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Advanced thermofluid mechanics

Analysis of fouling in industrial shell-and tube heat exchangers

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Introduction

This report focuses on shell and tube heat exchangers, and the fouling associated with them. The history of shell and tube heat exchangers is discussed, including when they first were used and how they have developed over time, followed by discussions based around the fouling mechanisms within them and the necessary maintenance practices used because of it.

The second section of this report discusses the design improvements that have been adopted to mitigate fouling, specifically the implementation of helical baffles as a result of research carried out by Ebert and Panchal (1997) who developed a fouling model, and the principles and theory behind this fouling model.

The final section of this report includes mathematical calculations to simulate the performance of a heat exchanger within a laboratory environment, calculations include with and without fouling to show how fouling impacts the operation of a heat exchanger, followed by a simulation where heat exchanger performance is calculated with fouling present and an increasing thickness to represent how the heat exchanger performs with a more severe increase in fouling in increments of 0.5mm up to 5mm.

Task 1: History of heat exchangers and the principle mechanisms of fouling.

What is a heat exchanger?

Whilst there are many types of heat exchangers, with various designs, they all have the same basic principle, to transfer heat from one fluid to another. This can be for the purpose to either heat or cool a fluid. Heat exchangers are widely used in numerous applications from chemical plants and power stations on the industrial end, to heating swimming pools and buildings on the commercial and domestic end. According to (Schmidt, 2011), apart from pumps, heat exchangers are the most widely used form of major equipment in chemical plants.

Shell and tube heat exchangers

This report focuses on heat exchangers of a shell and tube design, a typical shell and tube heat exchanger consists of multiple tubes, in the form of a tube bundle, within a cylindrical shell. One fluid flows through the internal tubes, whilst the other flows around the tubes within the cylindrical shell, with a temperature difference between the two fluids, heat energy is exchanged between them, heat exchangers can be arranged for parallel flow or cross/counter flow of the fluids. (Brogan, 2011)

Figure 1 below shows the basic arrangement of a shell and tube heat exchanger as described above.

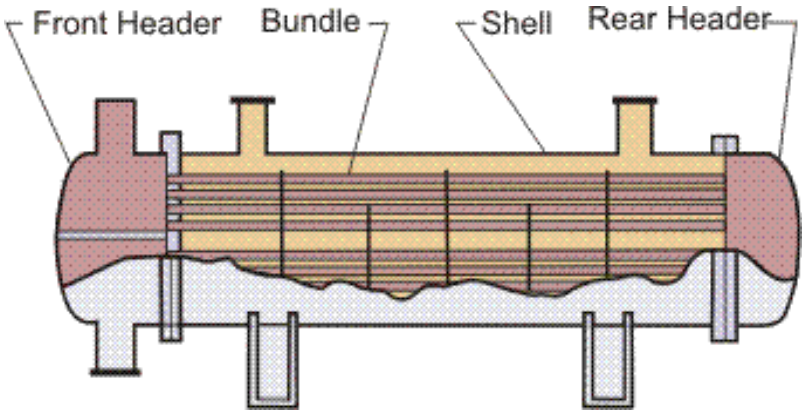


Figure 1 - Shell and tube heat exchanger (Brogan, 2011)

To simply explain how the heat exchanger shown in figure 1 operates, one fluid enters through the front header, flows through the tubes to the rear header, then flows back through the tubes and exits through the second nozzle of the front header. Whilst this is happening, the second fluid flows into the shell through one nozzle, flows around the tube bundle with multiple passes as directed by the baffles, and then exits the shell via the second nozzle. During this cycle heat energy is exchanged between the 2 fluids through the tube walls.

History of heat exchangers

The first use of industrial shell and tube heat exchangers can be traced back to the early 1900's, where they were first used for power plant applications, as condensers and feedwater heaters, and for the emerging oil industry, often requiring high pressure and high temperature applications for what can be considered "dirty fluids".

According to (Taborek, 2018), whilst heat transfer was far from efficient and was crudely estimated at the time, the major issue regarding these early heat exchanger designs was the material strength calculations for the components, particularly for the tube sheets. There were also considerable issues with the manufacturing techniques and methods used, such as the tube-to-tube sheet joints and the welding of flanges and nozzles, many of these problems are still present today.

It is generally recognised that the manufacturing technology became well developed during the 1920's as the result of a few major manufacturers developing heat exchangers for the oil industry. Furthermore, in the 1930's designers developed many sound designing principles based on intuition and data emerging from ideal tube-banks.

It wasn't until the 1940's that an industry standard was first developed by TEMA (Tubular exchangers manufacturers association), that standardised mechanical design of shell and tube heat exchangers for safety, quality control, uniformity of tolerances and orderliness in competition. This standard now being at a tenth edition is used world-wide and considered standard practice. (TEMA Standards, 2020)

In the mid 1950's, the first patent was filed for a shell and tube heat exchanger by Babcock and Wilcox co., then during the 60's right through to the 90's companies started using CAD software for the design of heat exchangers, as well as multiple standards being developed to classify the types of heat exchangers based on their applications, i.e., petrochemical, chemical or commercial. In the present day, heat exchangers are an integral part of many industries, and the design variants are extremely customizable as well as relatively lower in cost. (Mehta, 2021)

Figure 2 below shows a timeline of heat exchanger developed, made by (Mehta, 2021).

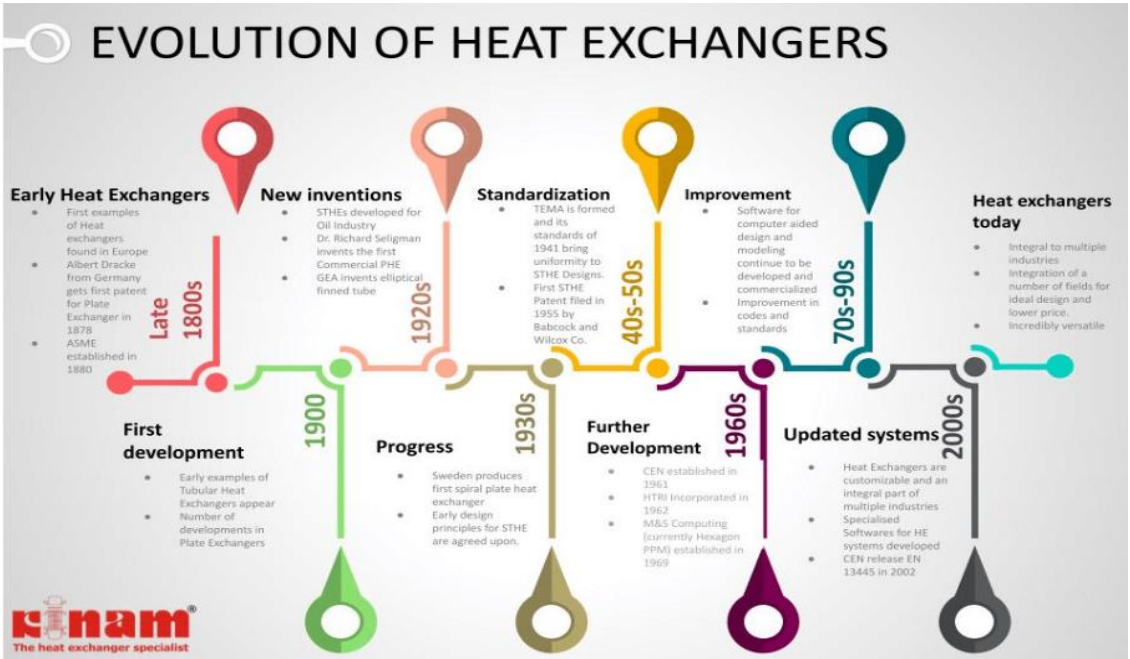


Figure 2 - Evolution of heat exchangers timeline (Mehta, 2021)

What is fouling in heat exchangers?

Fouling has been a major issue in heat exchanger performance in all uses since their invention, according to (Klaren Technology, 2022), fouling is the deposition or build up of unwanted materials on heat transfer surfaces. Fouling has a negative effect on heat exchanger performance as the unwanted build up acts as a lagging, preventing heat transfer and reducing efficiency and ethe effectiveness of the heat exchanger.

Figure 3 shows a typical example of crystallization fouling on a heat exchangers tube bundle caused by cooling water containing dissolved carbonates and sulphates. (Chemical Process Engineering & Simulation, 2018)



Figure 3 - Fouling on a tube bundle from a heat exchanger (Chemical Process Engineering & Simulation, 2018)

The severity of fouling varies depending on the application, some fluids are worse for fouling than others, pressures and flow rates can have an impact, as well as temperatures and the design of the heat exchanger. In severe cases of fouling, the heat exchanger can block and become inoperable.

Whilst there are a variety of terms used to describe the different types of fouling, dependent on the source, there is a consensus that there are 4 main types of fouling, according to (Hale, 2019) they are categorized and defined as follows:

- Chemical fouling, also known as scaling, occurs due to chemical changes in the processed fluid, this type of fouling increases with higher temperatures, concentration, and PH levels.
- Biological fouling, this occurs when organisms grow within the fluid and deposit on the heat exchanger surfaces, this kind of fouling can be avoided by selecting materials that are poisonous to such organisms such as brass.
- Deposition fouling, this occurs where particulates are contained within the fluid and deposit onto the heat exchanger surfaces, this is common for processes using lower velocities.
- Corrosion fouling, when a layer of corrosion products builds up on the heat exchanger tubes which can often have thermal resistance. This can be avoided through careful selection of materials of construction, so corrosion won't occur.

Cleaning and maintenance

An effective cleaning and maintenance program is essential for heat exchangers to remain efficient and safe to operate, as explained previously, fouling can be present in any heat exchanger and is known to severely limit heat exchanger efficiency if its not removed, however fouling isn't the only cause for concern, corrosion is another serious issue present in heat exchangers, and as mentioned this can lead to fouling but can also lead to more serious issues such as leaks and cross contamination of the 2 fluids.

To put into perspective, take a shell and tube heat exchanger operating as a reboiler on a distillation process, where the shell side contains a hazardous material which isn't corrosive on its own, however can produce hydrochloric acid if it meets water, and on the tube side steam is used to heat the hazardous fluid. If corrosion occurs to the tubes, and the steam and hazardous material meet, hydrochloric acid is formed which can corrode the shell of the heat exchanger, and eventually result in a leak of potentially boiling hydrochloric acid to the atmosphere. This scenario is based on an actual incident that occurred on a chemical manufacturing plant in the US, based from the authors knowledge.

Cleaning methods

As mentioned, fouling is of major concern to efficient heat exchanger operation, and fouling can only be removed through various cleaning methods, according to (Serck global, 2023), the cleaning methods fall into 2 main categories and are detailed below:

Chemical cleaning, this method often requires no disassembly of the heat exchanger and involves flushing the heat exchanger with cleaning fluids to remove fouling build up, this can involve filling the heat exchanger and leaving the cleaning chemicals inside for a set period of time before draining them or circulating the fluid continuously, however this flow rate achievable can be limited for a number of reasons such as; the size of the nozzle connections available to connect to the circulation rig, and severs fouling can limit the flow.

According to (Serck global, 2023), the common chemicals used for cleaning are acids, alkalis, oxidants, or solvents. One negative for this cleaning method is that the cleaning fluid can cause corrosion, this can often be mitigated through the additive of anti-corrosion inhibitors.

For chemical cleaning, it is important the process is designed carefully for it to work effectively and to prevent damage to the heat exchanger, but if done correctly is a proven method to restore heat exchanger efficiency.

Mechanical cleaning, often requires heat exchanger removal for the process of disassembling the heat exchanger in situ, and uses mechanical means to remove fouling build up, some of the mechanical methods are:

- Using brushes, drills, chisels, and scrapers to remove the build-up, although care must be taken to prevent damaging the heat exchanger surfaces.
- Using high pressure water jetting to remove the fouling, this can be done using a handheld lance or an automated machine.
- According to (EJ-Bowman, 2023), there are small diameter rods and brushed commonly used to clean inside of tubes, and steam cleaners can also be used for mechanical cleaning.

There are also ways in which both mechanical and chemical cleaning can be combined, namely a method called **vibrasonic cleaning**, used by (Serck global, 2023), which involves agitating a chemical

cleaning fluid using driven turbines to produce sinusoidal wave patterns throughout the cleaning fluid.

Maintenance methods

Maintenance of heat exchangers can be from monitoring operating parameters such as flow rates and temperatures for changes, to major inspections of the heat exchanger or repairs. As mentioned previously, corrosion can present significant danger to heat exchanger operation and is often present with fouling, and according to (Sterling thermal technology, 2023) there are methods used to monitor and predict corrosion, one of which being measuring tube thickness using IRIS inspections.

IRIS inspection/testing employs an ultrasonic beam scanned through the inside of a tube, with a turbine probe assembly being driven by water, this device is inserted into every tube and drawn through, measuring the material thickness throughout the tubes (IRIS NDT, 2023). This method done over time, can be used to predict at what rate corrosion is occurring, and mitigations such as tube bundle repairs/replacement can be planned to prevent a complete failure.

Figure 4 below shows the layout of the device used.

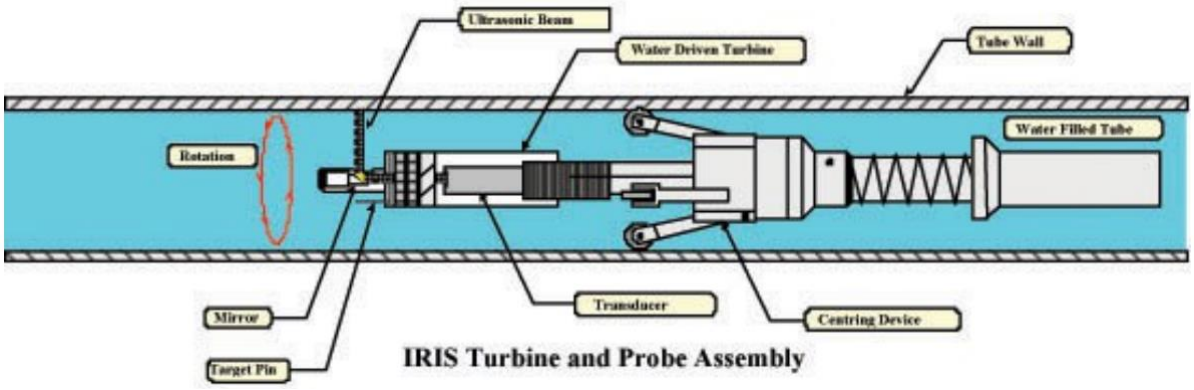


Figure 4 - IRIS turbine and probe assembly (IRIS NDT, 2023)

Task 2: Fouling model and resulting developments

As mentioned in the assignment brief, a development proven to mitigate fouling and improve heat exchanger efficiency is the invention of helical baffles which are a direct result of research carried out by Ebert and Panchal, who developed a fouling model known as "threshold fouling" which they introduced at a conference at San Luis Obispo in 1995 (Wilson, et al., 2015).

Ebert and Panchal's fouling model

The method was developed to describe the initial rate of crude oil chemical reaction fouling and is presented in the following model (Wilson, et al., 2015):

$$\frac{dR_f}{dt} = deposition\ - suppression$$

$$\frac{dR_f}{dt} = a_1 Re^{-b1} exp\left(\frac{-E_a}{RT_f}\right) - C_1\tau_w$$

Where:

$$Re = Reynolds\ number$$

$$T_f = Film\ temperature$$

$$R = Gas\ constant$$

$$\tau_w = Wall\ shear\ stress$$

a_1, b_1, c_1 & E_a *were obtained by regression of data sets from Scarborough et al.'s* (1979)*research*:

$$a_1 = 30.2 \times 10^6\ K\ m^2/kW\ h$$

$$b_1 = -0.88$$

$$c_1 = 1.45 \times 10^{-4}\ m^2\ K\ m^2/kW\ Pa\ h$$

$$E_a = 68\ kJ/mol$$

Ebert and Panchal described this equation as a "Threshold fowling" model as it gave 2 results:

1. Conditions which were estimated to give no fouling by trialling different combinations of shear stress and surface temperatures.
2. An estimation for the rate of fouling expected for different conditions based on surface/film temperature and fluid velocity.

This model/equation has been modified and improved numerous times since it was first introduced, however it is recognised as the first method for predicting at what rate fouling within heat exchangers will occur, which allowed users to plan maintenance and cleaning accordingly, or even adjust the operating conditions of the heat exchanger to reduce the rate of fouling or even eliminate it entirely.

Modern heat exchanger development incorporates the use of CFD (Computational fluid dynamics) for the design of heat exchangers where complex equations and simulations are used to calculate and predict the rate of heat transfer $\dot{Q}$, pressure drop, vibrations and fouling, during the development of heat exchangers.

Implementation of helical baffles

As a direct result of models and studies such as that by Ebert and Panchal, several improvements have been made to heat exchanger designs in recent years, one of which being the development of helical baffles as opposed to the conventional segmented baffles, as displayed in Figure 1.

Where a segmented baffle directs the flow of fluid in a zig-zag pattern to perform multiple passes within the heat exchanger, this results in several drawbacks:

- Increased vibration.
- Large pressure drops.
- Dead spots with zero flow.
- Increased build-up of fouling.

According to (Shinde, et al., 2012), a shell and tube heat exchanger equipped with helical baffles contains quadrant shaped baffle segments in the form of a continuous helix shaped baffle that are wrapped around the length of the tube bundle at an angle which provides a continuous helical flow path for the fluid with multiple passes, and it is claimed they provide the following benefits:

- A reduction in fouling as a result in an increase in turbulence and reduction of dead spots.
- Increased rate of heat transfer with a reduction in shell side pressure drop.
- A reduction in vibrations of the tube bundle.
- A reduction in costs such as operation and maintenance costs.

Figure 5 below shows the arrangement of helical baffle within a shell and tube heat exchanger (S. Shinde, 2013)

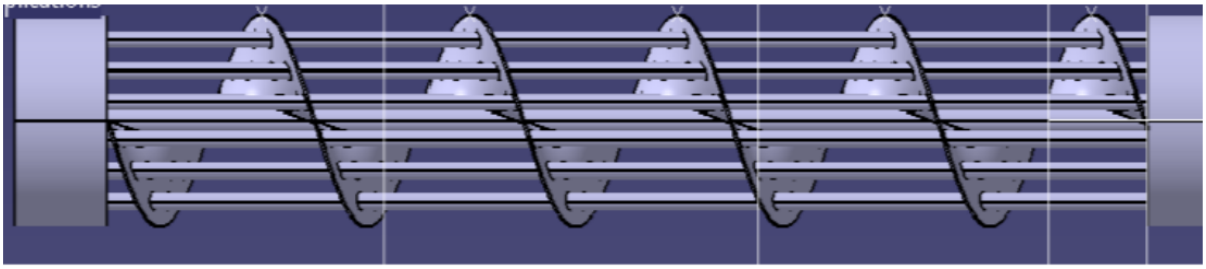


Figure 5 - Helical baffle arrangement within a shell and tube heat exchanger (S. Shinde, 2013)

As can be seen in figure 5, the baffle forms a spiral around the tube bundle which when compared to conventional segmented baffles, provides a much smoother flow as there are no harsh changes in direction, as is present with the zig-zag flow pattern in segmented baffle designs, whilst they are also known to increase turbulence.

Study of fouling with segmented and helical baffles

Since the development and introduction of helical baffles, there have been numerous studies into their operational characteristics and how their design can alter performance, ranging from the pitch of the baffles to the angle of lean of the baffles and how it affects fouling, heat transfer coefficient U and rate of heat transfer $\dot{Q}$, to name but a few.

One study by Wang and colleagues of Watlow, compared how fouling occurs where helical baffles are used as compared to segmented baffles, it was found that helical baffles did help eliminate dead spots and reduce fouling, the results are displayed in the graph below. (Long, n.d.)

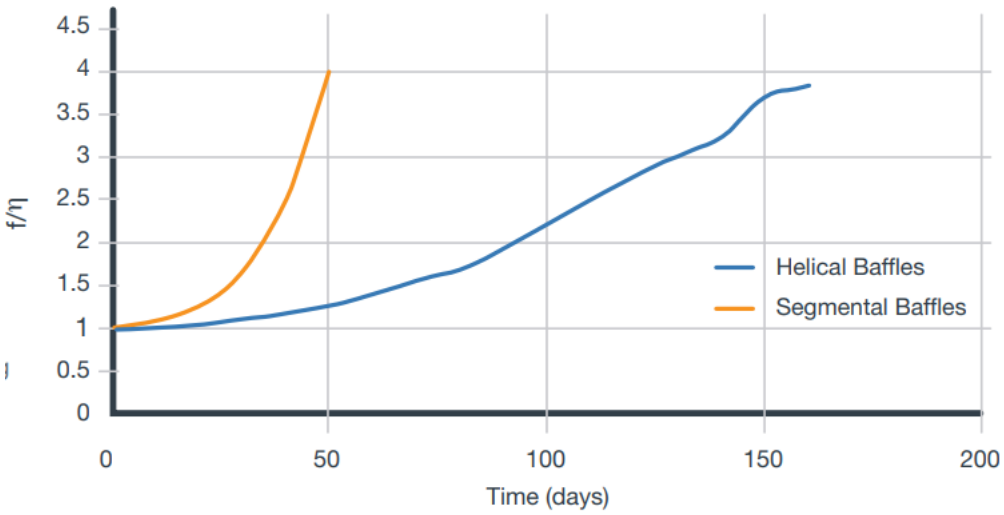


Figure 6 - Fouling occurrence in helical and segmental baffle HX's (Long, n.d.)

As can be seen in figure 6 above, the increase in fouling with segmental baffles has an exponential increase as time goes on, whereas the helical baffles have a much more linear increase in fouling, and for the same amount of fouling it took 3 times as long where helical baffles were present.

Task 3: Experimental laboratory investigation

With and without fouling

A scenario has been given of a laboratory set up that is used to investigate the effects of fouling within a simple concentric tube heat exchanger, which simulates a counter-flow single pass shell and tube heat exchanger. The experiment requires calculating the overall heat transfer coefficient U and the resulting rate of heat transfer Q, with and without fouling present.

The following model is given to calculate the overall heat transfer coefficient U where fouling is present.

$$\frac{1}{U} = \frac{1}{h_o.A_o} + \frac{R_{fo}}{A_o} + \frac{ln\left(do/di\right)}{2\pi.k.L} + \frac{1}{h_i.A_i} + \frac{R_{fi}}{A_i}$$

The data given to perform the necessary calculation is as follows:

$$inner\ pipe\ ID = 25.4mm \quad inner\ pipe\ OD = 38.1mm \quad L = 3.05m$$

$$Outer\ pipe\ ID = 50.8mm$$

$$T_{H_{in}} = 160℃ \quad T_{H_{out}} = 100℃ \quad T_{C_{in}} = 15℃ \quad T_{C_{out}} = 85℃$$

$$K = 54 \quad h_i = 100 \quad h_o = 7300$$

$$\dot{m}_H = 0.23\frac{kg}{s} \quad \dot{m}_c = 1.60\frac{kg}{s}$$

$$R_{fi} = 1.0578\ X10^{-3} \quad R_{fo} = 35.22\ X10^{-6} \quad Correction\ factor\ F = 0.96$$

The first step is to calculate the surface areas of both tubes and is as follows.

Surface areas:

$$A_i = \pi.D.L = \pi \times 25.4 \times 10^{-3} \times 3.05 = \mathbf{0.2434m^2}$$

$$A_o = \pi.D.L = \pi \times 38.1 \times 10^{-3} \times 3.05 = \mathbf{0.3651m^2}$$

The overall heat transfer coefficient U can then be calculated using the given equation.

Overall heat transfer coefficient U:

$$\frac{1}{U} = \frac{1}{h_o.A_o} + \frac{R_{fo}}{A_o} + \frac{ln\left(do/di\right)}{2\pi.k.L} + \frac{1}{h_i.A_i} + \frac{R_{fi}}{A_i}$$

Firstly, the overall heat transfer coefficient U can be calculated as if the equipment is in as new condition, where no fouling is present.

Overall heat transfer coefficient U, without fouling factors:

$$\frac{1}{U} = \frac{1}{7300 \times 0.3651} + \frac{ln\left(38.1_{\times 10^{-3}}/25.4_{\times 10^{-3}}\right)}{2\pi \times 54 \times 3.05} + \frac{1}{100 \times 0.2434} = 0.0419$$

$$\frac{1}{U} = 0.0419 \quad \therefore \quad U = \frac{1}{0.0419} = \mathbf{23.894\ {}^{W}/_{m^2 . K}}$$

Then the calculation was performed again, this time considering the fouling factors as if fouling was present.

Overall heat transfer coefficient U, with fouling factors:

$$\frac{1}{U} = \frac{1}{7300 \times 0.3651} + \frac{35.22_{\times 10^{-6}}}{0.3651} + \frac{ln\left({}^{38.1_{\times 10^{-3}}}/_{25.4_{\times 10^{-3}}}\right)}{2\pi \times 54 \times 3.05} + \frac{1}{100 \times 0.2434} + \frac{1.0578_{\times 10^{-3}}}{0.2434}$$

$$\frac{1}{U} = 0.0463 \quad \therefore \quad U = \frac{1}{0.0463} = \mathbf{21.601\ {}^{W}/_{m^2 . K}}$$

Before these U values can be used to calculate the overall rate of heat transfer Q, the temperature differential needs calculating, as all 4 temperature conditions are known for this scenario the LMTD (log mean temperature difference) method was used and is as follows.

LMTD (ΔTLM):

$$\Delta T_{LM} = \frac{\Delta T_O - \Delta T_I}{ln\left(\frac{\Delta T_o}{\Delta T_I}\right)}$$

$$\Delta T_0 = T_{HOT,out} - T_{COLD,in}$$

$$\Delta T_O = 100℃ - 15℃ = 85℃$$

$$\Delta T_I = T_{HOT,in} - T_{COLD,out}$$

$$\Delta T_I = 160℃ - 85℃ = 75℃$$

$$\Delta T_{LM} = \frac{85 - 75}{ln\left(\frac{85}{75}\right)} = \mathbf{79.9℃}$$

With all the required values to calculate the rate of heat transfer Q, the following calculations were performed to calculate this with and without fouling, also using the given correction factor F of 0.96.

Rate of heat transfer $\dot{Q}$:

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

$$\dot{Q} = 23.894 \times 0.2434 \times 0.96 \times 79.9 = \mathbf{446.095\ Watts\ (Without\ fouling)}$$

$$\dot{Q} = 21.601 \times 0.2434 \times 0.96 \times 79.9 = \mathbf{403.285\ Watts\ (With\ fouling)}$$

As can be seen, where fouling is present there is almost a 10% reduction in rate of heat transfer Q.

Zinc-sulfide growth (ZnS)

Following on from the previous calculations, it was found that the mineral oil contained quantities of zinc-sulfide (ZnS) which caused a fouling growth on the inner pipe diameter over time, this was modelled to predict it's affects on the rate of heat transfer Q as the growth thickness increase from 0.5mm to 5mm.

To simulate this, the overall heat transfer coefficient model required modifying to incorporate an extra value and can be seen below.

Overall heat transfer coefficient U (With fouling growth):

$$\frac{1}{U} = \frac{1}{h_o . A_o} + \frac{R_{fo}}{A_o} + \frac{ln\left({do}/{di}\right)}{2\pi . k . L} + \frac{1}{h_i . A_i} + \frac{R_{fi}}{A_i} + \frac{\boldsymbol{x_f}}{\boldsymbol{k_f . A_i}}$$

Where:

$$x_f = Growth\ thickness\ m$$

$$k_f = Thermal\ conductivity\ of\ ZnS = \ 25.1\ W/m\ K$$

Using Microsoft Excel, these calculations were performed where the surface area of the inner pipe Ai reduces with the fouling build up, and the results are displayed numerically in figure 7 below.

Fouling mm	Ai	U	Q̇	Fouling simulation
0	0.24338	21.5992	403.196	
0.5	0.23859	21.1358	386.779	
1	0.2338	20.6743	370.736	
1.5	0.22901	20.2146	355.064	
2	0.22422	19.7566	339.761	
2.5	0.21942	19.3005	324.824	
3	0.21463	18.8461	310.252	
3.5	0.20984	18.3935	296.042	
4	0.20505	17.9426	282.192	
4.5	0.20026	17.4935	268.699	
5	0.19547	17.046	255.562	

Figure 7 - Fouling simulation results

Following these calculations, the graph displayed in figure 8 on the following page was created to plot the reduction in surface are of the inner pipe Ai against the reduction in rate of heat transfer $\dot{Q}$.

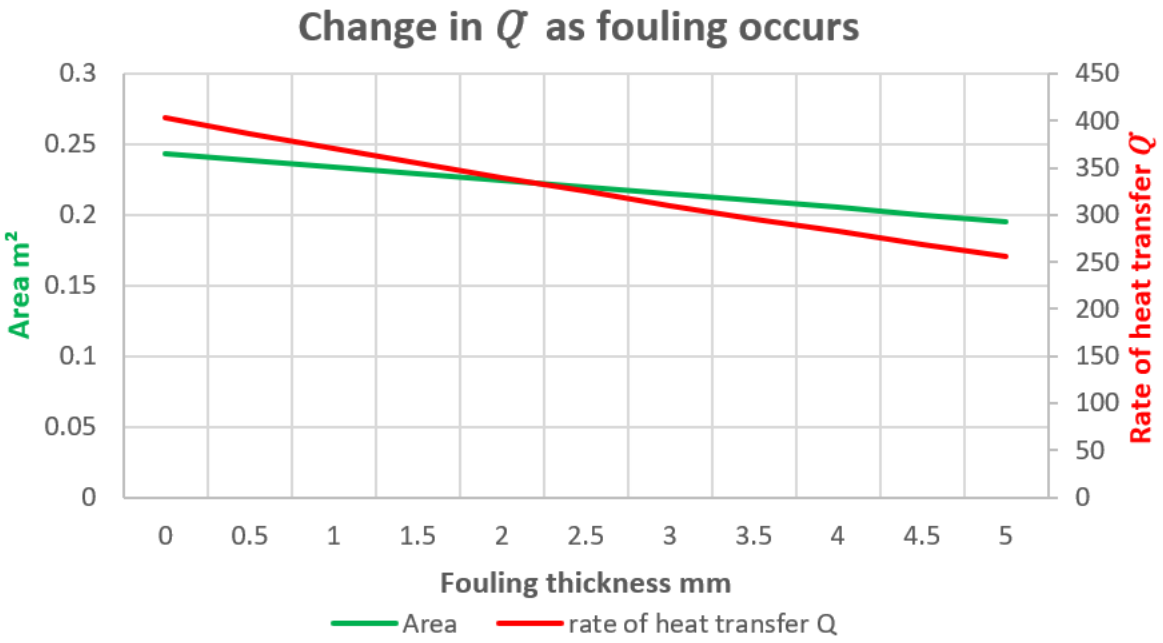


Figure 8 - Heat transfer reduction as Area reduces.

The graph shown in figure 8 above plots both the reduction in surface area of the inner pipe Ai and the reduction in the rate of heat transfer $\dot{Q}$.

The surface area of the inner pipe Ai is represented by the green line and is plotted against the primary vertical axis on the left in units m², and the rate of heat transfer $\dot{Q}$ is represented by the red line and is plotted against the secondary vertical axis on the right in watts.

Analysis of results.

From studying the numerical results displayed in figure 7 and the graph displayed in figure 8, the following conclusions can be made:

- There is a linear decrease in rate of heat transfer $\dot{Q}$ as the inner pipe diameter Ai reduces due to the build up of fouling.
- From there being 0 thickness to the final 5mm build up, there is approximately a 37% reduction in rate of heat transfer $\dot{Q}$.
- From there being 0 thickness to the final 5mm build up, there is approximately a 20% reduction in surface area.
- Based on the previous 2 points, there is a severe impact on the rate of heat transfer $\dot{Q}$ as fouling occurs.

Assumptions made.

The calculations performed to simulate the growth of zinc sulfide (ZnS) had several assumptions and certain factors were not considered:

- The growth is smooth within the pipe.
- The concentration of ZnS doesn't change the fouling factor for the oil.
- No consideration was given to mass flow rates, in real life this would decrease with the reduction in surface area.
- All 4 temperatures remained the same, with a reduction in rate of heat transfer this is unlikely.

Conclusion

To summarise this report, the following conclusions can be made:

- Heat exchangers are an essential piece of equipment in many industries.
- Fouling continues to be a serious problem for the operation and development of heat exchangers.
- Over 100 years of heat exchanger development has greatly improved the design of heat exchangers with regards to operation and the occurrence of fouling.
- Ebert and Panchal's initial fouling model have grown significantly and has lead to large investment and implementation of computer software for the design and analysis of heat exchanger operational parameters.
- Cleaning and maintenance are essential to the safe and efficient operation of heat exchangers.
- Helical baffles have had a significant impact on heat exchanger efficiency and greatly reduced the occurrence of fouling.
- From the calculations carried out in task 3, they prove that monitoring and predicting fouling effectively is essential to the efficient heat exchanger operation.

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