OPTIMIZING THE CLEANING OF HEAT EXCHANGERS

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Introduction

The proper performance of shell and tube type heat exchangers within a process can affect the cost of the final product, or even the production rate. Unfortunately, heat exchangers are prone to fouling, its nature depending on the fluids flowing within and over the tubes: and the reduction in heat transfer that results almost invariably has an impact on product cost. To reduce this impact, heat exchanger performance should be intelligently monitored and the heat exchanger cleaned at intervals that are determined from optimal economic criteria.

Heat Exchanger Fouling and its Effects

The principal types of fouling encountered in process heat exchangers include:

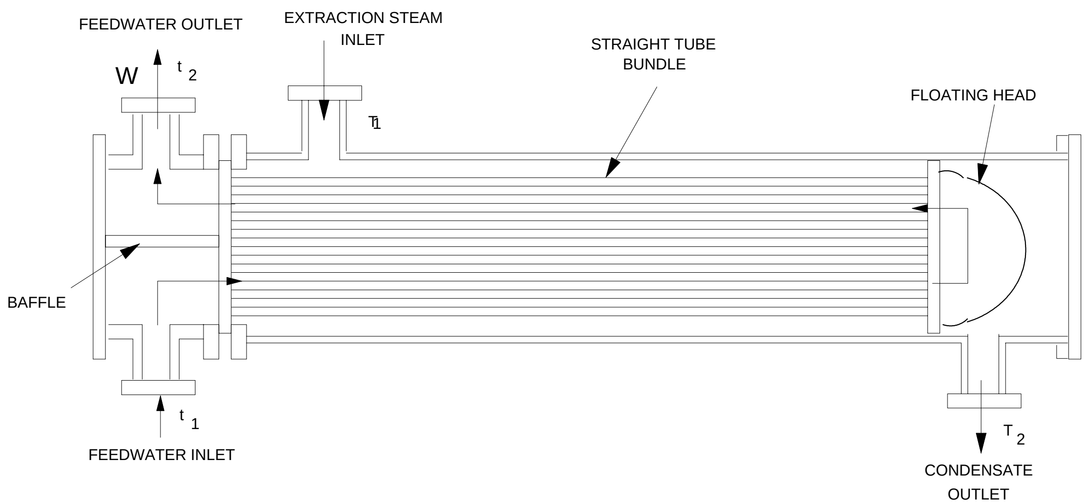
- Particulate fouling
- Corrosion fouling
- Biological fouling
- Crystallization fouling
- Chemical reaction fouling
- Freezing fouling

In most cases, it is unlikely that fouling is exclusively due to a single mechanism and, in many situations, one mechanism will be dominant. Fouling tends to increase over time, the trajectory being very site specific. Recognizing this, the Tubular Exchanger Manufacturers Association (TEMA, 1988) recommends that designers of heat exchangers include an allowable fouling resistance in their calculations, in order that some fouling can be tolerated before cleaning must be undertaken. But even though these allowances tend to prevent frequent process interruptions, fouling still has an economic impact. Thus, determining when to clean often requires striking a balance between maximizing the quantity of finished product from the process and its cost.

Monitoring Heat Exchanger Performance

The TEMA Standard (TEMA, 1988) includes methods for calculating heat exchange coefficients for a variety of shell and tube configurations, much of this based on the work of Nagle (1933), Underwood (1934) and Bowman et al (1940). Referring to Figure 1.0, the effective heat transfer coefficient (U_{eff}) for a heat exchanger may be calculated from the well-known Fourier equation:

$$U_{eff} = \frac{W * C_p(t_2 - t_1)}{A * LMTD} \tag{1}$$



DOUBLE-PASS HORIZONTAL SHELL AND TUBE HEAT EXCHANGER

STRAIGHT TUBE BUNDLE

FIGFURE 1.0

where log mean temperature difference (LMTD) is:

$$LMTD = F * \frac{\Delta T_{high} - \Delta T_{low}}{\log\left[\frac{\Delta T_{high}}{\Delta T_{low}}\right]} \qquad (2)$$

ΔT_{high} is the higher terminal temperature difference, ΔT_{low} is the lower terminal temperature difference and F is the factor applied to the basic log mean temperature difference in accordance with the configuration of the heat exchanger.

Included in the TEMA standard are sets of curves that allow the value of F to be determined from P, commonly known as temperature effectiveness, and R, where:

$$P = \frac{(t_2 - t_1)}{(T_1 - t_1)} \qquad (3)$$

and

$$R = \frac{(T_1 - T_2)}{(t_2 - t_1)} \qquad (4)$$

Figure 1.0, showing a two-pass heat exchanger, includes the location of the points where the above temperatures are measured. The set of LMTD Correction Curves for a two-pass heat exchanger is shown in Figure 2.0. Bowman et al (1940) derived the equations from which these curves can be calculated and plotted: Hewitt et al(1994) also includes an analysis.

Having established the value of U_{eff}, it is then compared with the basic design heat transfer coefficient *(U_{des})*, adjusted for any deviation in fluid flows from the original design values. The fouling resistance (R_f) may be calculated from:

$$R_f = \frac{1}{U_{eff}} - \frac{1}{U_{des}} \qquad (5)$$

Note that the value of R_f calculated using equation (5) represents the effect of fouling on both the insides and outsides of the tubes. Thus, to determine the fouling margin that remains, R_f must be compared with the *total* fouling thermal resistance allowance that was included in the original design.

Further, to improve confidence in these calculations, it is also important that the basic design heat transfer coefficient (U_{des}) be verified from a test conducted after the heat exchanger has just been cleaned.

Optimum Cleaning Criteria

Heat exchangers are a part of a process and, if fouling occurs, the temperature of the heating fluid must rise if the same amount of heat is to be transferred through the tubes. This temperature rise must be associated either with an increase in the total energy input to the process or a reduction in production rate, both of which represent a cost incurred due to fouling. Clearly, in order to make intelligent economic decisions, these costs must be quantified at a series of points in time and, preferably in relation to the fouling resistance as well.

Ma and Epstein(1981) indicated how optimum cleaning intervals could be determined by modeling and regressing the mean hourly costs of losses over time (the losses including the cost of cleaning) and, with falling rate processes, predicting when this mean hourly cost would approach a minimum. Putman(1994) applied this technique to steam surface condensers subject to fouling and confirmed that the forecasting principle functioned best with falling rate processes, represented by the fouling model shown in Figure 3.0. Note that the method often requires that the interest on borrowed money be also taken into account in order to obtain a discrete minimum point.

From the hourly cost of fouling calculated for a series of points in time, the cost of these losses from the last cleaning (t = 0) to the present (time = t_{cycl}) may be obtained from the following:

$$\begin{aligned}
&\text{Fouling cost per hour at time t} && = (Q_{act} - Q_{clean}) * \$/\text{MBTU/h} \\
&\text{Total cost over period} = T_{cst} && = \text{Cleaning Cost} + \sum_{t=0}^{t=tcycl} \text{Fouling cost at time t} \\
&\text{Mean Cost over period} = AV_{cst} && = T_{cst} / t_{cycl} \qquad (6)
\end{aligned}$$

Figure 3.0 shows a typical plot of the fouling resistance, the total cost since last cleaning and the cleaning criterion (the mean hourly cost of fouling) with respect to the time in hours since the last cleaning.

To predict the time when the mean hourly cost of losses will assume its minimum value, the data representing the mean hourly cost vs. time relationship over the past several months must be regressed to obtain a second or third order polynomial in terms of time, of the form:

From which:

$$AV_{cst} = a0 + a_1 * t + a_2 * t^2 + a_3 * t^3$$

$$\delta AV_{cst}/\delta t = a_1 + 2 * a_2 * t + 3 * a_3 * t^2 \quad (7)$$

$$= \text{zero at minimum}$$

Once the coefficients have been determined, the Newton-Raphson algorithm can be used to find the time t at which the differential coefficient $\delta AV_{cst}/\delta t$ will assume its minimum value.

Heat Exchanger Tube Cleaning Methods

To improve the performance of fouled heat exchangers requires that the tubes be cleaned periodically. Each time the tube deposits, sedimentation, biofouling and obstructions are removed, the tube surfaces are returned almost to bare metal, providing the tube itself with a new life cycle, the protective oxide coatings quickly rebuilding themselves to re-passivate the cleaned tube.

Tube cleaning procedures for shell and tube heat exchangers are performed *off-line*, the most frequently chosen and fastest method being mechanical cleaning. Figure 4.0 shows a mechanical tube cleaner in action.

Among other off-line methods is the use of very high-pressure water but, since the jet can only be moved along the tube slowly, the time taken to clean a heat exchanger can become extended. Great care must be taken to avoid damaging any tubesheet or tube coatings which may be present; otherwise the successful removal of fouling deposits may become associated with new tube leaks or increased tube sheet corrosion, which are only revealed after the unit has been brought back on-line.

Chemicals are also used for the off-line cleaning of heat exchanger tubes. Several mildly acidic products are available and will remove more deposit than most other methods; but it is expensive, takes longer for the operation to be completed, and the subsequent disposal of the chemicals, an environmental hazard, creates its own set of problems. It has also been found quite frequently that some residual material will still need to be removed by mechanical cleaning methods.

For off-line mechanical cleaning, the tool selected has to be the most appropriate for removing a particular type of deposit. Moulded plastic cleaners (pigs) are quite popular for some light silt applications. Brushes (Figure 5.0(a)) can also be used to remove these soft deposits as well as some types of microbiological deposit. Brushes are also useful for cleaning tubes with enhanced surfaces (e.g. spirally indented or finned); or those tubes with thin wall metal inserts or epoxy type coatings.

With harder types of deposit, metal cleaners of various designs have been developed, often with a particular deposit in mind. Figures 5.0(b) shows a current version of a cleaner consisting of several U-shaped tempered steel strips arranged to form pairs of spring-loaded blades. These strips are mounted on a spindle and placed at 90 degrees rotation to one another. Mounted at one end of the spindle is a serrated rubber or plastic disk that allows a jet of water to propel the cleaners through a tube with greater hydraulic efficiency. A stainless steel version of this cleaner is also available.

The water is directed to the tube being cleaned by a hand-held triggered device (also known as a gun shown in Figure 6.0(a)), the water being delivered by a pump operating at only 300 psig (2.07 MPa). Since the pump (shown in Figure 6.0(b)) is usually mounted on a wheeled base plate, the system can be conveniently moved from unit to unit within a plant or even moved to another plant.

A water pressure of 300 psig (2.07 MPa) is very effective for propelling the cleaning tools through the tubes (as demonstrated in Figure 4.0), preventing their exit velocity from rising above a safe level. Some other cleaning systems use air or a mixture of air and water as the propelling fluid; but the expansion of the air as the cleaner exits the tube can convert the cleaner into a projectile and place the technicians at risk.

Another advantage of using water as the cleaner propellant is that the material removed can be collected in a plastic container for later drying, then weighing to establish the deposit density (g/m^2) and followed in many cases by X-ray fluorescent analysis of the deposit cake.

Most metal cleaners are designed to have a controlled spring-loaded cutting edge: but, if effective deposit removal is to be the result, the dimensions of the cutting surfaces have to be closely matched to the internal diameter of the tube being cleaned, not only to improve the peripheral surface contact but also to ensure that the appropriate spring tension will be applied as the cleaner is propelled through the tube.

An increase in contact area can also improve deposit removal. A cleaner with 6 blades, known as the Hex cleaner (see Figure 5.0 (c)), rather than the two blades shown in Figure 5.0(b), is also available. This design not only reduced the cleaning time for 1000 tubes but it was found to be more efficient in removing tenacious deposits such as those consisting of various forms of manganese.

A later development involved a tool for removing hard calcite deposits, which were found difficult to remove even by acid cleaning. This is shown in Figure 5.0(d), and consists of a teflon body on which are mounted a number of rotary cutters, similar to those used for cutting glass. These are placed at different angles around the body, which is fitted with a plastic disk similar to those used to propel other cleaners through tubes. Used on condenser tubes that had accumulated a large quantity of very hard deposits, Stiesma et al(1994) described how cleaners of this type removed 80 tons (72.48 tonnes) of calcite material from this condenser. In the utility industry, it has now become a standard tool whenever hard and brittle deposits are encountered.

The tube bundles in many heat exchangers consist of U-tubes and a flexible cleaner (Figure 5.0(e)) has been designed to traverse these tubes where the deposits are not too hard.

For deposits that are the most difficult to remove, portable compressed air driven devices are available which bore into and remove the deposits as the drill bit or brush is pushed through each tube. A photograph of a Hydrodrill can be seen in Figure 7.0. It also requires a limited reservoir of water that softens and/or flushes deposits and serves as a coolant, even acting as a flame retardant in combustible atmospheres. These devices can clean tubes up to 40 feet long and having an inside diameter of between ¼ inch to 6 inches.

Soft deposits are normally removed with brushes using water or a water/biodegradable detergent as the flushing agent. Harder deposits might require drill bits or bit-brush combinations and water, biodegradable solvents or detergents as the flushing agents.

Conclusion

Shell and tube heat exchangers are a vital part of the process in which they are installed and their condition can significantly affect the process economics in several ways. Thus, to improve the performance of those heat exchanges prone to fouling problems, historical data should be acquired and analyzed and the fouling model developed. The costs of fouling must also be quantified and the cleaning criterion, mean hourly cost of losses, monitored. The optimum time to clean is when this criterion achieves its minimum value. Further, the cleaning method selected should be one that is not only able to handle effectively the type of fouling experienced with that heat exchanger, but also results in minimum annual maintenance and downtime costs.

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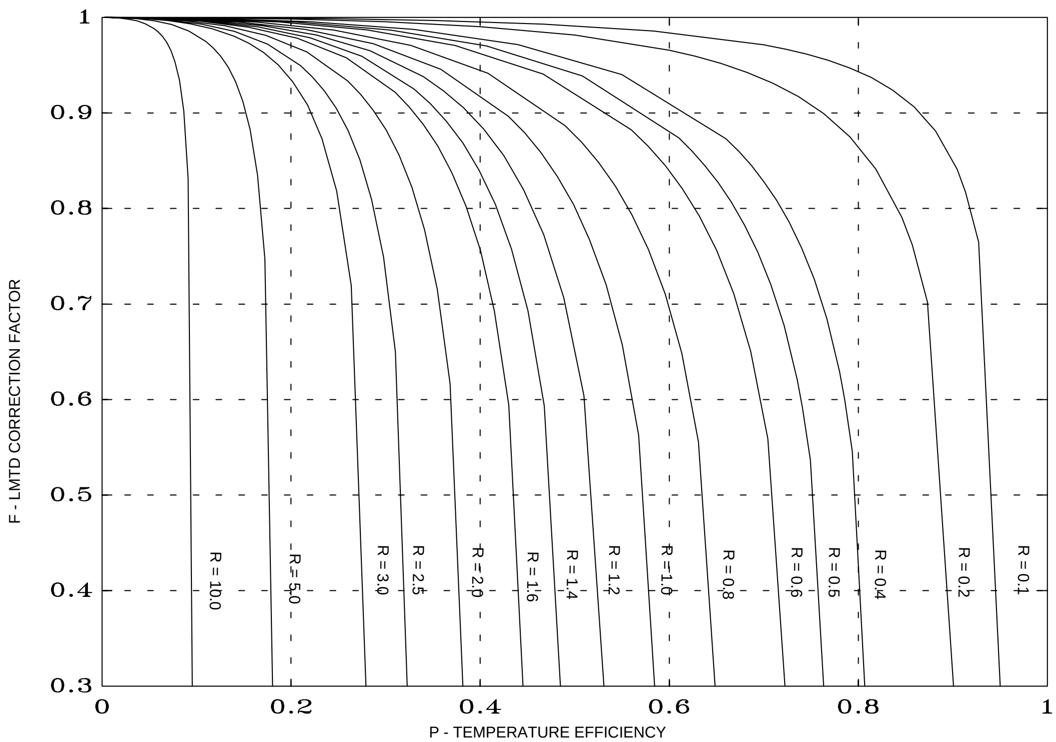
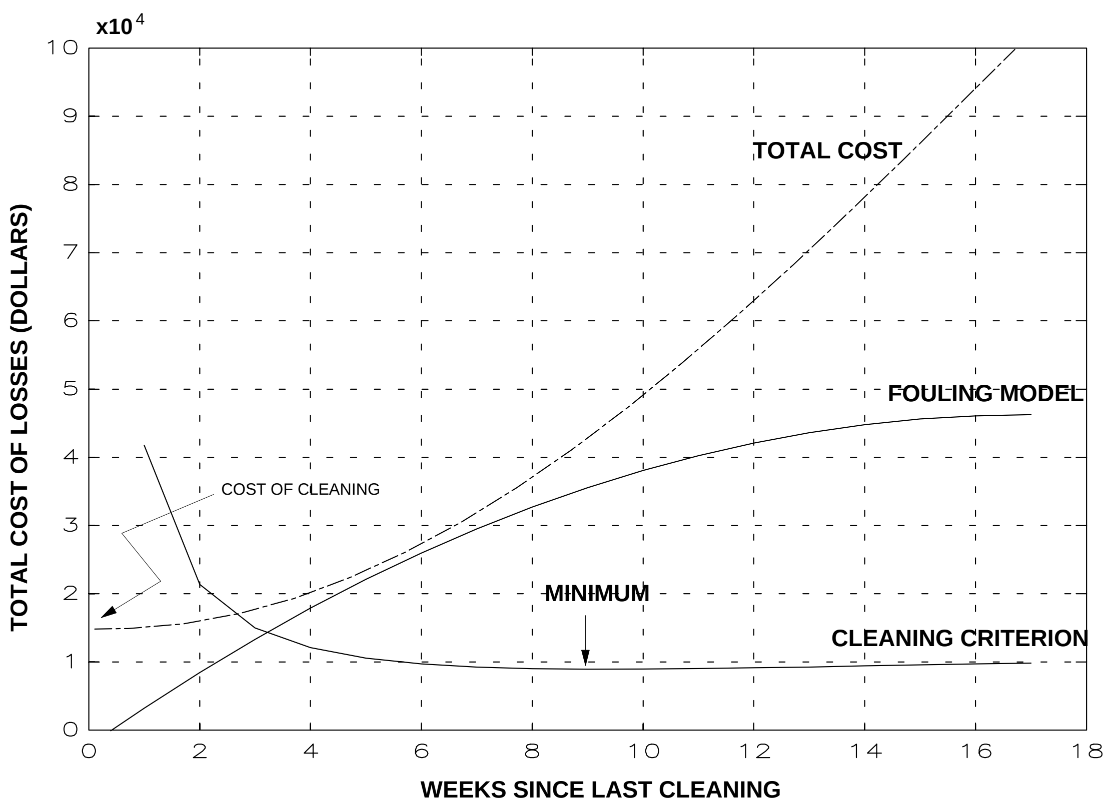


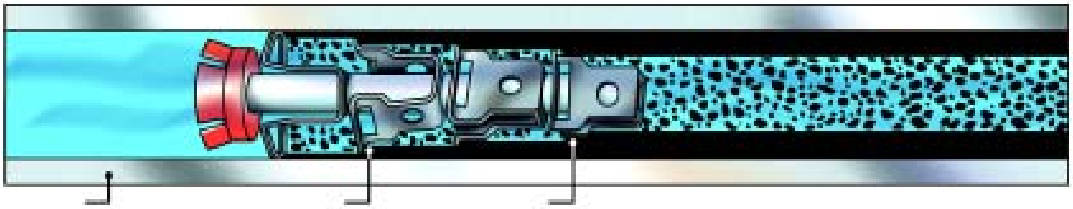
LMTD CORRECTION FACTORS FOR TWO-PASS HEAT EXCHANGER

FIGURE 2.0



FOULING MODEL AND CLEANING CRITERION

FIGURE 3.0



Mechanical Tube Cleaner in Action
Figure 4.0

Figure 5a Brush

Figure 5b Metal Tube Cleaners

Figure 5c Hex Cleaners

Figure 5d Calcite Cleaners

Figure 5e Flexible U-tube Cleaners
Figure 5 Mechanical Tube Cleaners

Figure 6a Water Gun

Figure 6b Portable Booster Pump

Figure 6.0
Water Gun and Pump System

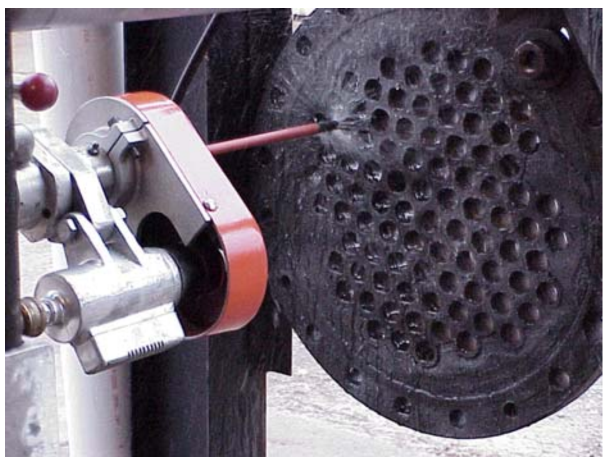


Figure 7.0
HydroDrill