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Analysis of Fouling in Industrial Shell and Tube Heat Exchangers

Plant and Asset Engineering ACMA6007

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1 Introduction

Shell and tube heat exchangers (STHE) are a type of heat transfer equipment that consist of a cylindrical shell with closely arranged tubes inside. Heat exchange is the mechanism by which heat is transferred from one body to another of comparable nature. The shell and tube design is the most prevalent kind of heat exchange, distinguished by its properties, the type of tubing, as well as other characteristics [1]. Incredibly common within industry they make up around 35-40% of heat exchangers used [2].

Shell and tube heat exchangers function by circulating a fluid, which can be in the form of gas or liquid, through the shell. In addition to the incoming fluid, the shell also houses tubes containing fluid of a different temperature, which can be either warmer or cooler. As the fluid flows, heat is transferred, and both fluids approach a state of thermal equilibrium at the same temperature [3] [4]. An example of a typical shell and tube heat exchanger can be found below in fig.1.

Figure 1 - Shell and Tube Heat Exchanger - [5]

The inception of shell and tube heat exchangers dates back to the early 1900s, primarily they were created to meet the demand for high-capacity heat exchangers in power plants. Typical uses included the transfer of heat in condensers and feedwater heaters that operated under high pressure conditions. Both shell and tube exchangers continue to be commonly used, along with their sophisticated and elaborate modern versions [6].

There are four types of shell and tube heat exchangers: Direct Contact Heat Exchangers, Recuperators, Regenerative Heat Exchangers, and Co-current (Parallel) Flow Heat Exchangers [7].

The most common modern applications found in industry are within the food, oil, chemical, and gas sectors [8]. The various uses include cooling of fluids, power generation, refrigeration, metals and mining, pharmaceutical production, to name a few [7] [9] [10].

Shell and tube designs have many advantages, in particular they exhibit superior heat transfer efficiency compared to other designs. Additionally, this design allows for easier dismantling, simplifying the process of repair and cleaning [11].

2 Shell and Tube Design

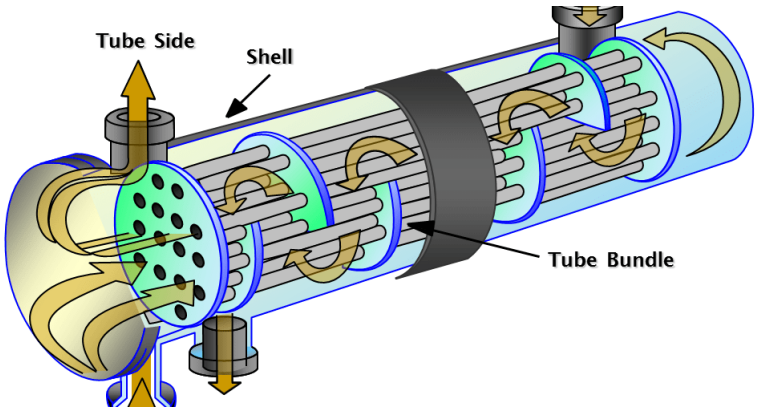

Figure 2 - Shell and Tube Heat Exchanger - Internal Diagram - [12]

An essential element within a shell and tube heat exchanger is the baffle (fig.2). Its primary function is to provide structural support to the tubes and ensure their proper positioning during operation. Additionally, it serves to prevent any vibrations that may occur in the tubes, while facilitating the transition of flow inside the tube system, so enhancing both heat transfer and flow velocity [30].

The segmented baffle geometry (fig.3) is a prominent characteristic of the shell and tube design. This design facilitates the smooth movement of fluid in and out by utilising a network of narrower tubes. Further the design enhances the heat exchanger's capacity for transferring heat from a fluid at a higher temperature to a fluid at a lower temperature [13].

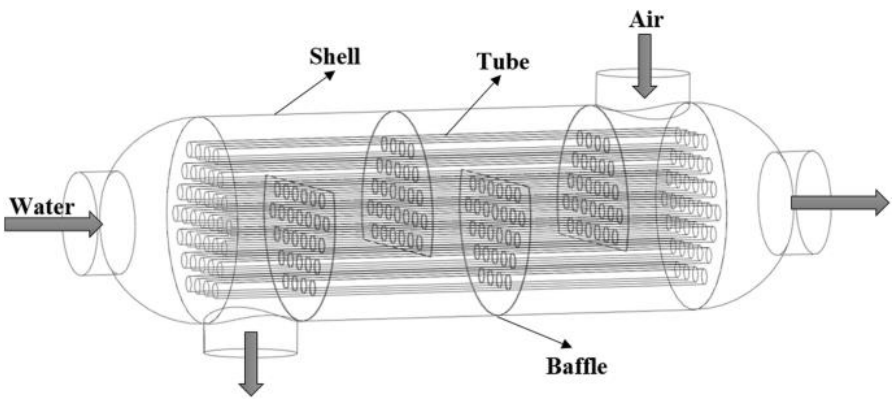

Figure 3 - Shell and Tube Heat Exchanger - Segmented Baffle - [14]

2.1 Shell-Side Fouling

An inherent drawback of the shell and tube heat exchanger design is its propensity to worsen the problem of fouling on the shell side. Fouling can be simply described as, '[...] the formation of unwanted material deposits on heat transfer surfaces during process heating and cooling' [15].

Side shell fouling can occur in five distinct forms: chemical fouling, corrosion fouling, biological fouling, freezing fouling, and deposition fouling. The occurrence of fouling in a heat exchanger is primarily determined by its specific application [16] [17]. The consequences of fouling have a

negative impact on the hydraulic and thermal efficiency of the side shell. Deposition can happen either on the external surface of the tubes or inside the gap between the shell and the tubes [18].

When fouling occurs in a system, it reduces the thermal efficiency of the system significantly [19]. In addition, it can lead to an escalation in mechanical breakdown and the formation of uneven temperature hotspots [20]. Further, it can result in a diminished heat transfer efficiency, increased resistance to fluid flow, and higher pressure drops [15]. All of these issues increase the energy expenditure by the heat exchanger, both short and long term, and addressing them can aid in reducing energy consumption and material waste.

2.2 Types of Fouling

2.2.1 Chemical Fouling

Chemical fouling (fig.4) is the result of chemical reactions in the fluid that lead to the development of a fouling layer formed on the surface of the tubes, this is similar to the effect seen with bathroom scaling [21]. The likelihood of fouling escalates as temperatures and pH levels increase [22].

Figure 4 - Shell and Tube heat Exchanger - Chemical Fouling - [16]

2.2.2 Corrosion Fouling

Corrosion fouling (fig.5) occurs when corrosive process media interacts with, high temperature operation, or high-velocity flow [23]. Corrosion is prevalent in situations where the components constituting the heat exchanger are already susceptible [16]. The extent of corrosive harm is influenced by the presence of fouling deposits. Identifying these deposits may not always be straightforward, as some of them may be concealed within the layer, making them more difficult to detect. Corrosion significantly diminishes the anticipated lifespan of the heat exchanger and has the potential to result in abrupt and irreversible malfunction [22].

Figure 5 - Shell and Tube Heat Exchanger - Corrosive Fouling - [24]

2.2.3 Biological Fouling

Biological fouling (fig.6) refers to the accumulation and proliferation of organisms, primarily bacteria, on the surfaces of heat exchangers. These microorganisms can exacerbate the effects of corrosion by modifying the composition of the chemicals employed. This type of fouling can affect shell and tube heat exchangers, although it is more common in compact heat exchangers [25].

Figure 6 - Shell and Tube Heat Exchanger - Biological Fouling - [26]

2.2.4 Deposition Fouling

Deposition fouling (fig.7) refers to a collection of undesirable substances on the inner surface of a heat exchanger. These can include scale, algae, insoluble salts, and suspended solids. These compounds accumulate when they come to rest on the surface, when the speed of the fluids drops below the critical velocity threshold [22].

Figure 7 - Shell and Tube Heat Exchanger - Deposition Fouling - [20]

2.2.5 Freezing Fouling

While freezing fouling (fig.8) is not common, it can inflict serious damage if it does happen. The blockage is a result of the fluid in the heat exchanger becoming immobilised and obstructing the flow. This phenomenon typically arises due to one of two causes: the solidification of the fluid flowing through the tubes, either partially or completely, or the interaction of humid air with a low-temperature surface [27].

Figure 8 - Shell and Tube Heat Exchanger - Freezing Fouling - [27]

3 Maintenance

Outlined below, are the recommended preventative and maintenance procedures for addressing each type of fouling:

3.1 Chemical Fouling

The design of the heat exchanger does not have the ability to control or counteract chemical fouling. To limit chemical damage, it is important to precisely regulate the temperature of the tube wall that comes into contact with the fluid [20]. In order to address the damage, fouling must undergo chemical treatment or mechanical descaling using methods such as water jets, drills, or wire brushes [13] [16].

3.2 Corrosion Fouling

To effectively mitigate corrosion fouling, it is advisable to utilise a material that is resistant to corrosion in the heat exchanger design and possesses excellent thermal conductivity. It will therefore be important before employing the use of a heat exchanger to understand what fluids will be flowing through the system. Regularly scheduled preventative maintenance should be conducted to remove grit, along with thorough cleaning [12].

3.3 Biological Fouling

To address biological fouling, it is necessary to apply biocides as a treatment. Shell and tube heat exchangers require a larger quantity compared to other types of heat exchangers. In order to prevent bacteria from developing resistance to treatment, it will be necessary to alternate the use of biocides. In order to carry out this particular form of treatment, it is important to first determine the specific strain of bacteria, followed by the administration of a suitable biocide to be introduced into the system. Enabling the biocide to circulate through the system will guarantee the eradication of any bacteria concealed within the tubing, hence preventing any possibility of the problem reoccurring [25].

3.4 Deposition Fouling

To prevent deposition fouling, the heat exchanger design must accurately calculate the necessary velocity for the mixture of fluids and particles that will pass through the system. Furthermore, it is the consumer's responsibility to verify that the heat exchanger being utilised is suitable for its designated purpose. It is advisable to position the heat exchanger in a vertical orientation to facilitate the slow removal of particles by gravity. For maintenance purposes, it is necessary to periodically clean the system through hand brushing and scraping [20].

3.5 Freezing Fouling

The preventive measures implemented to prevent freezing fouling will vary based on the properties of the fluids and the specific environmental conditions in which they are utilised [18]. To effectively combat freezing fouling, it is crucial to have a comprehensive understanding of the fluid characteristics and take proactive measures to prevent the creation of conditions that may lead to

freezing. Human error might potentially create fouling, making it crucial to not solely depend on the assumption that the appropriate conditions are consistently reached. Instead, active monitoring of the working environment is essential.

To effectively deal with freezing fouling, it is advisable to mitigate the potential risks associated with the fluids used by carefully selecting them. If the solidified fluid is located on the shell side, one can consider using electric tracing to warm up the equipment. In the case of wax deposits, melting the substance is a viable option. However, if none of these methods are feasible, the unfortunate solution would be to replace the tubing [27] [28].

4 Design Improvements

4.1 Elbert and Panchal's Fouling Model

In 1997, Elbert and Panchal introduced a fouling model that has had a direct impact on the design of shell and tube heat exchangers. This model has led to the industry-wide redesign of shell and tube heat exchanger baffles, which has seen a huge reduction in fouling and an improvement in thermal efficiency, in contrast to segmented designs [29].

The fouling model, also known as the 'threshold fouling' model, calculates the 'fouling rate', which is used to analyse static and dynamic heat transfer systems [30]. The model assumes that the overall fouling rate produces two types of quantitative outcomes, a suppression term and a deposition term. Firstly, it extrapolates combinations of fouling rate against surface temperature at a constant shear stress, thus determining the 'fouling threshold'. Secondly, it provides an interpolation framework for measured data sets to estimate the fouling rate for different combinations of fluid velocity and surface temperature [31]. From this, a predictive outcome can be derived, considering different circumstances and operational parameters. Consequently, this facilitates an improved understanding of the maintenance requirements of the heat exchanger and may be utilised to quantify and predict declines in efficiency over time [30].

4.2 Helical Baffles

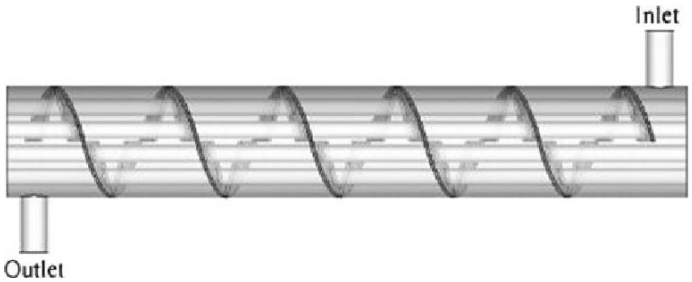

Figure 9 - Shell and Tube Heat Exchanger - Helical Baffle - [32]

The threshold fouling model, as previously mentioned, has led to the continual redesign of the standard segmented baffle commonly used in shell and tube heat exchangers. This redesign has resulted in the development of the helical baffle (fig.9), which wraps around the internal tubing instead of being divided into separate segments [33].

The helical design functions by directing the fluid flows in a manner that causes them to circulate around one another. The spiral configuration enhances the contact area between the fluid and the heat exchanger, hence enhancing its efficiency [34]. Their primary application is in applications where the shell side heat transfer coefficient is controlled, or lower amounts of fouling and pressure drop are anticipated [2].

Multiple issues were identified with the segmented baffle design, such as, (1) sudden and significant pressure drops on the shell sides, (2) fluid impacting the shell wall, (3) leakage between the shell wall resulting in reduced mass velocity, (4) excessive vibration leading to decreased operational time, and (5) low heat transfer efficiency due to stagnant flow between baffles and the shell wall [35].

The alternate helical design has improved upon these issues and has several advantages, including, (1) enhanced shell-side heat transfer rates and pressure drop ratio, (2) reduced shell-side fouling, (3) minimised bypass effects, (4) improved prevention of fluid flow induced tube vibration, and (5) decreased maintenance requirements [35] [36]. Each of these advantages contributes to enhanced productivity, decreased costs, and a more energy-efficient system, compared to the segmented baffle design.

4.3 Efficiency

Research has demonstrated that a helical design yields superior performance compared to a segmental baffle [37]. A study conducted by researchers [38] demonstrated that helical designs exhibit superior effectiveness and are more suitable for industrial applications. Further research conducted by [39] revealed that the helical design exhibited a heat transfer coefficient per unit pressure drop that was 72-127% higher compared to segmented baffles. Additionally, the helical design demonstrated a shell-side pressure drop that was 59-63% lower than segmented baffles.

In an investigation conducted by [40], it was observed that a helical baffle heat exchanger exhibited a 2.4% and 4.2% increase in heat transfer rate and shell-side heat transfer coefficient, respectively, when compared to a segmented baffle heat exchanger.

Further, a study by [41] was able to demonstrate the higher effectiveness of helical baffles in heat exchangers. Proving that they are able to aid in more efficient and accurate heat transfer and exhibited a lower pressure drop. The study concluded that all types of helical baffles, have higher heat transfer coefficients per pressure drop than segmented baffles.

Segmented baffle heat exchangers often suffer from significant flow leakage and pressure loss, resulting in decreased velocity and increased fouling risk. Pressure loss is experienced when the direction of fluid flow is changed alternately. Additionally, these issues lead to higher operational costs due to greater pumping demands [36]. Further, the presence of a segmented baffle design can exacerbate fouling by causing recirculation and creating dead patches [10].

4.4 Conclusion

From the studies reviewed it can be established that there exists a significant advantage to using a helical baffle design compared to a segmented baffle design. It can be known that from these higher efficiencies, that a helical baffle will be able to achieve a high heat transfer coefficient and therefore, a reduced rate of energy consumption, alongside lower costs and maintenance needs. Although the maintenance requirement is lower, it should still be performed on a regularly scheduled basis to ensure that standards are kept high. Using the fouling threshold model, can be an excellent aid in understanding the heat exchangers individual maintenance needs, and can be applied to understanding the fouling effects of the fluids that will be transitioning through the system. For the helical design to remain operational and efficient, it will be necessary to continue maintaining the system to attain optimal performance, despite its intrinsic lower requirements. With the appropriate application of the fouling model and maintenance procedures, the heat exchanger systems lifecycle will be extended significantly and thus reduce waste, with a less frequent replacement of parts and system required.

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