FOULING MITIGATION BY DESIGN

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ABSTRACT

Fouling is a nearly ubiquitous heat transfer phenomenon that costs world industry billions of U.S. dollars annually. However, many fouling mechanisms can be mitigated with proper design strategy. The key points of the design method described in this paper, regardless of service, are to maximize shear stress and control wall temperature. We also generally recommend replacing the use of fouling factors with 20% excess area. Application of this field-proven design methodology will significantly lower capital costs and substantially increase run time between cleanings.

INTRODUCTION

The accumulation of scale, organic matter, corrosion products, coke, particulates or other deposits on a heat transfer surface is a phenomenon called fouling and costs industry billions of dollars each year. These deposits will degrade heat exchanger performance over time compared with "clean" conditions at start up. The fouling layer is a conductive resistance to heat transfer that must be accounted for in the design heat transfer coefficient. Fouling thickness and thermal conductivity both contribute to the resistance. Reduced cross sectional flow area also increases pressure drop in the fouled region. This additional pressure drop must be accounted for in the pump design. Use of the guidelines presented here will reduce the fouling layer thickness and mitigate the effect on heat transfer efficiency and pressure drop.

Common fouling mechanisms are outlined below (Watkinson, 1988):

Particulate fouling results from sedimentation of dust, rust, fine sand, or other entrained solids.

Precipitation fouling is a solids deposition at the heat transfer surface from a supersaturated fluid. A common example is salt crystallization from an aqueous solution. Precipitation can also occur via sublimation, *e.g.* ammonium chloride in overhead and effluent vapors.

Chemical reaction fouling is the breakdown and bonding of unstable compounds at the heat transfer surface. Oil sludge and polymerization are examples of chemical reaction fouling.

Coking is a subset of chemical reaction fouling. It is one of the most problematic types of fouling. In the extreme, the coke deposit is a very hard layer of carbon, salts and other compounds.

Corrosion fouling is the accumulation of corrosion products, such as iron oxide, on the heat transfer surface.

Biological fouling is the growth of living organisms, like algae and mussels, on the heat transfer surface.

Fouling in service may be a combination of two or more mechanisms. Also, one mechanism may be a fouling precursor for another mechanism. Fluids may be categorized into three groups according to their potential for fouling (Watkinson, 1988):

Non-fouling fluids do not require regular cleaning. Some examples are non-polymerizing light hydrocarbons, steam, and sub-cooled boiler feed water.

Asymptotic fouling fluids reach a maximum constant fouling resistance after a short run time. The fluid velocity imparts a shear stress at the fouling layer that removes some of the deposit (Kern and Seaton, 1959). As the fouling layer thickens, flow area is reduced and velocity increases, thereby increasing the removal rate. When the rate of removal equals the rate of deposition, fouling reaches an asymptotic limit (Kern and Seaton, 1959). The thickness of the final asymptotic fouling layer is inversely proportional to the original velocity. Cooling tower water is an example of an asymptotic fouling fluid.

Linear fouling fluids have a fouling layer that is too tenacious to shear off at economic design velocities. The fouling layer continues to build as a roughly linear function of time. The rate of fouling over time is dependent on velocity. At low velocity, fouling is controlled by mass diffusion to the surface. Increasing velocity in this range increases mass diffusion, and thus promotes fouling. At high velocity, fouling is controlled by deposit shearing, residence time, and decreases with increasing velocity. Linear fouling mechanisms are also strongly dependant on surface temperature. Crude oils and polymerizing hydrocarbons are examples of linear fouling fluids.

The traditional method to accommodate fouling is to assign an individual fouling resistance, or “fouling factor”, to each stream. This fouling factor is the expected resistance due to fouling at end of run, based on user experience. The sum of the fouling, fluid, and metal resistances provides a total design resistance to calculate the required surface area. Although the Tubular Exchanger Manufacturers Association (TEMA) publishes fouling factors by service, these values have been the subject of considerable debate (Palen, 2002a).

The problem with this approach is that the fouling resistance is not a static value. Fouling is dependent on many factors, especially velocity, surface temperature, and chemistry. Actual fouling in service can vary greatly about the mean performance predicted by static fouling factors. This is most noticeable in exchanger performance where the fouling margin is large. Problematic services, or "frequent foulers", can reach the performance limit in a matter of days, rather than the full run cycle. Thereafter the user must clean the exchanger or live with reduced performance.

One approach to this problem is to further increase the margin for fouling. Unfortunately, this has diminishing returns (Palen, 2002a). The use of large fouling factors can be a self-fulfilling prophecy. The fouling resistance for most mechanisms is inversely proportional to velocity. Large fouling factors or other design margins result in added surface area. A design with large surface area will always have lower fluid velocity than a design with less area at the same given pressure drop. As surface area is added, velocity decreases. As velocity decreases, fouling increases. Thus, the prophecy is fulfilled.

An alternate approach is to avoid fouling altogether, by designing for critical velocity, surface temperature, and/or other factors that preclude significant fouling. As of this writing, Heat Transfer Research, Inc. (HTRI) is leading the effort to determine these critical design parameters (Longstaff and Palen, 2001; Palen, 2002b). As a result of the complexity of fouling, it may be some time before these criteria are fully developed. However, partial results are available now for some problematic refinery applications.

PART 1 – LIQUID HYDROCARBON SERVICE

HTRI has confirmed experimentally that fouling in crude oil preheat service depends primarily on velocity, surface temperature, and the relative amount of saturates, asphaltenes, resins and aromatics (Longstaff and Palen, 2001; Palen, 2002b). The fifteen crude oils HTRI has studied thus far suggest that tube side velocities above 2 m/s and wall temperatures below 300°C are reasonable guidelines for designing fouling resistant heat exchangers.

Note, however, that these guidelines will not always eliminate fouling. These guidelines also presume no fouling due to other mechanisms, such as sedimentation or precipitation. Finally, HTRI has concluded that, depending on conditions, crude oil fouling can be either much greater, or much less, than the TEMA recommended fouling factor (Longstaff and Palen, 2001).

It is tempting to extrapolate these design guidelines to other problematic refinery services such as vacuum residue product coolers. The authors feel that this is a reasonable conclusion, given that coking is so problematic, and the low-foul guideline noted above is probably conservative for other mechanisms. There are two qualifiers:

1. Fluids do not have heavy particulate matter such as catalyst fines
2. Fluids do not have high salt content (*e.g.* desalting malfunctions)

The tube side velocity guideline may also be extrapolated to the shell side by providing a design that results in similar shear stress. Putting this all together results in the following generalized design method for liquid hydrocarbon service in refinery applications. It has been used with success by at least two users to date. The crux of the low-foul method is to provide velocity equal to, or greater than, a critical velocity that significantly mitigates fouling (Kern and Seaton, 1959). The allowable pressure drop must be whatever it takes to get the desired velocity. Another essential feature is that fouling factors are not used. This reduces excess surface area requirements and the required pressure drop. However, a design margin may be added to account for statistical variation in predictive methods, uncertainty of physical properties, and/or a small amount of fouling.

Low-Foul Design Method

Scope. The low-foul design method is applicable to medium through high boiling point liquid hydrocarbon mixtures with API gravity less than 45. This API gravity cutoff was chosen from experience.

Application. Apply this method when short maintenance cycles, problematic hydraulic and/or thermal performance, vibration, or other problems are related to fouling. The user may also consider this method to reduce exchanger capital cost. In this case, exchanger installed cost shall be evaluated against the cost to provide the necessary pressure drop.

System Operation. The process scheme shall prevent premature shutdown due to fouling by providing the means to continue operation with shell(s) out of service, if needed, for on-line cleaning. Need for shells in parallel, or bypass around single shells, shall be evaluated. This is not to imply that the low-foul method has higher risk than traditional design methods. Rather, this is good design practice for problematic services in any event. The low-foul method should, in fact, provide much longer run times than traditional designs. The process scheme shall also consider turndown operation and the need for shells in parallel, pump recycle, or other means to maintain critical velocity during turndown operation. Where fluid bypass is used for process temperature control, the resultant exchanger velocity shall be maintained above the critical minimum velocity.

Numbered exchanger design guideline.

1.0 Minimum Liquid Velocity

1.1 Tube side velocity of 2 m/s. This velocity limit is applicable for tubes with outside diameters of 19.05 and 25.4 mm. Increase velocity to 2.2 m/s for diameters of 31.75 and 38.1 mm to maintain shear stress.

1.2 Shell side cross flow stream (B-stream) should be at least 0.6 m/s.

2.0 Maximum Temperature

The maximum tube wall temperature shall be 300°C.

3.0 Shell Side Design (Gilmour, 1965)

3.1 The B-stream fraction shall be at least 0.65.

3.2 Provide single segmental baffles.

3.3 Baffle cut orientation shall normally be horizontal for TEMA type E and J shells. Baffle cut orientation for TEMA type G and F shells shall be vertical.

3.4 Baffle cut for tubes in the window shall be 20 – 25% of the shell diameter, where 20% is preferred. Increase cut up to 25% if required to reduce leak streams. See 3.7 for no tubes in window (NTIW) designs.

3.5 Where impingement protection is required, use impingement rods. One row of rods is acceptable for 90°. Use two rows for staggered pitch. Do not use impingement plates.

3.6 Large baffle end spaces and low resultant velocity are sometimes unavoidable due to geometry constraints. Where this occurs, the designer may make a judgment call to consider the end space surface area largely ineffective. Provide additional area to compensate. Consider an annular distributor if the affected surface area is large.

3.7 The ratio of window velocity to cross flow velocity (including leak streams) shall be less than 2 for designs with tubes in the window (1.0 – 1.5 is preferred). For NTIW, the ratio of window velocity to cross flow velocity shall be less than 3.0 (1.5 – 2.0 is preferred).

This is a soft guideline at this time. The optimum ratio is intuitive and thus is an area for further quantitative investigation.

4.0 Excess Surface

Where both fluids are within the scope of this practice, provide approximately 20% excess surface, but do not apply a fouling factor. This design margin may be reduced where the designer has confidence in predictive methods and successful mitigation of fouling (usually based on prior experience for a similar service). Where only one fluid is within the scope of this practice, consider a fouling factor for the fluid outside scope. Omit the fouling factor if the fluid is non-fouling. For the fluid within scope, multiply the heat transfer coefficient by 0.83 and do not use a fouling factor. As above, the design margin may be reduced based on designer experience.

5.0 Allowable Pressure Drop

Pressure drop shall be provided as required to meet the minimum critical velocities noted in 1.0.

6.0 Longitudinal Baffles

If a longitudinal baffle is used in fouling service, the baffle shall be welded to the shell. For removable bundles, this requires the use of U-tubes with the U-bends in a horizontal plane (normally 4 or more tube passes). The designer should investigate differential thermal stresses across the shell. In general, a welded longitudinal baffle is probably acceptable where the shell side temperature difference across one shell does not exceed 89°C. Provide bundle slide rails in both top and bottom portions of the bundle.

Design Tricks of the Trade

Consider these construction features to improve shell side performance:

American Petroleum Institute Standard 660 requires a seal device (dummy tubes, rods, or strips) to be implemented from 25 – 75 mm from the baffle tips, and for every 5 – 7 tube pitches thereafter. Increase the number of seals if required to limit the bundle and pass lane leak streams.

Where the tube-to-baffle diametral tolerance (per TEMA) is 0.8 mm, the tolerance may be reduced to 0.4 mm if required to reduce the leak stream between tube and baffle hole.

The TEMA baffle-to-shell diametral clearance may be reduced to limit the baffle-to-shell leak stream. A clearance of 0.0035 – 0.004 times the shell diameter is achievable for shells rolled from plate, but use this extra tight clearance only if necessary, as it is hard to guarantee compliance. Extra tight clearance is not recommended for shells made from pipe (typically NPS 24 and smaller).

Consider baffled TEMA type F and G shells to increase shell side velocity, reduce number of shells in series, and/or improve the baffle spacing-to-shell diameter aspect ratio.

Comparison of Low-Foul and Conventional Designs

Our low-foul method was used to design three items on a recent project. These services were known to be problematic frequent foulers, and had fouling fluids on both the shell and tube sides. Table 1 compares the low-foul design with a standard design using fouling factors and typical allowable pressure drop. A third design utilizing conventional methods with 10% excess surface is also compared.

Table 1. Low-foul versus standard heat exchanger designs[a]

Parameter	Low-foul design	Standard design	Standard design with 10% coefficient margin
Surface area (m^2)	832	1 564	1 875
Estimated cost (US$)	996 000	1 527 000	1 775 000
Clean overall coefficient (W/m^2 K)	361	231	204
Total fouling resistance (m^2 K/W)	0.000 634	0.001 99	0.002 68
Fouling margin (% excess surface)	22	46	55
Shell side			
Pressure drop (kPa)	175	66.9	63.4
Velocity (m/s)	0.61	0.34	0.30
Shear stress[b] (Pa)	14.2	4.8	4.1
Tube side			
Pressure drop (kPa)	185	66.2	55.2
Velocity (m/s)	2.2	1.1	0.91
Shear stress (Pa)	15.6	4.5	3.3

[a]Service is residue stripper bottoms/preflash bottoms exchanger
[b]Shell side shear stress is weighted for window and cross flow

Table 2. Benefit of low-foul versus enhanced standard exchanger design

Parameter	Low-foul design	Standard design with increased pressure drop
Surface area (m^2)	832	1 254
Estimated cost (US $)	996 000	1 273 000
Clean overall coefficient (W/m^2 K)	361	316
Total fouling resistance (m^2 K/W)	0.000 634	0.001 99
Fouling margin (% excess surface)	22	62
Shell side		
Pressure drop (kPa)	175	122[a]
Velocity (m/s)	0.61	0.46
Shear stress (Pa)	14.2	8.48
Tube side		
Pressure drop (kPa)	185	166
Velocity (m/s)	2.2	1.9
Shear stress (Pa)	15.6	11.2

[a]Did not use all of the allowable pressure drop because smaller spacing and additional pressure drop resulted in leak streams that reduced overall exchanger efficiency

Shear stress is the metric to evaluate fouling tendency, rather than average velocity. Lower margins for fouling in the low-foul design are justified by shear stresses that are approximately 3 times greater than shear stresses of the conventional designs. Table 1 illustrates the futility of adding surface area with typical pressure drops to provide more design margin for fouling.

On the other hand, the use of the low-foul method has an "increasing returns effect". Lowering the fouling margin results in less surface area. Lower surface area yields a higher velocity at a given pressure drop. Higher velocities increase the heat transfer coefficient, which further reduces surface area, and so on. Table 2 compares the low-foul design with an enhanced standard design using fouling factors and the same allowable pressure drop. This enhanced design is not quite as bad as the conventional designs in Table 1. More pressure drop helps out, but the design still falls short of achieving the critical low-foul shear stresses. Part of the allowable pressure drop is lost to the extra surface required for the fouling factor.

Shell Side versus Tube Side

The conventional wisdom is to place fouling fluids on the tube side. This makes sense when the bundle is cleaned in place, because the tube side is accessible without removing the bundle. Shell side cleaning requires more maintenance hours since piping has to be uncoupled and the bundle removed. However, most users clean the bundle at a remote cleaning station, rather than in place. If this is the case, the bundle has to be removed anyway, and it takes more time to clean the tube side because it is generally done one tube at a time. Therefore, when the plant standard maintenance practice is to clean removable bundles at a remote location, it is actually preferable to place fouling fluids on the shell side (Gilmour, 1965). Another bias is that "the shell side will foul to a greater extent than the tube side" (Gilmour, 1965). However, application of the low-foul design recommendations to the shell side should mitigate fouling to the same extent as the tube side, given the same shear stress.

Having said this, the authors agree with the conventional wisdom for the following services. Tenacious, linear fouling deposits, *e.g.* crude oil preheat, are difficult to clean via standard hydroblasting on the shell side, especially in large bundles. Linear fouling fluids should be placed on the tube side, unless user experience indicates that these deposits can be softened with a preliminary chemical wash, or the bundle diameter is less than 760 mm. Fluids with heavy solids such as catalyst fines or other slurries are generally placed on the tube side. In cases where shell side flow is unavoidable, there has been some success using vertical cut baffles to allow sedimentation to exit the shell. Velocity sufficient to remove sedimentation, but avoid erosion, is a matter of experience for the particular slurry service.

Future Investigation

The following areas would benefit from further investigation. Maximizing velocity by itself is not enough to ensure low fouling on the shell side. Designs should eliminate "dead areas" (*e.g.* under impingement plates), maximize the number of tubes in cross flow, minimize leak paths, and minimize centrifugal force in the window turn around. The shell side design guidelines are an attempt to do all this, but they are admittedly intuitive at this point. A rigorous investigation with computational fluid dynamics is suggested to quantify the optimum design guidelines. Additional recommended fouling studies include services other than crude oil preheat to expand the generalized guidelines for velocity and temperature in liquid service, condensing and boiling services, and evaluation of low fin tubes and tube inserts.

PART 2 – COOLING WATER

System Design

Cooling water flow rate is normally based on a maximum temperature rise. For cooling tower water, this would be a maximum temperature of about 43°C minus the summer cold water temperature from the tower. This range gives the least amount of cooling water without an exchanger outlet temperature that causes corrosion and/or fouling problems in the heat exchanger, or other design problems for the cooling tower. The designer will maximize the allowable pressure drop where possible, but the actual pressure drop used will vary between items in the cooling water loop.

We suggest a different approach. All items in the cooling water loop should be designed to use the maximum allowable pressure drop. The cooling water flow rate for each item is adjusted to get the same pressure drop, more or less. When the adjusted flow rate is less than the desired target rate noted above, the designer must be mindful of not exceeding the tube wall temperature which may cause corrosion and/or fouling. A tube wall temperature less than 60°C is a reasonable upper limit for treated cooling water. Thus, the cooling water flow rate is based on equal pressure drop, not equal temperature range. The reason for this is that the cooling water will distribute itself to equalize the system pressure drop from inlet header to outlet header. If design pressure drop varies from exchanger to exchanger, the resulting cooling water flow to a given item may not be that required on the data sheet; some coolers will get more, others less. A large cooling water user at low design pressure drop can rob cooling water from the other users. Designing them all to the same pressure drop prevents this from happening and avoids poor performance due to unexpected low cooling water velocity. Do not skimp with allowable pressure drop for new installations. Allow at least 100 kPa for the clean exchanger pressure drop, in order to achieve high cooling water velocity.

Process Control

Cooling water should never be throttled to control the exchanger duty or process outlet temperature. The resulting low velocity and/or high outlet temperature will quickly result in problematic fouling. Where process control is required, it is preferable to bypass the process side. If the process stream is a fouling fluid, this may merely be the lesser of two evils. However, it may be possible to design the process side for the minimum critical low-foul velocity in the bypass mode, depending on how much fluid needs to be bypassed.

Exchanger Design

It is preferable to use a dynamic calculation for fouling resistance based on velocity, rather than a static fouling factor. Like hydrocarbon fouling, water fouling is dependent on velocity, temperature, and composition. Tube metallurgy is also a variable for untreated water where biological growth and corrosion are part of the fouling mechanism. Fouling factors may be predicted with design software, or developed empirically using a portable fouling test unit. For example, fouling for treated cooling water inside carbon steel tubes might be something like this:

$$R = 0.00062V^{-1.65} \tag{1}$$

Actual fouling resistance can vary significantly from the static value of 0.000 35 m^2 K/W that is typically specified. It is preferable to design for high velocity (1.8 – 2.1 m/s) in order to minimize fouling, rather than accommodate low velocity with a large fouling factor. In the absence of predictive software or an empirically derived correlation, Eq. (1) gives useful results for most treated cooling tower water.

Shell Side versus Tube Side

It is preferable to place cooling water on the tube side. Fouling is asymptotic, implying a soft deposit. However, there is a tenacious underlying layer that may be difficult to clean on the shell side. Also, heavy solids such as silt are handled better on the tube side. Where cooling water on the shell side is unavoidable, use the design guidelines for liquid hydrocarbons in Part 1.

Tube Metallurgy

Rough surface is a fouling precursor for organic growth and sedimentation. Reduced fouling rates have been observed with non-corrosive alloys and smooth surface obtained from surface treatment such as chrome plating (Gilmour, 1965). Copper and its alloys also reduce organic growth, as this material is toxic to the organisms.

SUMMARY

Recommendations for heat exchanger design and operation outlined in this article are theoretically sound and field proven for minimizing fouling. Regardless of service, one wants to minimize wall temperature and maximize shear stress by maximizing fluid velocity. Distribute pressure drop across trains to maximize velocity in problem exchangers when possible. Material selection also has a pronounced effect on fouling, particularly when biological fouling is a concern.

NOMENCLATURE

R Fouling resistance to heat transfer, m^2 K/W
V Average velocity, m/s

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