a longer period of time. This test can also help evaluate the resistance levels a batch of coated materials can withstand. This method has the benefit of being able to provide results over a short period of time.

An example test would be to take three pieces of material: One uncoated, another coated in paint, and the last given a hot dip galvanised coating. The uncoated material can provide a baseline corrosion rate after it has been through the salt spray test. The two coated materials could then be compared to the first piece to see how well the coating has protected the material.



Image of a salt spray chamber. (Tensionmachine.com, 2023)

Another method of testing for electrochemical corrosion is with corrosion coupons, shown in the image below (droptestkits.com, 2023) is several tags made of different materials. This test involves installing these tags in the location you wish to know how corrosive an environment is for metals. The benefit of these tags is that they can provide a clear visual indication in the changes of a material. However, the results must be completed in real time. Meaning, compared to salt spraying, this method can take some time before any real results are revealed.



Image of corrosion testing coupons. (IndiaMart, 2023)

The tags can also indicate material loss. To do this, the tags should be weighed prior to installation and once again after being exposed to the environment for a designated amount of time. The weight difference can provide a material loss/time rate.

Erosion

The increased wall thickness reduction rates of the tubing could be due to erosion. Erosion corrosion can cause the thinning of pipes due to a few factors such as turbulent flows, water hammer, or even temperature. The velocity of the inner material could be applying force on any existing electrolytic corrosion in the tubing. This could then pull any weakened material from the wall, thinning it. This would then prevent the existing corrosion from building a protection layer for itself, resulting in exposing more unaffected material for the electrolytic corrosion. This cycle would continue to reduce the wall thickness until the tubing wall fails and a leak occurs. This would be the worst-case scenario as it would not only mean water would get into the Methanol, but the Methanol could potentially contaminate the process water supply.

Alternatively, it could be the Methanol in the condenser that is also applying force upon the tubing, as it travels through the system it may be moving at velocities high enough to impact the tubing outer walls.

Ways of helping to mitigate erosion in piping/tubing include:

- Coatings/Linings
 - Providing a sacrificial layer within piping can help increase its lifespan. In piping this can be achieved via methods such as thermal spray coatings or using a plastic liner such as PTFE/PVA. However, in tubing this is can be more difficult due to the small diameters of tubing.

- Erosion Monitoring
 - Technology such as sensors that can measure wall thicknesses can be used to monitor the reduction of material in a pipe/tube wall. Some of this technology can be used to detect coating or piping wall thickness reduction using ultrasound waves, such an example is the thickness gauge pictured below (epkusa.com, 2023).



Image illustrating the use of a material thickness gauge. (ElektroPhysik, 2023)

- Reducing Flow Velocity
 - By decreasing the velocity of the fluid flow, you can reduce the friction forces produced by the particles onto the inner wall of the tubing. This can be achieved by either controlling the flow rate through operational means or by using valves to throttle the flow.
- Flow Optimisation
 - Making changes to the format of the routing can assist in promoting less turbulent flows within piping/tubing set ups. This can take the form of providing less aggressive bends and directional fluid flow in the line. Alternatively, the introduction of flow control devices like reducers in the line. These reducers use Bernoulli's principle that an increase in flow will tend to mean lower pressure and vice versa. So, to decrease the flow velocity, the pressure should be increased, this can be achieved by having the diameter of the tubing expand prior to a bend in the line.

Microbiological Corrosion

Water is the cooling element that runs through the tubing in the condenser, so when the system is ever offline there is a chance for the water to become stagnant. As previously mentioned, when water becomes stagnant it gives any bacteria in the line a chance to feed on any material nearby; in this case it would be the tubing itself. As a result, the bacteria could produce hydrogen sulphide in the line, overtime, making the stagnant water progressively more acidic. This acidity can eat away at the tubing, also thinning the inner walls.

A method of preventing this from occurring is to ensure water does not remain stagnant for too long. This can be done through a couple of actions:

- Reduce downtime frequency – By having the downtime minimised, the length of time the water is stagnant in the tubing is reduced, lowering the window of opportunity for corrosion to take place. However, this could then negatively influence the maintenance team, as they will then be given tighter work schedules to complete the maintenance tasks. By applying this additional pressure to rush the workers, possible mistakes could be made during maintenance.
- Drain the system when it is not running – This would eliminate the opportunity for water to stagnate as there would be none left in the system to react with the tubing. However, to minimise the risk of any residue in the system causing corrosion, the system should be blown dry with the use of N₂ or process air supply. The downside to this would be the tubing would then need to be refilled with water before allowing the methanol to pass through the condenser. This could lead to a slower start up process when the plant goes back online.

Section 4: Standards

As with all companies, we must comply with the legislations put in place by the government and monitored by the HSE agency. These regulations apply to the factors such as the Health and Safety at work act, COSHH, RIDDOR and other areas of the working environment. Not only this, but there are standards that are more specific to the materials and manufacturing factors to the condenser itself.

Health and Safety

General health and safety standards included in 'The Health and Safety at work act 1974' (HSE.gov.uk, 2023) that affect Dow include:

- PPE regulations that ensure workers are provided and use the correct personal protective equipment when maintaining, installing, or demolishing equipment on the plant.
- Working at height regulations ensure the employer has gone through the hazard controls hierarchy to minimise the risks when it comes to the hazard of working at height.
- The workplace must have procedures in place for any working activities that would occur during the maintenance activity. The condenser maintenance activity has procedures on file that the worker must follow to minimise any unnecessary risks when working on or operating the equipment.

The HSE have guidelines when it comes to Inspections and NDT (Non-Destructive testing) techniques used on equipment in industrial settings. These tests have the benefit of not needing the system to be offline to complete. Such examples of NDT include:

- Radiography – testing using gamma rays or x-rays to pick up changes in density and wall thicknesses as well as any defects such as cracks.
- Visual Checks – Using general sight to spot any imperfections such as signs of wear, pitting and discolouration.
- Infrared Thermography – Thermal cameras can be used to detect defects through temperature variations on a material surface.
- Leak Testing – Examples can include pressure testing and vacuum testing can be used to locate any locations where cracks have formed in the material.

COSHH

As a chemical company, Dow must follow the COSHH regulations when it comes to substances that may encounter a worker. According to the HSE (HSE.gov.uk, 2023), substances under the COSHH legislation that affect Dow include Chemicals, vapours, gases, dusts, and other potentially harmful materials on site. 'The Control of Substances Hazardous to Health Regulations 2002' is a regulation that covers different aspects involving chemicals in the workplace including risk assessment guides and requirements for safety data sheets for the chemicals.

RIDDOR

In a case where something goes wrong and someone experiences a form of injury or worse, the workplace needs to report these in accordance with 'The Reporting of Injuries, Diseases and Dangerous Occurrences Regulations 2013' legislation. Examples of such reportable injuries according to the HSE (HSE.gov.uk, 2013) include Fractures, serious burns, loss of consciousness caused by head injury or asphyxia and other such examples. A specific section of this legislation that relates to this equipment falls under Schedule 2: Part 1: Paragraph 21, which is in relation to pipelines and the uncontrolled release of any materials within the pipe (legislation.gov.uk, 2013).

ASTM

Standards set by the American Society for Testing and Materials cover a variety of factors involving the choice of a material, what service it is used in, how it is manufactured, and how it can be tested.

There are more specific standards that can be applied to the tubing of the condenser. Such examples include the standard ASTM A192/A192M-17, which covers the scope of using seamless carbon steel boiler tubes in high pressure services (ASTM.org, 2017). This covers the requirements for tubing wall thicknesses, testing methods such as hydrostatic and hardness tests, and the chemical composition the steel should meet.

ASTM A554-21 (ASTM.org, 2021) covers the specifications for welded stainless-steel tubing. If the tubing in the condenser is made of stainless steel, this standard covers the welding practices and the minimum wall thickness requirements of the tubing. According to the standard, the wall thickness of the tubing would need to be at least 0.51mm for welding.

There are standards specifications for tubing made of various materials that are to be used in condenser and heat-exchanger services. These standards also cover the minimum wall thicknesses of the tubing, welding practices, and standards for the U-tubes that are needed on the ends of the condenser. These examples are:

- B163-22 – Seamless Nickel and Nickel Alloy (2022)
- B395/B395M-18 – Seamless Copper and Copper Alloy (2019)
- A214/A214M-19 – Electrical Resistance -Welded Carbon steel (2019)
- B891/B891M-19 – Seamless Titanium and Titanium Alloy (2019)
- A1098/A1098M-18 – Welded Austenitic, Ferritic, Martensitic and Duplex Stainless Steel (2022)

API/ISO Standards

The API standard 660 (API.org, 2015) covers shell and tube heat exchangers. The standard provides guidelines for the design of the heat exchangers, what materials the exchanger should be made of, testing specifications, shipment standards and other related information.

There are standards that are more specific to the tubing itself. Specifications that are related to tubing are:

- API Spec 5CT/ISO 11960: Specification for Casing and Tubing (fushunspecialsteel.com, 2006)
- API RP 5A5/ISO 15463: Field Inspection of New Casing, Tubing, and Plain-End Drill Pipe (API.org, 2005)
- PI TR 5C3/ISO/TR 10400: Technical Report on Equations and Calculations for Casing, Tubing, and Line Pipe Used as Casing or Tubing (ISO.org, 2018)

ASME Standards

The ASME B31.3 Process Piping Standards (ASME, 2023) covers the design, fabrication, inspection, safety and testing of general process piping. This is relevant to the condenser as its operational function is to cool down a process fluid (Methanol). This will have less relevance to the tubing but will be of great significance to the pipework that routes the Methanol and water lines to the equipment. Changes to the design of the condenser and the attached pipework will need to comply with this set of standards.

Other example ASME standards that are related to the condenser are:

- ASME SA516 Gr.70 - The shell body material of the existing condenser meets to this ASME standard which covers the material specifications for this grade of steel.
- ASME SA179 - The spacer tubes within the condenser meet to this ASME standard which covers the specifications of tubing made of low-carbon steel for the use of heat exchangers and condenser units.

BSI (British Standards)

The tubing material of the existing condenser meet to the British standard BS 3059 which covers the specifications of steel boiler and super heater tubes. More specifically, the PT.2 S1 360 CAT.2 section of the standard that covers carbon, alloy and austenitic stainless-steel tubing.

Section 5: The Condenser Unit

Types of Heat Exchanger Units:

The goal of the heat exchanger is self-explanatory, it is to transfer heat between two different fluids without allowing the materials to mix via the use of a physical barrier. An example of a barrier would be housing one of the materials withing tubing/piping.

The main reasons for using a heat exchanger in a system can be one of the following:

- Heat a cooler Fluid.
- Boil a liquid.
- Condense a gaseous fluid.
- Reduce the temperature of a hot fluid.
- To boil a liquid whilst condensing a hotter gas.

The main types of exchangers used in industries are:

- Shell and Tube
- Plate and Frame
- Plate and Fin
- Regenerative

Shell and Tube

The general set up of these types of exchangers consists of a series of tubes contained within a metallic shell. These are the most common type of exchangers, with uses in a variety of industries including:

- Power plants - Condenser and boilers used to exchange heat between steam and water.
- food and beverage - For pasteurization and other heating/cooling processes.
- HVAC systems - Used in chillers and heaters to control building temperatures.
- The Chemical industry - Used for controlling the temperatures of chemicals in the process.

The main parts of a shell and tube condenser include:

- Shell
 - The outer container that houses all the material and other main parts of the heat exchanger. It guides the shell-side fluid flow around the tubes and out back into the system.
- Tube Bundle
 - A set of tubes which contains one of the fluids in the system. The tubes can be in straight formations or U-shaped. Often, the material looking to change the temperature of the shell-side material. In systems aiming to cool, this will often be materials such as cold water.
- Tube Sheets
 - Plates that divide the fluids on the shell's side from the tube side and secure the tubes in place at either end of the shell.
- Baffles
 - Internal plates or discs within the shell that guide the fluid flow on the shell's side across the tubes. This has the added effects of improving heat transfer and stabilising the tubes, reducing vibration.

- Inlet/Outlet Nozzles
 - The entry and exit locations for fluids that traverse through the shell-side and tubing areas.
- Head
 - The end cover of the shell. This can be either fixed or removable. The head will allow access to the tube bundle within the shell, allowing for maintenance tasks when the exchanger is not in use.

General Pros and Cons for Shell and Tube

Advantages

Efficiency

High heat transfer efficiency due to large surface area.

Versatility

Can handle a wide range of temperatures and pressures.

Scalability

Available in various sizes to suit different applications.

Maintenance

Easy to clean and maintain, especially with removable tube bundles.

Disadvantages

Size and Weight

Can be bulky and heavy, requiring significant space.

Cost

Higher initial cost compared to other types of heat exchangers.

Complexity

More complex design and construction, particularly for floating head and U-tube designs.

Fouling

Build up of dirt and unwanted material can build up in areas baffles are located.

Plate and Frame

This type of heat exchanger is a combination of multiple plates stacked on each other with corrugated flat flow passages. By employing different pathways for the hot and cold fluids to flow, each of the cold fluid streams is surrounded by two hot fluid streams. This results in a very effective heat transfer. These heat exchangers are used primarily in the Food and beverage industries for tasks such as pasteurisation, sterilisation and other temperature management processes. However, they are also sometimes used in the chemical, pharmaceutical and Renewable energy industries applications.

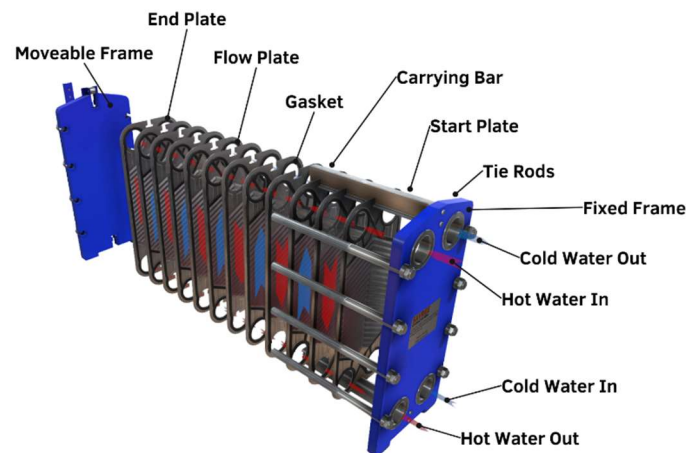


Diagram of a Plate Heat Exchanger. *Savree.com (2023)*

The main parts for a Plate and Frame Heat Exchanger include:

- Plates
 - The plates act as the main heat transfer surfaces and are made up of thin, corrugated metal sheets that are usually composed of stainless steel or other materials resistant to corrosion. The passages between the plates are sealed by a gasket on each plate.
- Frame
 - The frame consists of a few parts:
 - Fixed Frame (head) – This is the end of the frame that does not move. Due to this, it is also the location of the inlet and outlet ports where the fluids can travel in and away from.
 - Movable Frame (follower) – This is the adjustable frame that allows for plates to be adjusted, added or removed. This also allows for easy access for maintenance tasks.
 - Tie Bars/Bolts – These are parts that allow the plates to be secured together and to maintain the pressure within the plates.
- Gaskets
 - These are seals that are placed around the edges of the plates to prevent any leaks when the system is pressurised.
- Inlet/Outlet Ports
 - These are openings on the fixed frame that allows the fluids to travel in and out of the heat exchanger.

General Pros and Cons for Plate and Frame

Advantages

Efficiency

High thermal efficiency due to large surface area and turbulence created by corrugations.

Compact Size

Requires less space compared to shell and tube heat exchangers.

Flexibility

Easy to add or remove plates to adjust capacity

Maintenance

Plates can be easily removed for cleaning and replacement.

Low Fouling

Smooth surface and high turbulence reduce the tendency for fouling.

Disadvantages

Pressure Limitations

Generally, not suitable for very high-pressure applications

Temperature Limitations

Gaskets may limit the maximum operating temperature.

Initial Cost

Can be more expensive initially compared to some other types of heat exchangers.

Plate and Fin

This type of heat exchanger is like the plate and frame heat exchangers as both types used stacked sheets which are clamped together. Plate and Fin heat exchangers are small, light, and incredibly effective pieces of equipment that transfer heat between fluids. They are especially useful in situations where efficiency, weight, and space are important considerations.

This type of exchanger is used a lot in the following industries:

- Aerospace - Cooling of aircraft engines and electronic equipment due to their lightweight and high efficiency.
- Automotive - Radiators, intercoolers, and oil coolers in vehicles.
- Cryogenics - Used in processes requiring efficient heat exchange at very low temperatures.
- Chemical Industries

The main parts of this heat exchanger are:

- Plates
 - Thin, flat sheets that serve as the main heat-transfer surface and structure. For optimal heat conductivity, they are often composed of metals like stainless steel or aluminium.
- Fins
 - Placed in between the plates are thin, corrugated sheets. They improve the heat exchange efficiency by increasing the surface area available for heat transmission and encouraging turbulence in the fluid flow. Fin designs vary and might include wavy, louvred, or straight patterns.
- Headers
 - Placed at the end of the plates and fins that allow the fluid to travel into and back out of the channels once it has cycled through the heat exchanger.
- Side Bars
 - These are used to seal the edges of the plates and fins, thus preventing any fluids from leaking and escaping the exchanger. It also helps to direct the fluid flow through the designated paths.
- Flow Channels
 - The spaces created between plates and fins through which the fluids flow. These channels can be configured for parallel or counterflow arrangements.

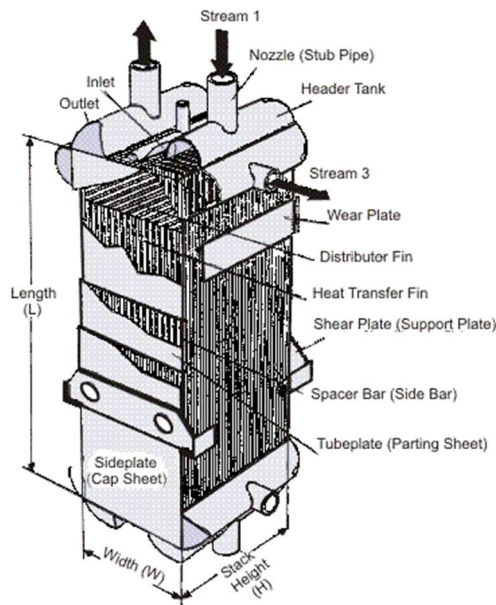


Diagram of Plate and Fin heat exchanger. *Thermopedia.com (2023)*

General Pros and Cons for Plate and Fin

Advantages

Efficiency

Excellent heat transfer performance due to large surface area and enhanced turbulence.

Compact Size

Smaller and lighter compared to other types of heat exchangers, making them ideal for applications with space constraints.

Versatility

Capable of handling various fluids, including gases and liquids, and accommodating multiple flow configurations

Low Weight

Especially beneficial in aerospace and automotive applications.

Customisability

Easily adapted to specific application requirements by varying plate and fin geometry.

Disadvantages

Complexity

More complex design and manufacturing process compared to simpler heat exchangers like shell and tube.

Fouling Sensitivity

Narrow channels and high surface area can be prone to fouling, requiring regular maintenance.

Pressure Drops

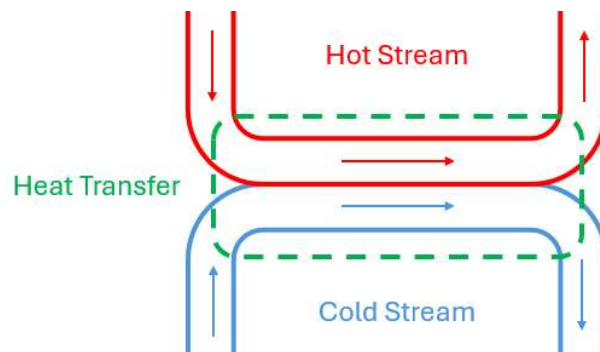
Higher pressure drops due to the intricate flow paths and increased turbulence, which may require more powerful pumps.

Flow Types

Heat exchangers can utilise one of the three main types of flow to get the most efficient heat transference between fluids. Each type of flow has its advantages and can be selected based on the specific needs of the heat exchanger application. These three types of flow are Parallel, Counter and Cross flow.

Parallel Flow

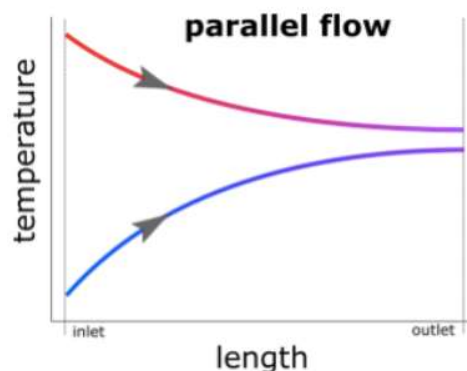
This is where fluids in a system are flowing in the same direction. This is a simple design but often offers lower efficiency over the other options. These can be seen in basic heating/cooling systems.



Heat Exchanger Parallel Flow Diagram. *L. Knight (2024)*

Temperature Gradient:

As the two fluids travel together in the exchanger, the temperature difference between the two fluids will diminish over time. This means the greatest heat transference occurs at the inlets where the fluids first meet, and their respective temperatures are the furthest apart. As the gap in heat difference reduces, so does the rate of heat transference. Meaning the efficiency of the heat exchange decreases over time until the fluids reach the outlet. The graph below gives a visual representation of how the temperatures initially alter rapidly but then gradually slow down until they reach the outlet. Eventually the heat transference would become so insignificant it would take far too long after this point to see any meaningful temperature changes. Side note, the temperature values of the two fluids will never cross on the graph, this is because heat transference would stop the moment the temperature values of both fluids reached equilibrium.



Graph of temperature distribution for Counter Flow Configurations. *Wattco.com (2024)*

General Pros and Cons for Parallel Flow

Advantages

Simple Design

Far easier to design and construct compared to other methods of flow.

Compact

In comparison to the other methods, Parallel flow designs can be made smaller for certain applications.

Disadvantages

Lower Efficiency

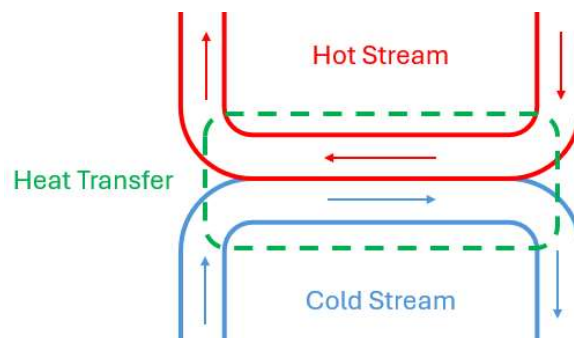
In comparison to counterflow, this provides less efficient heat transference.

Temperature Limitations

The system will struggle to heat or cool down fluids by a substantial amount by the time it passes through the system.

Counter Flow

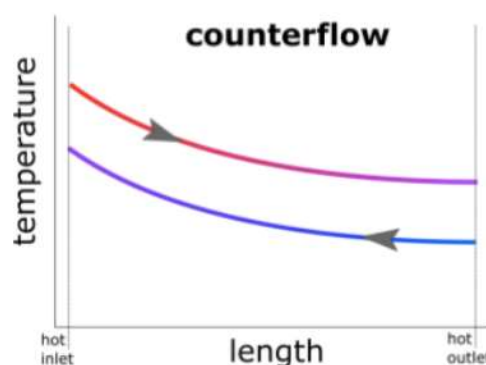
This is where the fluids flow in opposite directions from one another. This method generally provides a higher heat transfer efficiency than the other flow types. Counter flow is used in applications that require larger amounts of heat transfer.



Heat Exchanger Counter Flow Diagram. *L. Knight (2024)*

Temperature Gradient:

Having the inlets of the two fluids come from different directions means that the two extremes of temperature are at the ends of the exchanger. Due of this, the heat difference between the two fluids throughout the system becomes more constant in comparison to the parallel flow chart, thus meaning heat transference also becomes more constant. The graph below illustrates this constant temperature gap between the two fluids, which suggests that the heat transference value would remain constant from the inlet to outlet locations.



Graph of temperature distribution for Counter Flow Configurations. *Wattco.com (2024)*

General Pros and Cons for Counter Flow

Advantages

Higher Efficiency

Maximizes heat transfer efficiency and can achieve a higher overall heat transfer rate.

Temperature Approach

The cold fluid can be heated to a temperature close to the inlet temperature of the hot fluid, and vice versa.

Disadvantages

Complex Designs

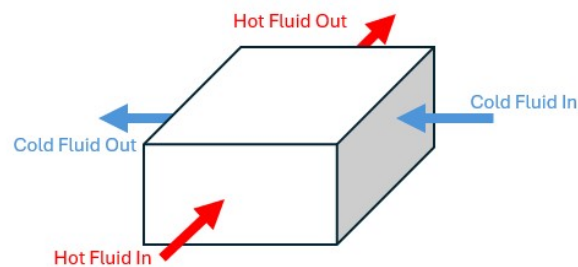
More complex and potentially more expensive to design and manufacture.

Larger Size

May require more length to achieve the same heat transfer as a parallel flow design

Cross Flow

Fluids in cross flow systems will travel perpendicular to one another. This could be one fluid flowing through plates or tubes whilst another fluid flows around them. In comparison to the other types of flows, this provides a moderate level of efficiency. This method can be made for compact systems such as automotive radiators and HVAC systems.



Heat Exchanger Cross Flow Diagram. L. Knight (2024)

General Pros and Cons for Counter Flow

Advantages

Compact Design

Can be more compact in certain configurations, making it suitable for applications with space constraints.

Flexibility Operation

Can handle varying flow rates and is adaptable to different heat exchange requirements.

Disadvantages

Moderate Efficiency

Typically, more efficient than parallel flows but not as efficient as counterflow designs.

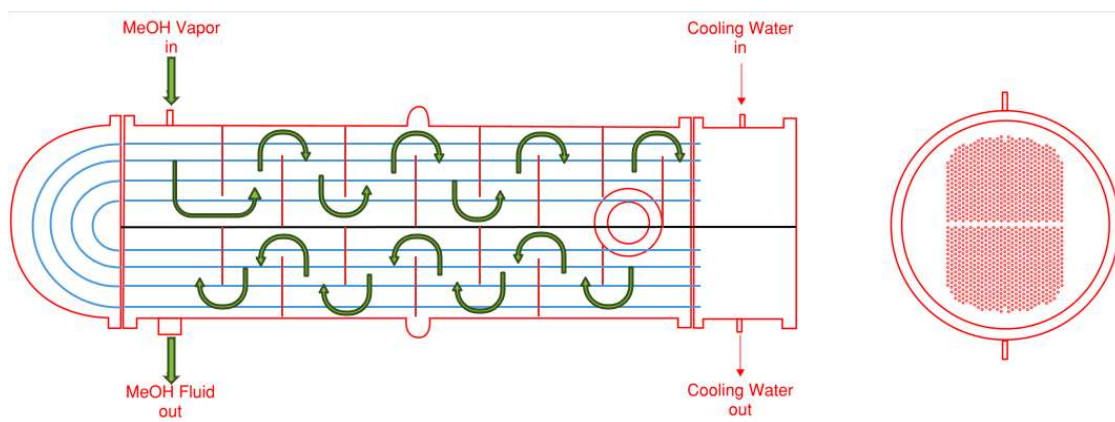
Complex Analysis

The temperature and heat transfer analysis can be more complex due to the perpendicular flow paths.

The 3544 MeOH Condenser

The current 3544 MeOH Column Overhead condenser unit is a shell and tube type of heat exchanger. The condenser consists of two main inputs and outputs that I am focusing on. The MeOH inlet/outlet and the cooling water tubing inlet/outlet. There is also an extra vapour outlet, but this project will focus on these main four.

As can be seen in the diagram below. The vapour flows into the condenser from one of the top inlets and then traverses through a series of segmented baffles. As shown via the green arrows, the MeOH initially travels from the left to right and then completes a second journey back to the left where the MeOH material that has condensed can leave the equipment. The cooling water tubing, depicted by the blue lines, travels in the opposite direction, creating a cross flow system. The tubing in the bundle is held in place thanks to the baffles. These two materials are in a two-pass arrangement, which means the water is exposed to the MeOH twice the length of the condenser unit, meaning exposure is twice as long as it could have been in a single pass system.



General Layout of the shell and Tube Heat Exchanger. *L.Knight (2024)*

This two-pass system provides additional travel time for heat transference to occur and more time for the MeOH vapour to cool down and become fluid. The inclusion of the baffles that are placed in the condenser contribute to slowing down the movement of the MeOH material by creating disturbances in the flow whilst forcing it to move in a particular direction. These disturbances create pockets of turbulence throughout equipment. This is beneficial to the operation of the condenser, as turbulent flows allow for greater heat transference between materials.

The reason that turbulent flows are better for heat transference compared to laminar flows can be down to a couple of facts.

- Increased mixing
 - In turbulent flow, fluid particles move in a chaotic and uneven fashion, causing eddies and vortices. The enhanced mixing increases the contact between the fluid and the heat transfer surface, allowing more uniform temperature distribution and better heat transfer.
- Higher heat transfer coefficient
 - The continuous disruption of the boundary layer in turbulent flow reduces thermal resistance, resulting in a higher heat transfer coefficient.
- reduced thermal resistance.
 - The thinning of the boundary layer in turbulent flow decreases thermal resistance, allowing heat to transfer more readily.

These factors suggest that ensuring a turbulent flow in the heat exchanger is essential for the most efficient heat transference rate.

The general arrangement drawing of the condenser tubing provided by the vendor (Unit Superheater Engineering limited, 2015) gives the key dimensional figures of the tubing. There is a total of 1108 tubes that travel 4000mm down the length of the condenser.

All the tubes have an OD of 19.05mm (3/4") from end to end of the condenser. However, not all the tubes have uniform ID dimensions. 982 of these tubes are 10SWG (3.25mm thick) and 126 are 8SWG (4.1mm thick) with the ends bored out to match the ID of the rest of the tubing where the tubing is surrounded 80mm thick tube sheet.

Key Figures attend from vendor information

	MeOH	Water
Temp In	93°C	51°C
Temp Out	24°C	31°C
Flow Rate In	3.0056kg/s	136.7355kg/s
Flow Rate Out	3.0056kg/s	136.7355kg/s
Cp	1.605kJ/kg K	4.192kJ/kg K

Table of fluid property values in the Heat Exchanger. *L. Knight (2023)*

Using these values, it is possible to work out what the heat transfer rate of the 3544 condenser unit.

The heat transference rate of the MeOH fluid based off the provided values from previous table:

$$\dot{Q} = m_H C_{P_H} \Delta T_H$$

$$\dot{Q} = 3.0556 \times 1605 \times 42$$

$$\dot{Q} = 202.6 \text{ kw}$$

I can also use figures from both Water and MeOH values to calculate the logarithmic mean temperature difference (LMTD).

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

$$\Delta T_{LM} = \frac{(T_{Ho} - T_{Ci}) - (T_{Hi} - T_{Co})}{\ln \left(\frac{T_{Ho} - T_{Ci}}{T_{Hi} - T_{Co}} \right)}$$

$$\Delta T_{LM} = \frac{(51 - 24) - (93 - 31)}{\ln \left(\frac{51 - 24}{93 - 31} \right)}$$

$$\Delta T_{LM} = \frac{(27 - 62)}{\ln \left(\frac{27}{62} \right)}$$

$$\Delta T_{LM} = 42.01^\circ\text{C}$$

This would be correct for basic parallel and counterflow heat exchangers, however, as this is a shell and tube variation with two passes, a correction factor should be used to more accurately calculate the LMTD value.

I first needed to work out the Ratio value of the total heat capacity:

$$R_1 = \frac{(t_1 - t_2)}{(T_2 - T_1)}$$

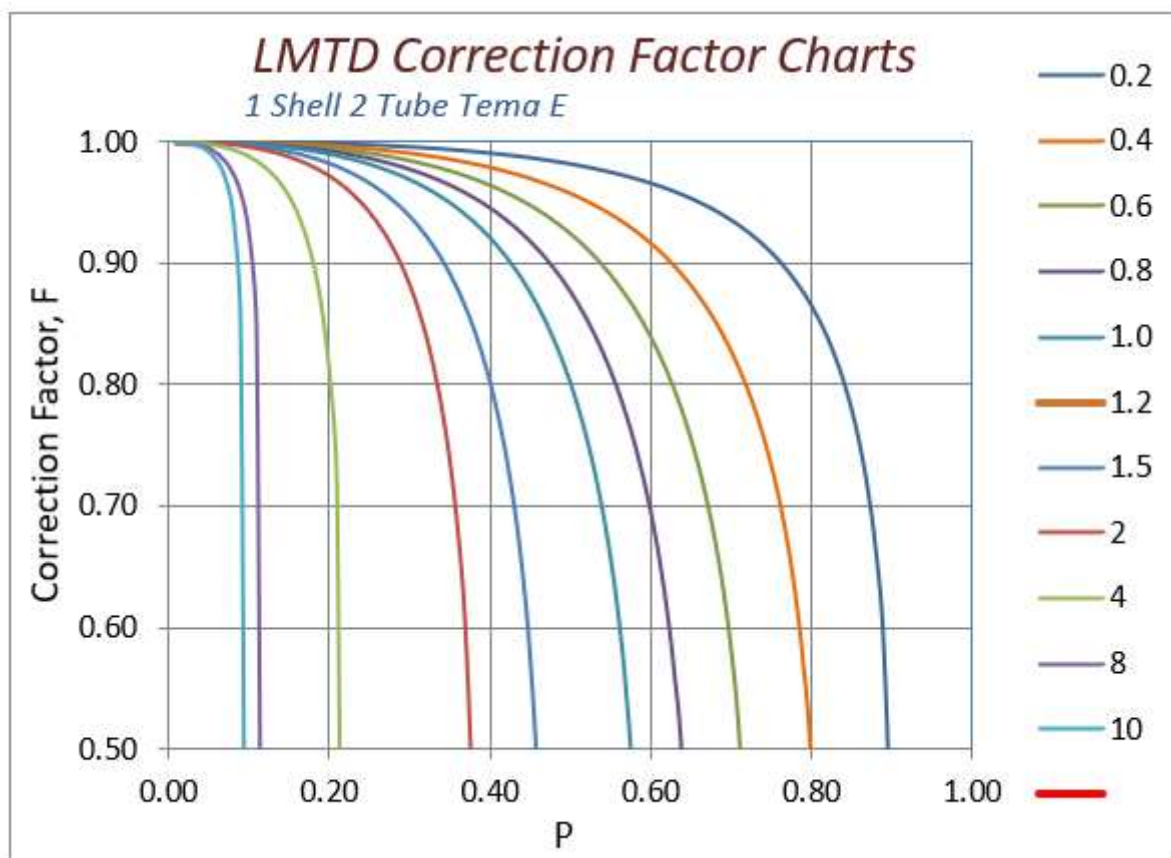
$$R_1 = 6$$

Next, the pipe's effectiveness value was calculated:

$$P_1 = \frac{(T_2 - T_1)}{(t_1 - T_1)}$$

$$P_1 = 0.1014$$

Using the 'R' and 'P' values calculated in the previous equations, I can use the standard LMTD correction factor chart below (CheGuide.com, 2023) and plot my values to find the correction factor 'F'. There are similar graphs for different variations of heat exchangers. This one is used to calculate the correction factor for single shells with two passes of tubing.



Standard graph used to determine the correction factor for LMTD calculations for 1 Shell, 2 Tubing Heat Exchangers. CheGuide.com (2023)

Once the values were plugged into the graph, the below graph was generated with results shown using the red line. The Table gave a resulting LMTD Correction Factor of 0.9707.

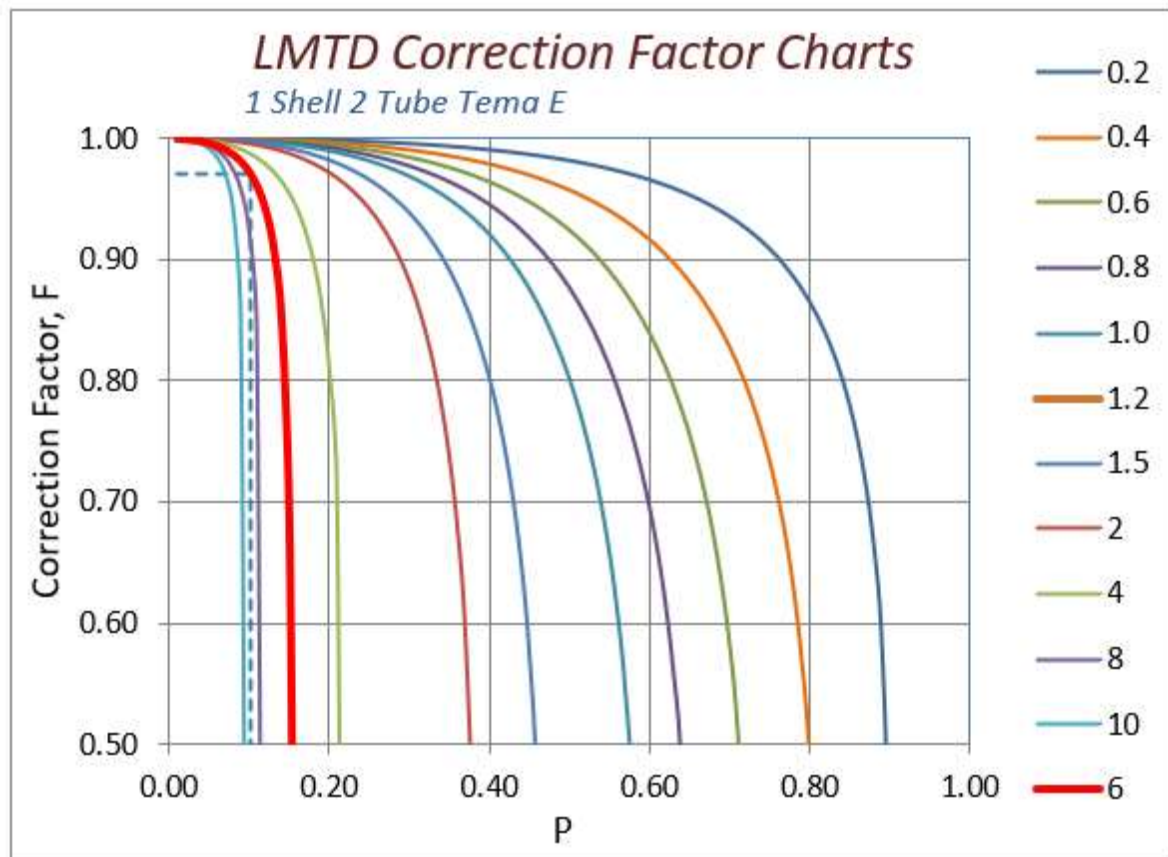


Table showing results of correction factor for LMTD calculations for 1 Shell, 2 Tubing Heat Exchangers. *CheGuide.com (2023)*

With these results the new LMTD value was calculated as:

$$\Delta T_{LM} = 42.01 \times 0.9707$$

$$\Delta T_{LM \text{ Corrected}} = 40.868^{\circ}\text{C}$$

Section 6: Inspections

The tubing for the 3544 Condenser unit is inspected annually to confirm the condition on the tubing walls in the bundle. This is completed when the system is in a shut down and the fluids have been drained and purged. Once the condenser is suitably cleaned and dried and confirmed to be safe to inspect, the integrity team will have an individual come out and conduct a couple of inspection tasks.

Types Of Inspections

Visual Inspections

The first inspection task conducted is a visual inspection for any physical defects. One of the main physical issues the bundle may face is the build up of 'crud' or foreign material that has built up around the baffles/tubing, causing fouling. The importance of clearing this dirt is in two parts. Firstly, the build up of this material can envelop the tubing and create a form of insulation around it. By doing this, the water in the tube is being prevented or at least has its heat transfer efficiency greatly hindered. This means the overall heat exchanger will not be working to its greatest capability. The second important reason for cleaning this dirt off is to prevent the fouling from causing corrosion on the external face of the tubing. If left unchecked, the corrosion could eat away at the outer wall of the tubing, reducing the wall thickness and potentially leading to a high risk of leak points being created in the bundle. Fouling also has effects such as increasing pressure drops in the system. This is because the build up of material will cause the flow passages to narrow and increase resistance, thus requiring more energy to maintain the flow rates. A major effect of the fouling material is that it can be a leading cause for the accelerated wear and tear on the equipment, greatly shortening the equipment's lifespan.



Image depicting fouling of a heat exchanger. (*Intechopen.com,2023*)

Eddy Current

Another example of inspection that is completed is the eddy current exam, which is performed on several of the tubes in the bundle. This is a non-destructive testing method that uses electromagnetism to detect any flaws within a material. The activity of performing this inspection technique falls under the standard ASTM E690-15(2020) as well as it being a basic requirement according to the API 660 standard Pg25 8.4.2. This standard gives the correct procedures that should be followed during the activity and outlines the specific challenges of inspecting installed tubing in heat exchangers. Using a probe that contains a coil that generates and detects magnetic fields. When there are any irregularities in the surface such as corrosion, cracks or other changes, these are picked up via the changes in magnetic field and the probe can convert that information into a readable format. This data can then be reviewed to indicate any issues with the tubing.

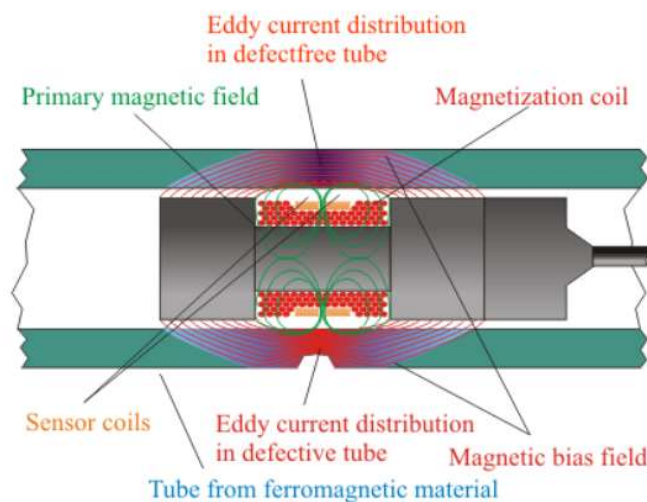


Diagram of the Eddy Current Inspection Equipment. (*Kontolltechnik.com, 2024*)

The main advantage of completing this form of inspection is that it is non-destructive which means it will cause no damage to the equipment itself and allow the equipment to still be used post inspection. Another Advantage is that the probe is quite sensitive which means it can pick up some of the slightest changes in material condition. This helps to pick up on potential issues earlier in the equipment's lifecycle. In general, the process to inspect a singular tube is swift. This makes it ideal for inspecting many tubes like those in the bundle.

Inspection Reports

The inspection reports from 2020 and 2021 indicate that out of the 1108 tubes in the bundle only 241, or 21%, were actually tested. One of the main reasons for this is time. The shutdown period in total will typically last 2-3 weeks for any particular job. However, this time period includes the time the system is prepared for shut down, the emptying and cleaning of the equipment, time to conduct inspections and then any maintenance tasks that need to be performed prior to the equipment being boxed back up and post maintenance checks are done before the system goes online. Due to the busy period in this short window, a sample of tubes are selected to be tested. It is noticeable in the visual reports that there is a pattern for choosing the tubes that get tested.

The Inspection documents show the varying amount of wall loss amongst the tubes in the bundle. The diagram indicates that the tubes that experience the most wall thickness reduction are those that are located on the sides of the condenser units. For this reason, tests are usually conducted in these problem areas. Tests are then conducted further in until the wall reduction value trend goes down to more acceptable values (<10%).

The inspection reports show that the tubing used in the current design experience wall thickness reduction up to around 49%. With the tubing currently having a wall thickness of 4.1mm (Dow, 2020), this would mean that the wall on the worst affected tubes is being reduced by nearly 2mm. This would bring the thinnest walls to a thickness of 2.1mm, a significant loss. This is right at the very minimum the tube wall thickness is allowed to be according to the API 660 standards (Pg10, 7.5.1.2, Table 1).

Table 1—Minimum Thickness of Tubes

Dimensions in millimeters (inches)

Tube Material	Minimum Thickness ^a
Carbon steel, low-alloy steel (max. 9 % chromium), aluminum, and aluminum alloy	2.11 (0.083)
Copper and copper alloys	1.47 (0.058)
High-alloy [austenitic, ferritic, and austenitic/ferritic (duplex)] steel and other nonferrous materials	1.47 (0.058)
Titanium	1.07 (0.042)
^a Tubes shall be furnished on either a minimum wall basis or an average wall basis, provided the tube thickness is not less than that specified above.	

Table of the minimum allowable thicknesses of tubing. (API, 2015)

This loss of material can be due to a couple of reasons such as:

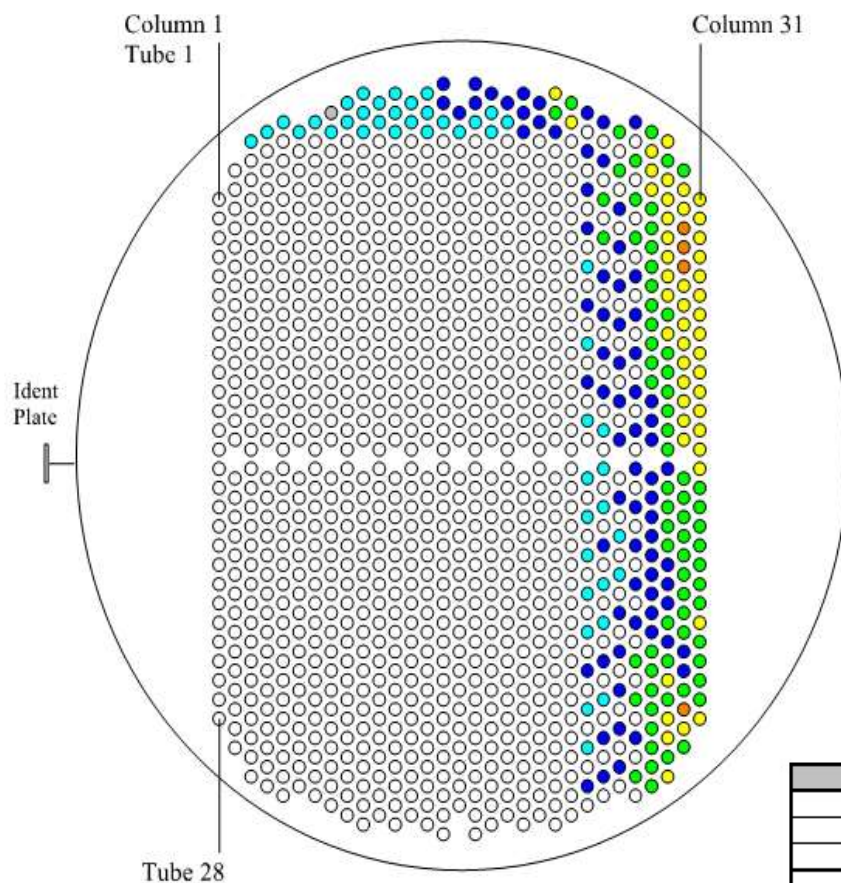
- Chemical Reactions with the material
- Particles/dirt in the fluids flowing through the system.
- Crystallisation
- Corrosion Processes
- Biological Mass Accumulation

I have already covered most of these in section 3.

Tubular Inspection data 29th-30th September 2020

3.0 Tubesheet Map
Dow Silicones UK Ltd
Barry
W931-3544-10025920
IR-20-10-1426

Viewed from
Inlet/Outlet End



Tube Material : Carbon Steel
Tube OD : 19.05mm
Tube NWT : 3.25mm & 4.06mm (Col 24 - 31)
Tube Length : 3968mm
No of Tubes : 1108
Unit : Uninstalled

Wall Loss Value	Number of Tubes
<10%	45
10-19%	75
20-29%	70
30-39%	47
40-49%	4
50-59%	0
60-69%	0
=>70%	0

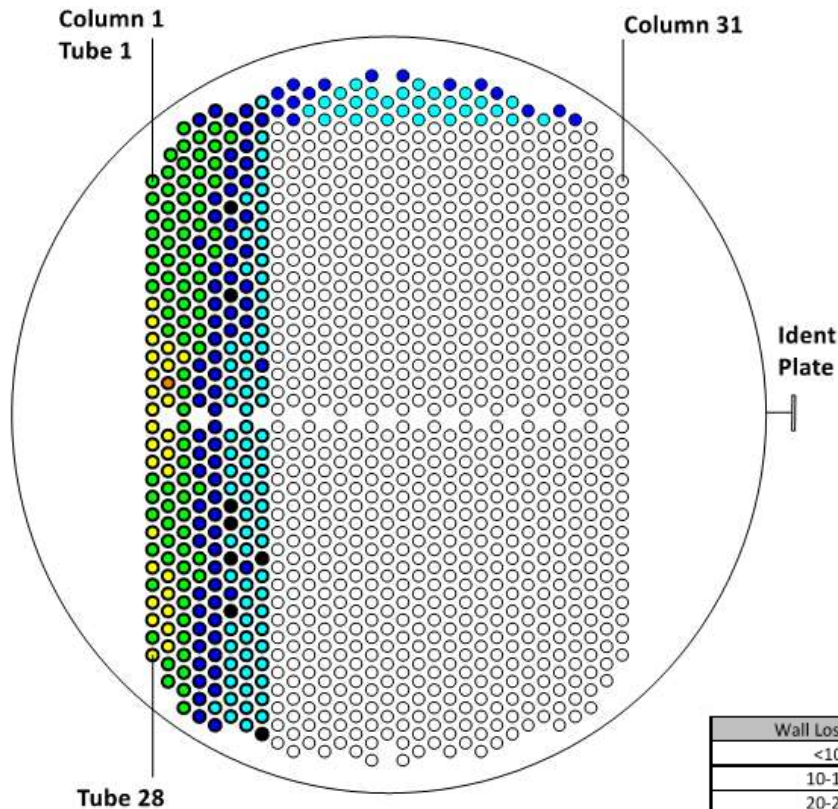
Legend (% Wall Loss)			
● < 10 (45 Tubes, 4%)	● 30-39 (47 Tubes, 4%)	● 60-69 (0 Tubes, 0%)	X Plug (0 Tubes, 0%)
● 10-19 (75 Tubes, 7%)	● 40-49 (4 Tubes, 0%)	X >70 (0 Tubes, 0%)	● NTP (0 Tubes, 0%)
● 20-29 (70 Tubes, 6%)	● 50-59 (0 Tubes, 0%)	○ Not Tested (866 Tubes, 78%)	● Inaccessible (1 Tubes, 0%)

Inspection report of 3544 Condenser unit tubing Bundle (Dow, 2020)

Tubular Inspection data 3rd-4th September 2021

3.0 Tubesheet Map
Dow Silicones UK Ltd
Barry
W931-3544-30327B
IR-21-09-1343

Viewed from
Return End



Tube Material : Carbon Steel
Tube OD : 19.05mm
Tube NWT : 3.25 & 4.06mm
Tube Length : 3968mm
No of Tubes : 1108
Unit : Uninstalled

Wall Loss Value	Number of Tubes
<10%	103
10-19%	87
20-29%	86
30-39%	27
40-49%	1
50-59%	0
60-69%	0
=>70%	0

Legend (% Wall Loss)			
● < 10 (103 Tubes, 9%)	● 30-39 (27 Tubes, 2%)	● 60-69 (0 Tubes, 0%)	⊗ Plug (0 Tubes, 0%)
● 10-19 (87 Tubes, 8%)	● 40-49 (1 Tubes, 0%)	⊗ >70 (0 Tubes, 0%)	● NTP (8 Tubes, 1%)
● 20-29 (86 Tubes, 8%)	● 50-59 (0 Tubes, 0%)	○ Not Tested (796 Tubes, 72%)	● Inaccessible (0 Tubes, 0%)

shown.

Inspection report of 3544 Condenser unit tubing Bundle (Dow, 2021)

Section 7: Materials

Tubing Material Options

There are a few existing options when it comes to tubing materials for shell and tube exchangers. Each will have their benefits and drawbacks including costs, manufacturability, thermal conductivity (Engineeringtoolbox.com, 2023), maintainability and corrosion resistance.

	Carbon Steel	Copper	Aluminium	Titanium
Cost per Kg	£1.20-£2.50	£6.00-£8.00	£2.50-£4.00	£25.00-£35.00
Thermal Conductivity	At 122°C - 33W/m K	At 127°C - 392W/m K	At 127°C - 240W/m K	At 127°C - 20.4W/m K
Corrosion Resistance	High	Very High	High	Very High
Manufacturability	High	Very High	High	Medium

Table showing the general characteristic values of the tubing materials. (Knight. L, 2024)

To work out what the conductive heat transference of each of these materials, I will need to use the following formula from Fourier's law:

$$Q = \left(\frac{k}{s}\right) A \Delta T$$

Where Q = Heat Transfer, k = Material Thermal Conductivity, s = Material Thickness, A = Area, T = Temperature

The thermal conductivity value can be taken from the table shown above (Knight. L, 2024). The material thickness of the tubing is 4.1mm and the temperatures of the lines are from the vendor information (Unit Superheater Engineering limited, 2015). The missing information needed to calculate these figures is the tubing area. The condenser has 1108 tubes with a 19.05mm diameter within the bundle, each at the length of 3968mm according to the reports (Dow, 2020). With this information I can calculate the following area:

$$A_{Outer} = \pi DL$$

$$A_{Outer} = \pi \times 0.01905 \times 4396.544$$

$$A_{Outer} = 263.12m^2$$

With this figure, I plugged in the values for each of the materials. For example, this is:

$$Q = \left(\frac{33}{0.0041}\right) \times 263.12 \times (93 - 51)$$

$$Q = 88947395 \text{ W/(m.K)} \text{ or } 88947.4 \text{ KW/(m.K)}$$

	Carbon Steel	Copper	Aluminium	Titanium
Conductive heat Transference (KW/(m.K))	88947.4	1056587.2	646890.1	54985.7

Table showing conductive heat transference of the tubing materials. (Knight. L, 2024)

The results of the table give a theoretical heat transference value for each material. The table suggests that titanium would be the worst choice for conductive heat transference, with copper coming out on top.

Section 8: Condenser Design

Baffle Design

The current design of the 3544 condenser follows the standard two pass shell design with F-type shell with segmental shaped baffles alternating down the length of the condenser body. There are several types of baffles that can be used in shell and tube condensers.

Segmental Baffles

In the current design, each baffle is a segment of a circle with areas cut out on one side. The image below shows the general layout and how they are incorporated into the heat exchanger (intechopen.com, 2019). The flow pattern of the shell side fluid is forced into a zigzag motion, which helps to force the shell side fluid to make contact with the tube bundle more frequently than it otherwise would have. This design can come in two main variations, single and double segmented. The variations differ in that one forces the flow through a single direction whilst the double will allow for a two-pass flow across the tubes.

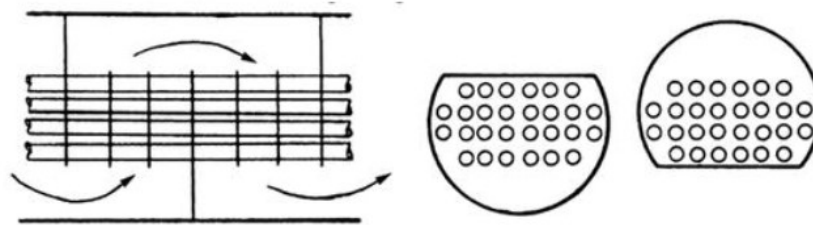


Diagram of segmental Baffles. (intechopen.com, 2019)

General Pros and Cons for Segmented Baffles

Advantages

Improved Turbulence

Segmental baffles generate a crossflow pattern, which enhances fluid turbulence and improves the total heat transfer coefficient.

Multiple Passes

The design forces the fluid to pass across the tube bundle multiple times, maximizing the heat transfer surface area utilization.

Controlled Flow Distribution

Promotes equal fluid distribution throughout the tube bundle, limiting the possibility of hot patches or places with poor heat transfer.

Disadvantages

Increased Pressure Drops

The crossflow pattern and multiple passes through the baffles increase the resistance to fluid flow, resulting in a higher pressure drop across the heat exchanger.

Flow-Induced Vibration

The increased turbulence and fluid velocity can produce high levels of vibrations in the tubes, which, if not properly managed, can lead to tube wear and failure.

Potential for Fouling

Particles and fouling may build up on the baffles and tubes because of the increased turbulence and flow velocity. Resulting in flow pathways being obstructed, thus decreasing efficiency.

Energy Costs

Higher pressure drops require more pumping power, increasing the operational energy costs.

Disk and Doughnut Baffle

The disk and doughnut baffle design utilises both shapes to cause turbulence within a heat exchanger. The doughnut shape is a full-face baffle with a diameter removed from the centre, this is where it allows the fluid to travel through. The disk is the inverse of the doughnut and forces the fluid to travel on the outer edges of the shell. The support for the tube bundle comes from the doughnut baffle as the disk baffle offers no support for the central tubes.

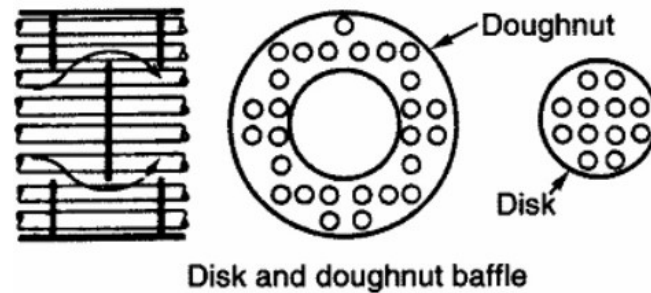


Diagram of Disk and Doughnut Baffles. (*ijester.com*, 2019)

General Pros and Cons for Disk and Doughnut Baffles

Advantages

Improved Turbulence

The alternating baffle design induces higher turbulence levels within the shell-side fluid, improving the heat transfer coefficient

Optimised Flow Distribution

Promotes a more uniform flow distribution and minimizes dead zones compared to segmental baffles

Lower Pressure Drops

The design creates a more streamlined flow path, reducing the overall pressure drop compared to segmental baffles.

Vibration Reduction

Compared to segmental baffles, the design helps distribute the forces more evenly, reducing the likelihood of flow-induced vibrations and associated tube damage.

Disadvantages

Complex Manufacturing

The alternating disk and doughnut shapes can be more challenging to manufacture and assemble compared to simpler baffle designs.

Operational Limitations

Disc and doughnut baffles are useful in many applications, although they might not be appropriate for all fluid types, especially those with extremely high viscosities or particle loads.

Maintenance Challenges

The alternating baffle design can make it more difficult to access certain areas of the tube bundle for inspection and maintenance.

Grid/Rod Baffles

Grid and rod baffles designs that are used in shell-and-tube heat exchangers that require as little pressure drop as possible whilst also providing some heat transference. The Grid baffle is made with a lattice like structure that covers the shell's cross-sectional area. This lattice provides minor turbulence in the fluid whilst also offering support to the tube bundle. The Rod baffle comprises of rods that are placed along the cross section of the shell in either a parallel or crisscross layout. Like the grid baffle, it offers support to the tubing whilst providing a means to produce some turbulence within the shell.

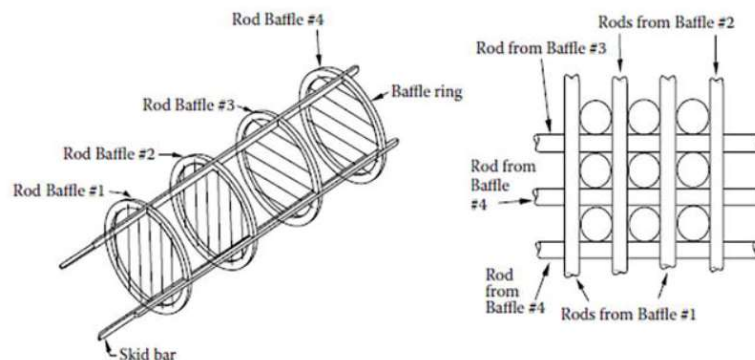


Diagram of Rod Baffle layout. (intechopen.com, 2019)

General Pros and Cons for Grid and Rod Baffles

Advantages

Low Pressure Drop

There is reduced resistance to fluid flow due to the open design of the rod and grid baffles, which lowers the pressure drop. This also means that the design requires less energy to pump the fluids through.

Reduced Fouling

The designs for the grid and rod baffles have less areas where dirt and crud can accumulate, meaning the likelihood of fouling is greatly reduced.

Uniform Flow

Since the design has minimal turbulence in comparison to other baffles, it produces a more consistently even flow. Meaning the heat transfer efficiency is generally good.

Vibration Reduction

The open design and uniform distribution of flow can extend the tubes' lifespan by decreasing flow-induced vibrations.

Disadvantages

Lower Heat Transfer

In comparison to segmental baffles, the open design may produce little pressure drops but that comes at a cost of producing less turbulence, which will result in a lower heat transfer coefficient.

Operational Limitations

The grid and rod baffle are not suitable for all applications. This is especially true for services that handle very viscous fluids or need extremely high heat transfer rates

Maintenance Challenges

In comparison to other options fouling can be reduced, however, the design could cause accessing all areas of the tube bundle for inspection and maintenance to be more difficult.

Helical Baffles

Helical baffles are a more complex design that is used in some heat exchangers. As shown in the diagram below (iv-soft, 2019), the baffles coils as it travels down the length of the heat exchanger, forming one continuous shape that promotes a similarly continuous flow for the shell side fluid. The helical shape still invokes a level of turbulence from the fluid whilst also not giving it the chance to stagnate anywhere. An additional benefit to this is that build up of dirt or foreign materials is far less likely, this is because the particles would have less places to sit.

This variation of baffles was designed by Ebert and Panchal (1997) whose aim was to increase heat transfer efficiency, lower pressure drops, reduce fouling, and improve operating performance. The design they came up with is said to extend the operation life cycle of equipment roughly 3-4 times longer in comparison with other designs. However, the helical design is more difficult to manufacture as the tubes in the bundle will now come in at an angle rather than the flat surfaces the other options require. This additional difficulty translates to increased manufacturing time to produce, thus higher production costs.

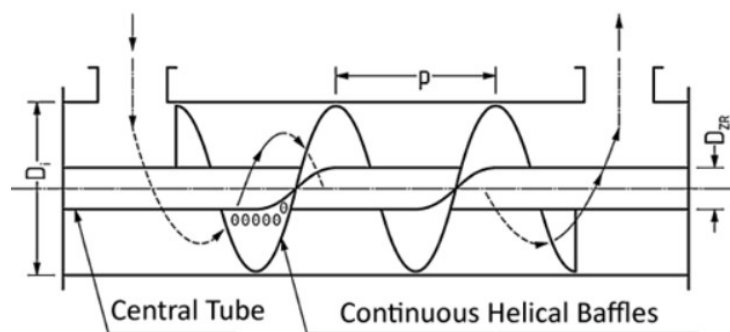


Diagram of Helical Baffle layout. (iv-soft.de, 2019)

General Pros and Cons for Grid and Rod Baffles

Advantages

Enhanced Heat Transfer

The helical flow pattern boosts heat transfer rates by significantly increasing turbulence. The heat transfer efficiency is increased due to the fluid and tube surfaces being in constant contact.

Lower Pressure Drop

There is less of a pressure drop with the helical design in comparison with conventional segmental baffles thanks to the lower flow resistance.

Disadvantages

Complex Manufacturing

Compared to other baffle types, helical baffle designs and construction tasks are more intricate and costly. This means that there will be higher initial cost of manufacture and installation. This may offset any savings that the design could save during operation.

Maintenance Difficulties

Despite the overall reduction in fouling, the helical baffle design will make it more difficult to access specific areas of the tube bundle for cleaning and inspection. Meaning that maintenance downtime could last longer than with other options.

Reduced Fouling

High turbulence and shear forces help to minimise particle accumulation, reducing fouling and maintenance needs. The design gives a self-cleaning effect.

Vibration Reduction

The continuous helical flow protects the tube bundle from mechanical damage by reducing flow-induced vibrations.

Looking at the pros and cons of each of these designs and taking the needs of the 3544-condenser unit into consideration, I was able to conclude on what design I believe would work best. The grid and rod variations do have a reduced fouling rate as well as minimal pressure drops, unfortunately, they have insufficient heat transfer efficiency to be viable for the service. The disk and doughnut option, in comparison to the segmented baffle design, does offer lower pressure drops with its more consistent even flow, however the more complex design does mean it could cost more financially to install whilst also potentially more challenge to maintain but with very little difference in performance. The helical design is the most complex out of the designs meaning that it will likely have the greatest initial costs to install. However, the benefit of being far less susceptible to fouling, implying an operation lifecycle that lasts multiple times longer than the current design, means that the drop in maintenance costs can balance out those initial costs. It also maintains a high heat transfer coefficient.

Section 9: Conclusion and Recommendations

From the research conducted in this project, I have discovered that one of the main reasons for fouling in the 3544-condenser unit is the frequent build-up of particles and dirt. The current design of the segmented baffles does provide a large amount of turbulence with the shell side fluid, meaning it also provides high levels of heat transfer efficiency. However, this same design allows for the material build up to occur where fluid tends to stagnate, meaning that sections of the tubing is encased and unintentionally insulated. This also becomes an area that promotes corrosion on the external wall of the tubing. The helical design mitigates this problem by allowing the build up material to pass with the flow of the fluid as there are minimal stagnant locations. The drawback of the helical design is that it is more complicated to fabricate the tubing as it will need to be fixed to the baffles at an angle rather than a flat surface. This is a driving point for selecting the material of the tubing. Looking at the research conducted, titanium would be the material that would theoretically survive the longest during operation. However, titanium is very difficult to manufacture with and has poor thermal conductivity. Meaning that titanium, despite its longer life cycle, would generally perform poorer than carbon steel. The Carbon Steel material has the benefit of being easily machinable to fit the complex designs of the helical baffles. To perhaps extend the operation life of carbon steel, a coating such as galvanisation of the tubing could help to protect the tubing from external contaminants.

If I was to complete this project again, I would have liked to have performed experiments with samples of each potential tubing material. Placing them in a smaller scaled version of the typical operation environment could help me simulate the long-term effects of constant exposure to the fluids. I would have also liked to have tested material samples to find the thermal transference rates in a controlled environment. Another possible option could be to use software such as MATLAB to create a program that could simulate the thermal transference of the fluids.

To Summarise, the optimal choice for the condenser unit would be to use the helical design for the baffles whilst fabricating them using the carbon steel material.

Section 10: References

- Abramek, Karol & Stoeck, Tomasz & Osipowicz, Tomasz. (2015). *Statistical Evaluation of the Corrosive Wear of Fuel Injector Elements Used in Common Rail Systems*. *Strojniski Vestnik*. 61. 91-98. 10.5545/sv-jme.2014.1687. Available at: https://www.researchgate.net/figure/Examples-of-pitting-corrosion-Bosch-fuel-injector-nozzle-tip_fig1_272368689 (Accessed: 12 March 2023)
- AMPP (2023) *Forms of corrosion*, AMPP. Available at: <https://www.ampp.org/technical-research/what-is-corrosion/forms-of-corrosion> (Accessed: 02 June 2023).
- American Petroleum Institute (March 2015) *API STANDARD 660: NINTH EDITION: Shell-and-Tube Heat Exchangers*. (Accessed: 15 February 2023).
- American Petroleum Institute (July 2005) *API Specification 5CT: Eighth Edition: ISO 11960:2004, Petroleum and Natural gas industries-steel pipes for use as casing or tubing for wells*. (Accessed: 15 February 2023).
- ASTM (ed.) (2017) *Standard specification for seamless carbon steel boiler tubes for high-pressure service, A192/A192M*. Available at: https://www.astm.org/a0192_a0192m-17.html (Accessed: 12 February 2023).
- Corbett, N. (2021) *Crevice corrosion: What to know and how to stop it*, *Spear Industrial*. Available at: <https://spearindustrial.com/crevice-corrosion-what-to-know-and-how-to-stop-it/> (Accessed: 12 April 2024).
- Corbett, N. (2021) *Intergranular Corrosion: A Quick Guide*, *Spear Industrial*. Available at: <https://spearindustrial.com/intergranular-corrosion-a-quick-guide/> (Accessed: 12 April 2024).
- Detloff, C. (2017) *Maximizing pump efficiency through reduced corrosion and erosion*, *Empowering Pumps and Equipment*. Available at: <https://empoweringpumps.com/sulzer-maximizing-pump-efficiency-through-reduced-corrosion-erosion/> (Accessed: 20 June 2023).
- Durex Industries (2023) *Corrosion resistance of different materials*, *EngSection05*. Available at: https://www.durexindustries.com/documents/pages/CorrosionResistance_DifferentMaterials.pdf (Accessed: 14 July 2023).
- Engineeringtoolbox, E. (2024) *Metals, metallic elements and alloys - thermal conductivities*, *Engineering ToolBox*. Available at: https://www.engineeringtoolbox.com/thermal-conductivity-metals-d_858.html (Accessed: 24 February 2024).
- Epkusa (2023) *Ultrasonic Thickness Gauge, PosiTector UTG Wall Thickness Gauge*. Available at: <https://www.epkusa.com/product/PT-UTG> (Accessed: 05 July 2023).
- Garavaglia, M. et al. (2023) *Advanced shell-and-tube longitudinal flow technology for improved performances in the process industry*, *IntechOpen*. Available at: <https://www.intechopen.com/chapters/88335> (Accessed: 20 February 2024).
- Garikaib (2022) *Experiment: The corrosion of metals by acids*, *Free ZIMSEC & Cambridge Revision Notes*. Available at: <https://revision.co.zw/experiment-corrosion-metals-acids/> (Accessed: 19 March 2023).

Herbrecht, M. (2022) *Dezincification: The enemy of brass plumbing fixtures*, *Technorm*. Available at: <https://technorm.ca/en/articles/dezincification-the-enemy-of-brass-plumbing-fixtures/> (Accessed: 12 March 2024).

HRS (2022) *Comparison of laminar & turbulent flow: Resource*, *HRS Heat Exchangers*. Available at: <https://www.hrs-heatexchangers.com/resource/comparison-of-laminar-and-turbulent-flow/> (Accessed: 27 January 2024).

HSE (ed.) (2023) *Inspection/Non Destructive Testing*, *Inspection/Non destructive testing*. Available at: <https://www.hse.gov.uk/comah/sragtech/techmeasndt.htm> (Accessed: 22 February 2023).

HSE (ed.) (2023) *What is a 'substance hazardous to health'?*. Available at: <https://www.hse.gov.uk/coshh/basics/substance.htm> (Accessed: 24 February 2023).

Ibrahim, H.A.-H. (2012) *Fouling in heat exchangers*, *IntechOpen*. Available at: <https://www.intechopen.com/chapters/39353> (Accessed: 20 February 2024).

IndiaMart (2023) *Corrosion coupon (strip type)*, *indiamart.com*. Available at: <https://www.indiamart.com/proddetail/corrosion-coupon-strip-type-12750242848.html?pos=5&pla=n> (Accessed: 20 June 2023).

lv-Soft (2024) *Continuous helical baffles*, *Lauterbach Verfahrenstechnik gmbh – software und engineering im Apparatebau und Anlagenbau*. Available at: <https://www.lv-soft.de/modulehelp/en/wts/index.html#!WordDocuments/continuoushelicalbaffles.htm> (Accessed: 13 February 2024).

Kontroll Technik (2024) *The eddy current principle with superimposed DC field magnetization, Magnetic Bias EC*. Available at: <https://www.kontrolltechnik.com/methods/tube-inspection/magnetic-bias-ec> (Accessed: 02 March 2024).

Larsen, K.R. (2020) *A closer look at microbiologically influenced corrosion*, *MaterialsPerformance.com*. Available at: <https://www.materialsperformance.com/articles/chemical-treatment/2015/08/a-closer-look-at-microbiologically-influenced-corrosion> (Accessed: 10 April 2023).

Malhotra, V. (2022) *Role of a good quality coating layer for corrosion resistance*, *Testing Instruments*. Available at: <https://www.testing-instruments.com/blog/role-of-a-good-quality-coating-layer-for-corrosion-resistance/> (Accessed: 22 February 2024).

Methanol.org (2023) *Methanol Technical Data Sheet*, *Methanol.org*. Available at: <https://www.methanol.org/wp-content/uploads/2016/06/Methanol-Technical-Data-Sheet.pdf> (Accessed: 03 July 2023).

Mya, N.S. (2019) *Baffle design of shell and tube heat exchanger*, *International Journal of Scientific Engineering and Technology Research*. Available at: <http://ijsetr.com/uploads/214536IJSETR17552-89.pdf> (Accessed: 03 March 2024).

Nelly (2020) *20 examples of physical and chemical changes of matter*. Available at: <https://www.experimentosfaciles.com/20-ejemplos-de-cambios-fisicos-y-quimicos-de-la-materia/> (Accessed: 20 February 2023).

Neutrium (2013) *THERMAL CONDUCTIVITY OF METALS AND ALLOYS*. Available at: <https://neutrium.net/heat-transfer/thermal-conductivity-of-metals-and-alloys/> (Accessed: 24 February 2024).

Parsons, J.F. (2020) *Stress corrosion cracking - metallic corrosion*, AZoM. Available at: <https://www.azom.com/article.aspx?articleid=102> (Accessed: 10 April 2023).

Primo, J. (2020) *Shell and tube heat exchangers - basic calculations*, PDH Online. Available at: <https://www.pdhonline.com/courses/m371/m371content.pdf> (Accessed: 20 February 2024).

Roldeta (2019) *Explanation pump cavitation.*, Rodelta. Available at: <https://www.rodelta.com/pump-cavitation/> (Accessed: 13 March 2023).

saVRee (2023) *Plate heat exchanger (PHE)*, saVRee. Available at: <https://savree.com/en/encyclopedia/plate-heat-exchanger-phe> (Accessed: 20 February 2024).

Schaeffler (2022) *Investigating bearing failure-spot the clues & uncover the root cause*, IBT Industrial Solutions. Available at: <https://ibtinc.com/bearing-failure-analysis/> (Accessed: 22 March 2023).

Tensiontestmachine.com (2017) *Salt spray test chamber, 108L 270 liters salt spray test chamber resistance corrosion Test Machine/environmental test chamber/corrosion test cham*, Perfect International Instruments Co., Ltd. Available at: <https://www.tensiontestmachine.com/sale-10149862-108l-270-liters-salt-spray-test-chamber-resistance-corrosion-test-machine.html> (Accessed: 25 March 2023).

Vishal Steel India (ed.) (2023) *BS 3059 GR 360 Part 2 Carbon Steel Boiler tubes*, Vishal Steel India. Available at: <https://www.vishalsteelindia.com/bs-3059-part-2-grade-360-boiler-tube.html> (Accessed: 13 October 2023).

Wilkinson Coutts (2021) *Salt is bad for your health! - corrosion basics*, Wilkinson Coutts Engineering Training Ltd. Available at: <https://wilkinsoncoutts.com/salt-is-bad-for-your-health-corrosion-basics/> (Accessed: 19 March 2023).

UKGov (2013) *The reporting of injuries, diseases and dangerous occurrences regulations 2013*, Legislation.gov.uk. Available at: <https://www.legislation.gov.uk/uksi/2013/1471/contents/made> (Accessed: 25 March 2023).