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1 Abstract

Shell and tube heat exchangers are among the most commonly used heat transfer devices in industry due to their flexibility, robustness and durability while operating under harsh and demanding conditions. Although liked due to their advantages their long term performance is drastically reduced by fouling which increases thermal resistance, reduces efficient heat transfer and increases costs. The first part of the report reviews the historical development, design, and industrial applications of the shell and tube heat exchanger. It will also look at the major fouling mechanisms which are crystallisation, chemical fouling, corrosion fouling and biological growth. Maintenance and cleaning methods such as mechanical, chemical, ultrasonic and operational strategies are evaluated as good asset management strategies. The second part will look into analysing the Ebert and Panchal fouling model looking at its advantages, disadvantages and industrial relevance to industrial application. Finally, the report will look at recent developments, particularly helical baffles and how they improve fouling issues.

2 Introduction

Shell and tube heat exchangers are an important tool used in industry for thermal management, as they are capable of exchanging the flow of thermal energy between two or more fluids mainly through convection (Kumar Gupta and Pawar, 2021). Shell and tube heat exchangers are used in industries such as refineries, chemical processing and power generation, making them used in 35 – 40% of global heat transfer processes. They have a reputation for being robust and versatile due to being able to handle high pressures, hazardous fluids and variable operating conditions. Although they are known for their strong qualities, they are subject to issues such as fouling which is the accumulation of undesired materials on the heat transfer surfaces, which causes a reduction in their heat transfer performance, pressure capabilities and increases their maintenance costs (Gautam *et al.*, 2017). This report will look into the history, design, industrial applications, fouling issues, maintenance, management using the Ebert and Panchal fouling model and innovations such as helical baffles and how they reduce fouling rates, improve thermal performance and energy efficiency. Figure 1 below shows a typical shell and tube heat exchanger used in industry.



Figure 1: Shell and tube heat exchanger. (Aaron stock)

3 Shell and tube heat exchangers: history, design and applications

3.1 History of Shell and Tube Heat Exchangers

The shell and tube heat exchanger first made an appearance in the early 19th century for industrial power systems and gained its prominence in the late 19th to early 20th century after developments in steam cycle technology and the need for condensers and feedwater heaters in power plants (Kuppan, 2013). Shell and tube heat exchangers were then adopted by the oil industry around the 1920s where they put them to work as oil heaters, coolers, reboilers and condensers. This period also gave some improvements such as the materials like stainless steel and titanium which were used for the tubes.

In 1955 a patent was filed by Babcock and Wilcox Co, with inventor Johannes H Ammon which was eventually granted in 1965. This patent brought to light improvements such as better tube supports and shell side flow control known as baffles (Ammon Ey and Am Mon, 1965). Over the years shell and tube heat exchangers have had improvements such as better tube geometries and baffle configurations.

3.2 Design of Shell and Tube Heat Exchangers

A shell and tube heat exchanger's design involves thermodynamic principles, mechanical engineering and practical considerations to ensure that it is capable of transferring heat efficiently. The classic design which consists of tubes, shell, tubesheets and baffles is favoured in industry due to its flexibility and customisation. It works by transferring thermal energy between two fluids that are separated by the tube wall. One of the fluids flows through the tube bundle known as the tube side and the other through the shell known as the shell side. Figure 2 below shows a basic design of a shell and tube heat exchanger.

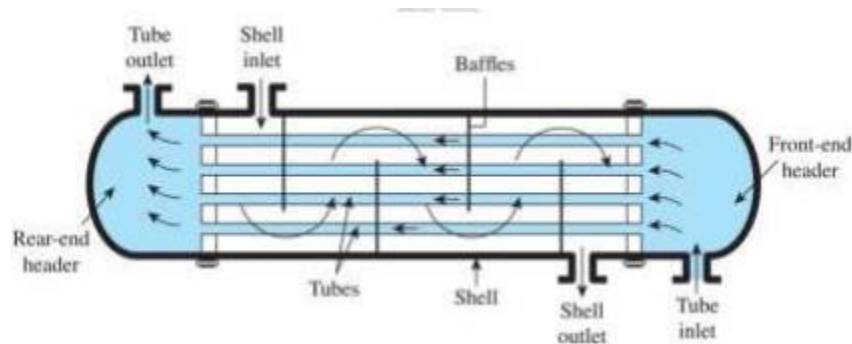


Figure 2: Shows basic design of shell and tube heat exchanger. (Kumar Gupta and Pawar, 2021)

- Tubes – Form the heat transfer surface. The material that the tube is made off is based on the type of fluid being used, corrosion resistance and temperature. The tube configuration depends on its intended use, but typically a triangular pitch is used for higher heat transfer and a square pitch for easier cleaning (Kuppan,2013) as shown in Figure 3 below.

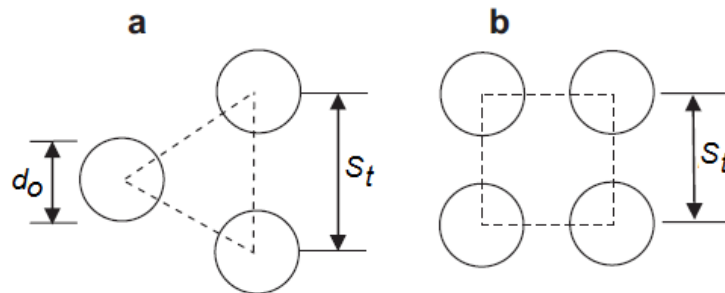


Figure 3:Shows triangular and square pitch. (Rifka Aisyah, 2017)

- Shell – This is the outside cylindrical vessel that surrounds the tubes. Its dimensions and material depend on its use, diameter, and shell side fluid properties. The shell is seen in Figure 1 in the introduction.
- Tubesheets – These are heavy plates drilled to accept the tubes and mechanically anchor them. They also create fluid isolation between the shell side and tube side.
- Baffles – These are plates that are inside the shell that direct the shell side fluid, enhance the heat transfer and support the tubes. The arrangements of the baffles impact the pressure drop, heat transfer coefficient, and risk of tube vibration.

There are many design variants of shell and tube heat exchangers such as:

- U tube bundles which reduce the thermal expansion stress.
- Floating head and fixed head designs.
- Enhanced surfaces which have either finned or corrugated tubes.
- Hybrid exchangers which combine shell and tube with plate and fin heat exchangers.

3.3 Industrial applications

Many industries use and rely on shell and tube heat exchangers due to their robust and scalable design. Some of the industrial uses are:

- Oil and gas – crude oil preheaters, condensers, cooling and separation units.
- Power generation – they are used for feedwater heaters, condensers and steam generators.
- Chemical – reactor heating, fluid cooling and evaporating process streams.
- HVAC and Refrigeration – chillers and cooling towers.
- Water treatment – heat recovery and preheating.

These industries rely on shell and tube heat exchangers due to their ability to hand high pressure and high temperatures, modular design, and ease of cleaning and repairing.

Although they have a lot of advantages, they are subject to a major disadvantages called fouling.

4 Fouling in heat exchangers

4.1 Definition and importance

Fouling is the accumulation of unwanted deposits on the surfaces that transfer heat such as the tube and shell walls as seen in Figure 4 below. These deposits can be of the following forms: solids, scale, biofilms, crystallised salts, corrosion caused by products and colloids (*T_R_Bott_Fouling_of_Heat_Exchangers_Chem*). Fouling creates additional thermal resistance known as added fouling resistance R_f , which reduces the overall heat transfer coefficient.



Figure 4:Fouling in shell and tube heat exchangers.

The reason why fouling is a major issue in shell and tube heat exchangers is because it:

- Increases thermal resistance, reducing the efficiency of the heat transfer process.
- Decreases the pressure in the system which increases the pumping power needed.
- Can cause flow blockages and hotspots.
- Requires cleaning causing downtime and increasing maintenance costs.

4.2 Principal mechanisms of fouling

Fouling can be identified and modelled by mechanism or deposit type such as the following:

1. Particulate deposition: these are suspended solids such as dirt, silt and rust that stick onto the tube surfaces and behind the baffles which are places where flow velocity is insufficient to keep them suspended known as dead zones. Other causes include poor filtration and low turbulence near the baffle's crevices
(*T_R_Bott_Fouling_of_Heat_Exchangers_Chem*).
2. Crystallisation/scaling: this is caused by dissolved mineral salts such as calcium carbonate, which crystallise at higher temperatures or concentrations. This forms a hard layer that insulates the tube walls affecting thermal conductivity
(*T_R_Bott_Fouling_of_Heat_Exchangers_Chem*).
3. Chemical fouling: this is fouling caused by polymerisation, oxidation and decomposition reactions in fluids that have unstable constituents
(*T_R_Bott_Fouling_of_Heat_Exchangers_Chem*). These chemical products make a strong adherent layer that needs aggressive cleaning.
4. Corrosion fouling: this is when there is formation of insoluble oxides due to an electrochemical reaction caused by fluid pH or by the presence of oxygen (Kumar Dey *et al.*). This causes a layer that clings onto the tube's surfaces.
5. Biological fouling: this is from microorganisms such as bacteria or algae from biofilms in heat exchangers that are water cooled. This obstructs the flow of fluid creating regions of thermal resistance (Kumar Dey *et al.*, 2018).

The mechanisms mentioned above reduces the heat transfer area, increases pressure drop, and increases the operating costs. Research shows that fouling can cause a heat exchanger to lose 20 – 40% of its effectiveness along with increased energy usage and risk of unplanned downtime (Gautam *et al.*, 2017).

4.3 Cleaning and maintenance

Due to the fouling mechanisms, research gives us some cleaning and maintenance strategies that can be used on shell and tube heat exchangers such as:

- Routine inspection: this is a way of predictive and preventative maintenance, by putting in place some inspection intervals and a schedule for cleaning.
- Mechanical cleaning: this method uses physical tools like brushes and drills to clean the tubes as shown in Figure 5. After scrubbing low pressure water is used to flush out the remaining dirt. This method is quick and reduces the amount of wastewater created.
- Chemical cleaning: this is used when mechanical cleaning has not yielded the results wanted. This is common with scale build up which is tough to remove by just scrubbing alone. It is done by circulating a cleaning solution through the heat exchanger. This cleaning solution dissolves the deposits without having to have the heat exchanger taken apart. This method is less labour intensive and is only effective if the correct chemical solution is used (Dey et., 2019).
- Ultrasonic cleaning: this method is more recent and uses high frequency sound waves and a cleaning solution liquid to create cavitation bubbles. These bubbles and cleaning fluid create a forceful jet of water that cleans the tubes surfaces. This is useful for removing fine particles and its ability to get to the hard to reach areas in the heat exchanger.
- Thermal cleaning: this method is mainly used for contaminants such as oil as it is quite effective in cleaning them. It involves the use of high temperatures to burn off residues inside the heat exchanger.



Figure 5: Image showing mechanical cleaning. (Baron Blakeslee)

5 Fouling model

5.1 Ebert and Panchal Fouling Model

In 1997 Ebert and Panchal created the threshold fouling model to assist in modelling crude oil fouling in the shell side of the shell and tube heat exchangers (Wilson *et al.*,). This model visualises the fouling growth by balancing between material deposition and removal. As the deposition layer gets thicker, the rate of growth slows down. This model calculates the average linear fouling rate based on conditions such as flow speed and temperature but also includes a threshold condition where below it the fouling growth becomes minor.

The Ebert and Panchal fouling model formula is as follows:

$$\frac{dR_f}{dt} = r_{deposition} - r_{removal}$$

Where:

- R_f is the fouling resistance.
- $r_{deposition}$ is the rate at which deposits accumulate.
- $r_{removal}$ is the rate at which fouling is chemically or mechanically mitigated.

This model uses a threshold which means that fouling starts when conditions exceed a certain level. Ebert and Panchal suggested that below the threshold very little to no fouling occurs. The threshold is of significant value as it helped explain why in some cases fouling begins after a delay known as lag time, rather than occurring immediately. The model is used to predict fouling under different operating conditions on equipment such as preheaters in crude oil processing plants.

Since the introduction of the Ebert and Panchal model it became the staple used method to model fouling. The model does not treat fouling as fully empirical as it combines theoretical data with experimental data. This means it offered a mechanical approach whereas older models were only empirical but managing to also retain its simplicity. Although the Ebert and paschal fouling model has given industry great insights for modelling and predicting fouling, it does have its disadvantages such as:

1. Linearity and simplicity: where assuming that there is consistent deposition oversimplifies real life fouling dynamics, which is often asymptotic and has accelerating or decelerating patterns meaning the model may underpredict fouling at the heat exchangers early operation and over predict it at later stages.
2. Threshold calibration: the threshold value is often tuned to a particular system due to it being empirical. This means that any small error in tuning can give big prediction errors and limits its transferability to different systems.
3. Ignoring heterogeneity: this makes the heat exchanger seem uniform by bypassing the flows, dead zones, and local flow variations but CFD studies have shown that local fouling rates differ by 200 – 400% across the tube bundle which the model cannot show.

Due to these limitations, there has been a number of extensions, modifications and alternative models that have been made to address these issues such as the Crittenden model 2007 which include nonlinear suppression terms.

The Ebert and Panchal fouling model plays a big part in fouling prediction due to its simplicity and mechanistic basis, but its disadvantages cause it to be less accurate for newer heat exchanger designs. This means it remains key for trend prediction and screening, but not for a detailed lifecycle of a shell and tube heat exchanger.

6 Helical Baffle Design and Technical Justification

Since fouling deposition has been linked with flow patterns such as dead zones, design considerations such as altering the shell side flow were made. This brought the replacement of segmented baffles with continuous helical baffles shown in Figure 6 below, a redesign that was driven by Ebert and Panchal fouling model (De, Pal and Bandyopadhyay, 2017).

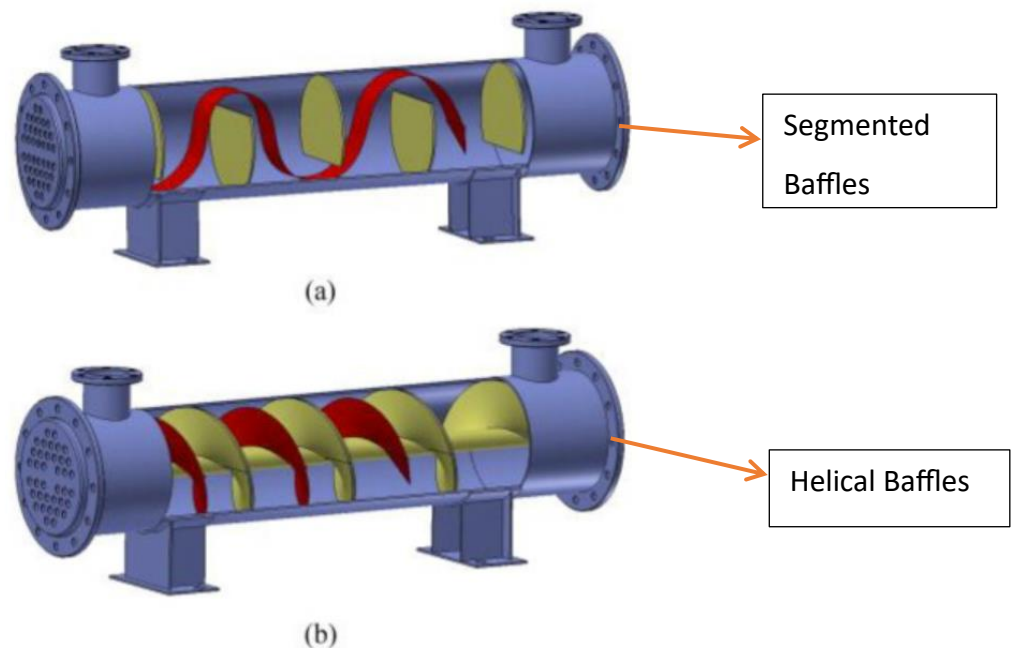


Figure 6: Shows segmented and helical baffles. (Klemeš et al., 2020)

The helical baffles wrap around the tube bundle and guides the shell side flow using the helical path compared to the segmented baffles cross flow method. The key concepts of the helical baffles are as follows:

- **Geometry:** The helical baffles direct the shell side fluid along the spiral path. This helps by eliminating the dead zones and pockets of stagnant flow which are common areas that cause fouling with segmented baffles.
- **Flow:** Research using computational fluid dynamics (CFD) has confirmed that helical baffles create uniform flow. This has reduced the amount of bypass and has allowed for some self-cleaning (De, Pal and Bandyopadhyay, 2017).
- **Pressure Drop:** Studies have shown that although it is more complex and expensive to manufacture helical baffles, they achieve a 20 – 30% reduction in pressure drop.

This reduces costs as it reduces the amount of pumping energy used (Gowthaman and Sathish, 2014).

- **Fouling Mitigation:** Cases studies have shown that there are 40% lower fouling factors in helical baffles over longer run periods. This means that with helical baffles there is a reduction in downtime due to the extended cleaning intervals (Gowthaman and Sathish, 2014).
- **Waste and Sustainability:** The reduction in the fouling rates from helical baffles reduces the amount of harsh chemicals needed for cleaning and also reduces water usage to flush waste. This has been shown to save 10 – 15% in energy costs (De, Pal and Bandyopadhyay, 2017).

Although the helical baffles give good performance advances, it has a major disadvantage of initial costs being high as there are retrofit costs and training costs for the plant staff.

7 Conclusion

Shell and tube heat exchangers are key in industrial thermal systems due to their robustness and adaptability. Although they are key fouling significantly impacts their performance and efficiency which leads to reduced heat transfer, increased needed pumping power and higher maintenance and operational costs. Understanding the principal fouling mechanisms is important for effective shell and tube heat exchanger management.

The Ebert and Panchal fouling model provides a solid way to predict fouling patterns, highlighting threshold conditions and the relationship between deposition and removal. Although this model is a great way to predict fouling it does have its limitations such as how it oversimplifies fouling and does not accurately represent real world heat exchanger conditions.

Helical baffles supported by fouling modelling and CFD research, provide tangible improvements in flow distribution, fouling mitigation, pressure drop reduction and energy efficiency. This shows the importance of integrating fouling research into the shell and tube heat exchangers design.

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