1.6. Fouling in Heat Exchangers

1.6.1. Typical Fouling Resistances.

"Fouling" is a general term that includes any kind of deposit of extraneous material that appears upon the heat transfer surface during the lifetime of the heat exchanger. Whatever the cause or exact nature of the deposit, an additional resistance to heat transfer is introduced and the operational capability of the heat exchanger is correspondingly reduced. In many cases, the deposit is heavy enough to significantly interfere with fluid flow and increase the pressure drop required to maintain the flow rate through the exchanger.

The designer must consider the effect of fouling upon heat exchanger performance during the desired operational lifetime and make provisions in his design for sufficient extra capacity to insure that the exchanger will meet process specifications up to shutdown for cleaning. The designer must also consider what mechanical arrangements are necessary to permit easy cleaning.

Allowance for fouling is largely a matter of experience. There are tables of typical values for various services (e.g., Ref.10 and the TEMA Standards (9), and there is a proprietary correlation available for cooling water. An adaptation of the TEMA table is included here as Table 1.2. However, fouling behavior is strongly dependent upon many variables and these interactions are very complex, so each problem really needs to be examined for unexpected pitfalls and special considerations.

The best general survey of fouling in heat exchangers is by Taborek, et al. (15, 16). Other important contributions are Refs. (17) to (21).

1.6.2. Types of Fouling

There are several different basic mechanisms by which fouling deposits may be created and each of them in general depends upon several variables. In addition, two or more fouling mechanisms can occur in conjunction in a given service. In this section we will identify the major mechanisms of fouling and the more important variables upon which they depend.

a. Sedimentation fouling. Many streams and particularly cooling water contain suspended solids which can settle out upon the heat transfer surface. Usually the deposits thus formed do not adhere strongly to the surface and are self- limiting; i.e., the thicker a deposit becomes, the more likely it is to wash off (in patches) and thus attain some asymptotic average value over a period of time. Sedimentation fouling is strongly affected by velocity and less so by wall temperature. However, a deposit can "bake on" to a hot wall and become very difficult to remove.

b. Inverse solubility fouling. Certain salts commonly found in natural waters - notably calcium sulfate - are less soluble in warm water than in cold. If such a stream encounters a wall at a temperature above that corresponding to saturation for the dissolved salt, the salt will crystallize on the surface. Crystallization will begin at special active points - nucleation sites – such as scratches and pits, often after a considerable induction period, and then spread to cover the entire surface. The buildup will continue as long as the surface in contact with the fluid has a temperature above saturation. The scale is strong and adherent and usually requires vigorous mechanical or chemical treatment to remove it.

c. Chemical reaction fouling. The above fouling mechanisms involve primarily physical changes. A common source of fouling on the process stream side are chemical reactions that result in producing a solid phase at or near the surface. For example, a hot heat transfer surface may cause thermal degradation of one of the components of a process stream, resulting in carbonaceous deposits (commonly called "coke") on the surface. Or a surface may cause

polymerization to occur, resulting in a tough layer of low-grade plastic or synthetic rubber. These deposits are often extremely tenacious and may require such extreme measures as burning off the deposit in order to return the exchanger to satisfactory operation.

d. Corrosion product fouling. If a stream corrodes the metal of the heat transfer surface, the corrosion products may be essential to protect the remaining metal against further corrosion, in which case any attempt to clean the surface may only result in accelerated corrosion and failure of the exchanger.

e. Biological fouling. Many cooling water sources and a few process streams contain organisms that will attach to solid surfaces and grow. These organisms range from algae and microbial slimes to barnacles and mussels. Even when only a very thin film is present, the heat transfer resistance can be very great. Where macroscopic forms like mussels are present, the problem is no longer one of heat transfer - there won't be any through the animal - but rather of plugging up the flow channels. If biological fouling is thought to be a problem, the usual solution is to kill the life forms by chlorination, or to discourage their settling on the heat transfer surface by using 90-10 copper-nickel (Alloy C70600) or other high copper alloy tubes. As an alternative to continuous chlorination, intermittent "shock" chlorination may be successful.

f. Combined mechanisms. Most of the above fouling processes can occur in combination. A common example is the combination of (a) and (b) in cooling tower water. Most surface waters contain both sediment and calcium carbonates, and the concentrations of these components rise as the water is re-circulated through the cooling system. It is therefore common to find deposits composed of crystals of inverse solubility salts together with finely divided sediments. The behavior of these deposits is intermediate between the two limiting cases: the crystals tend to hold the sediment in place, but there are planes of weakness in the structure that fail from time to time and cause the deposit to break off in patches.

1.6.3. Effect of Fouling on Heat Transfer

As noted above the effect of fouling is to form an essentially solid deposit upon the surface, through which heat must be transfer red by conduction. If we knew both the thickness and the thermal conductivity of the fouling, we could treat the heat transfer problem simply as another conduction resistance in series with the wall. In general, we know neither of these quantities and the only possible technique is to introduce the additional resistance as fouling factors in computing the overall heat transfer coefficient as previously discussed.

Fouling effects inside the tube usually cause no particular problems if allowance has been made for the reduction in heat transfer and the small increase in flow resistance. However, fouling on the outside of finned tubes can be a more complicated matter, because in extreme situations there is a possibility that the finite thickness of the fouling layer can effectively close off the flow through the fins. On the other hand, finned surfaces are sometimes found to be more resistant to fouling than plain surfaces (Ref. 21); the reasons for this are not well-established, though it may be that the expansion and contraction of the surface during normal operational cycles tends to break off brittle fouling films. Caution is advised, however, in applying finned tubes to services known to be significantly fouling.

High-finned tubes are commonly used only with air and other low pressure and relatively clean gases. Such fouling as does occur is mostly dust deposition, which can easily be removed by blowing.

1.6.4. Materials Selection for Fouling Services

Potential fouling problems may influence materials selection in one of three ways. Most obvious perhaps is the minimization of corrosion-type fouling by choosing a material of construction, which does not readily corrode or produce voluminous deposits of corrosion products. If chemical removal of the fouling deposit is planned, the material selected must also be resistant to attack by the cleaning solutions.

Secondly, biological fouling can be largely eliminated by the selection of copper-bearing alloys, such as 90-10 copper-nickel (UNS 70600) or 70-30 copper-nickel (UNS 71500). Generally, alloys containing copper in quantities greater than 70% are effective in preventing or minimizing biological fouling.

Thirdly, some types of fouling can be controlled or minimized by using high-flow velocities. If this technique is to be employed, the possibility of metal erosion should be considered as it is important to restrict the velocity and/or its duration to values consistent with satisfactory tube life. Some metals, such as titanium or stainless steels, can be quite resistant to erosion by the high velocity effluent. Recently, a new copper-nickel alloy containing nominally 83% copper, 17% nickel and 0.4% chromium has been developed by the International Nickel Company (Alloy C72200). This alloy is similar to the other copper-nickels relative to its corrosion resistance, but, however, has a much greater resistance to velocity attack, being capable of operating in sea water at velocities approaching 25 feet per second.

1.6.5. Removal of Fouling

If fouling cannot be prevented from forming, it is necessary to make some provision for its periodic removal. Some deposits can be removed by purely chemical means, e.g., removal of carbonate deposits by chlorination. The application of chemical cleaning techniques is a specialized art and should be undertaken only under the guidance of a specialist. However, since chemical cleaning ordinarily does not require removal of the equipment nor disassembly of the piping (if properly designed), it is the most convenient of the cleaning techniques in those cases where it can be used.

There are a number of techniques for mechanical removal of fouling. Scraping or rotary brushing are limited to those surfaces that can be reached by the scraping tool – a problem that is eased on the shell side by the use of large clearances between tubes and/or the use of rotated square tube layout. (It should be noted that scraping should not be used on finned tubes.) Use of very high velocity water jets is very common both inside and outside the tubes, though for the shell side the jets will not be very effective deep inside a large tube bank.

For situations where there is a high premium for maintaining a high degree of cleanliness, e.g., large power plant condensers, it may be possible to install a system for the continuous on-stream cleaning of the interior surfaces of the tube. The Amertap® System utilizes slightly oversized, sponge rubber balls which are continuously recirculated through the tubes on a random basis. As the balls pass through the tubes, they remove the accumulation of scale or corrosion products. A mesh basket in the outlet piping collects the balls and a ball pump re-injects them into the entering water flow. The type of balls having an abrasive secured to the outer surface should be used only with great caution as continuous abrasive action may shorten tube life due to the removal of the protective corrosion film formed in copper and copper-base alloys.

The M.A.N.® System provides for on-stream cleaning by passage of brushes through the tubes. On heat exchangers, which use this system, plastic baskets or cages are installed at both ends of every tube. A plastic brush designed to fit the interior of the tube is installed into one basket. Periodically the water flow through the tubes is reversed, forcing the brushes through the tubes where they are caught in the basket at the far end of the tube. The cooling water flow is again reversed to its normal flow direction. The brush returns to the cage at the discharge end of the tube. Because of the relative simplicity of the system, it may be used on all sizes of heat exchangers provided the cooling water flow can be reversed.

TABLE 1.1

EROSION LIMITS: MAXIMUM DESIGN FLUID VELOCITIES FOR FLOW INSIDE TUBES

Water

Low carbon steel	10 ft/sec
Stainless steel	15 ft/sec
Aluminum	6 ft/sec
Copper	6 ft/sec
90-10 Cupronickel	10 ft/sec
70-30 Cupronickel	15 ft/sec
Titanium	> 50 ft/sec

Other Liquids

$$[\text{Allowable velocity for given liquid}] = [\text{Allowable velocity for water}]\left[\frac{Density\ of\ Water}{Density\ of\ given\ liquid}\right]^{1/2}$$

Gases and Dry Vapors

The maximum design velocity for steel tubing may be estimated from:

$$V,\ ft/\sec = \frac{1800}{\sqrt{[(Absolute\ \ pressure\ \ in\ \ psia)(Molecular\ \ weight)]}}$$

Allowable velocities for other metals may be taken to be in the same ratio as for water.

TABLE 1.2

FOULING RESISTANCES FOR TYPICAL PROCESS APPLICATIONS

Adapted from Standards of Tubular Exchanger Manufacturers Association

The values given in this table are typical of the situations described, but allowances must be made for substantial variations from one case to the next. The resistances are referenced to the surface area in contact with the fluid and are to be used in connection with equations of the form of (1.19) and (1.20).

The units on the resistances are $ft^2°F/Btu$.

I. Water

Temperature of Heating Medium	Up to 240°F		240°F - 400°F*	
Temperature of Water	125°F or less		Over 125°F	
Types of Water	Water Velocity ft/sec		Water Velocity ft/sec	
	3 ft and less	Over 3 ft	3 ft and less	Over 3 ft
Sea Water	0.005	0.001	0.003	0.002
Brackish Water	0.002	0.001	0.003	0.002
Cooling Tower and Artificial Spray Pond:				
Treated Makeup	0.001	0.001	0.002	0.002
Untreated	0.003	0.003	0.005	0.004
City or Well Water (Such as				
Great Lakes)	0.001	0.001	0.002	0.002
Great Lakes	0.001	0.001	0.002	0.002
River Water:				
Minimum	0.002	0.001	0.003	0.002
Mississippi	0.003	0.002	0.004	0.003
Delaware, Schuylkill	0.003	0.002	0.004	0.003
East River and New York	0.003	0.002	0.004	0.003
Bay				
Chicago Sanitary Canal	0.008	0.006	0.01	0.008
Muddy or Silty	0.003	0.003	0.005	0.005
Hard (Over 15 grains/gal)	0.003	0.003	0.005	0.005
Engine Jacket	0.001	0.001	0.001	0.001
Distilled	0.0005	0.0005	0.0005	0.0005
Treated Boiler Feedwater	0.001	0.0005	0.001	0.001
Boiler Blowdown	0.002	0.002	0.002	0.002

TABLE 1.2 (continued)

*Ratings in columns 3 and 4 are based on a temperature of the heating medium of 240°F-400°F. If the heating medium temperature is over 400°F and the cooling medium is known to scale, these ratings should be modified accordingly.

II. General Industrial Fluids

Gases and Vapors	
Manufactured Gas	.01
Engine Exhaust Gas	.01
Steam (non-oil bearing)	.0005
Exhaust Steam (oil bearing)	.001
Refrigerant Vapors (oil bearing)	.002
Compressed Air	.002
Industrial Organic Heat Transfer Media	.001
Liquids	
Refrigerant Liquids	.001
Hydraulic Fluid	.001
Industrial Organic Heat Transfer Media	.001
Molten Heat Transfer Salts	.0005
Fuel Oil	.005
Transformer Oil	.001
Engine Lube Oil	.001
Quench Oil	.004

III. Chemical Process Streams

Gases and Vapors	
Acid Gas	.001
Solvent Vapors	.001
Stable Overhead Products	.001
Liquids	
MEA & DEA Solutions	.002
DEG & TEG Solutions	.002
Stable Side Draw and Bottom Product	.001
Caustic Solutions	.002
Vegetable Oils	.003

IV. Natural Gas/Gasoline Process Streams

Gases and Vapors	
Natural Gas	.001
Overhead Products	.001
Liquids	
Lean Oil	.002
Rich Oil	.001
Natural Gasoline & Liquified Petroleum Gases	.001

TABLE 1.2 (continued)

V. Oil Refinery Streams

Crude & Vacuum Unit Gases and Vapors	
Atmospheric Tower Overhead Vapors	.001
Light Naphthas	.001
Vacuum Overhead Vapors	.002

Crude Oil

	0-199 F			0-199 F		
	Velocity in ft./sec			Velocity in ft./sec		
	Under 2 ft	2 – 4 ft	4 ft and over	Under 2 ft	2 – 4 ft	4 ft and over
Dry	0.003	0.002	0.002	0.003	0.002	0.002
Salt*	0.003	0.002	0.002	0.005	0.004	0.004

	300-399 F			400-499 F		
	Velocity in ft./sec			Velocity in ft./sec		
	Under 2 ft	2 – 4 ft	4 ft and over	Under 2 ft	2 – 4 ft	4 ft and over
Dry	0.004	0.003	0.002	0.005	0.004	0.003
Salt*	0.006	0.005	0.004	0.007	0.006	0.005

*Normally desalted below this temperature range. (Asterisk to apply to 200-299*F, 300-4990F, 500'F and over.)

Gasoline	.001
Naphtha & Light Distillates	.001
Kerosene	.001
Light Gas Oil	.002
Heavy Gas Oil	.003
Heavy Fuel Oils	.005
Asphalt & Residuum	.010

TABLE 1.2 (continued)

Cracking & Coking Unit Streams	
Overhead Vapors	.002
Light Cycle Oil	.002
Heavy Cycle Oil	.003
Light Coker Gas Oil	.003
Heavy Coker Gas Oil	.004
Bottoms Slurry Oil (4 ½ ft/sec minimum)	.003
Light Liquid Products	.002
Catalytic Reforming, Hydrocracking, & Hydrodesulfurization Streams	
Reformer Charge	.002
Reformer Effluent	.001
Hydrocracker Charge & Effluent**	.002
Recycle Gas	.001
Hydrodesulfurization Charge & Effluent**	.002
Overhead Vapors	.001
Liquid Product over 50* A.P.I.	.001
Liquid Product 30'-50* A.P.I.	.002

**Depending on charge characteristics and storage history, charge resistance may be many times this value.

Light Ends Processing Streams	
Overhead Vapors & Gases	.001
Liquid Products	.001
Absorption Oils	.002
Alkylation Trace Acid Streams	.003
Reboiler Streams	.003
Lube Oil Processing Streams	.003
Feed Stock	.002
Solvent Feed Mix	.002
Solvent	.001
Extract*	.003
Raffinate	.001
Asphalt	.005
Wax Slurries*	003
Refined Lube Oil	.001

*Precautions must be taken to prevent wax deposition on cold tube walls.

Nomenclature

Since the wide variety of geometries and correlation requires a bewildering variety of subscripts and multiple usages, a detailed listing and, where necessary, description of the specific symbols used in this section follows each major symbol definition.

A	Surface area for heat transfer. A_o and A_i are the corresponding values for the outside and inside surface, respectively, and A_m denotes the logarithmic mean of A_o and A_i. A^* is a generalized area, corresponding to U^*. A_{fin} is the total heat transfer area for the fins on a tube, A_{root} is the area of the bare tube remaining between the fins, and A_{eq} is the combination of these two values defined by Eq. (1.38).	ft^2
C_p, c_p	Specific heat of the flowing fluid. The capitalized symbol usually refers to the hot fluid and the lower case to the cold fluid, but they may instead refer to fluid outside and inside the heat transfer surfaces, respectively.	Btu/lb°F
d	Diameter of a tube. d_o and d_i are the outside and inside diameters, respectively, and dm denotes the logarithmic mean. d_r is the root diameter of a finned tube: the distance from the tube axis to the base of the fins. d_{eq} denotes an equivalent diameter defined for a non-circular conduit; there are numerous such definitions and they will be individually given and explained where they are used.	in. or ft.
E_w	Weighted fin efficiency as defined by Eq. (1.42).	dimensionless
F	Correction factor for the logarithmic mean temperature difference (LMTD) to make it applicable to heat exchangers in which the flow is not entirely counter-current or co-current.	dimensionless
G	Mass velocity (mass flow rate of fluid per unit cross-sectional area for flow). G_v and G_ℓ are superficial mass velocities for vapor and liquid respectively; “superficial" means the values are calculated as if the given fluid were flowing alone, using the entire cross-sectional area.	lb_m/ft^2 hr
g_c	Gravitational conversion constant.	4.17×10^8 lb_m ft/lb_f hr^2
H	Fin height from root to tip.	in. or ft.
h	Film heat transfer coefficient. h_o and h_i are the values for the outside and the inside of the heat transfer surface, respectively. h_f is an equivalent heat transfer coefficient for any fouling that may be present, equal to the reciprocal of the fouling resistance.	Btu/hr ft^2°F
k	Thermal conductivity of a material. k_w refers to the wall material, while k_o and k_i refer to the fluids on the outside and inside of the heat transfer surface, respectively.	Btu/hr ft^2°F
L	Length, usually of a tube.	ft.
MTD	Mean temperature difference, defined by Eq. (1.24).	°F

m	Quantity characterizing fin geometry and properties, defined by Eq. (1.34).	dimensionless
P	Parameter in MTD calculations, defined by Eq. (1.31b).	dimensionless
Q	Heat flow.	Btu/hr
q	Heat flux (Heat flow per unit area of heat transfer surface). q_s is the sensible heat flux and q_λ is the latent heat flux respectively, in the Colburn-Drew analysis for condensing binary mixtures.	Btu/hr ft^2
R	Parameter in MTD calculations, defined by Eq. (1.31a).	dimensionless
R_f	Resistance to heat transfer due to fouling. R_{fo} and R_{fi} are fouling resistances on the outside and inside of a heat transfer surface, respectively.	hr ft^2 ^oF/Btu
R_{fin}	Resistance to heat transfer in a fin, given by Eq. (1.49).	hr ft^2°F/Btu
Re	Reynolds number for flow through or past a surface. There are many different definitions depending upon the particular geometry involved. Eq. (1.9) is the definition for flow inside tubes.	dimensionless
r	Radius of a tube. r_o and r_i are the outside and inside radii respectively; r_m is the logarithmic mean of r_o and r_i. r' is the outside radius of the inner tube and the inside radius of the outer tube in a bimetallic tube.	in. or ft.
T, t	Temperatures. Both symbols (usually subscripted) are used more or less interchangeably and for this reason every temperature must be carefully defined for each particular discussion. Usually, capital letters refer to the hot fluid and lower case to the cold fluid, but sometimes capitals refer to the outside fluid and lower case to the inside. T_i and t_i usually refer to the inlet temperatures of the two streams and T_o and t_o to the outlet temperatures.	°F
T_{abs}	Absolute temperature of a surface, used only in radiation calculations.	°R
U	Overall heat transfer coefficient for heat transfer between two fluids separated by a surface. U^* is a generalized value defined by Eq. (1. 17). U_o and U_i are values referenced to the outside and inside surface areas, respectively.	Btu/hr ft^2°F
V	Mean velocity of a fluid flowing in a conduit. V_{max} is the maximum velocity of flow, which occurs at the centerline of a tube. For tube banks, V_{max} is calculated as the mean velocity at the point where the tubes are closest together.	ft/sec
W, w	Mass flow rates of the fluids in a heat exchanger. W and C_p are always associated with one stream, and w and C_p with the other.	lb_m/hr
x	Usually, a length variable, especially when it appears as Δx_w, the wall thickness of a tube. But see further.	ft.

x	For two-phase vapor-liquid flows, the quality of the flow: the weight fraction of the flow that is vapor.	dimensionless
Y	Thickness of a fin.	in. or ft.
y	Fraction of a component in the vapor phase. Y_v is the composition in the bulk vapor phase and Y_i the composition at the interface.	dimensionless
Z	Fraction of a component in the liquid phase. Z_ℓ is the composition in the bulk liquid phase and Z_i the composition at the interface.	dimensionless

GREEK

ε	Emissivity for radiation from a surface.	dimensionless
Λ	Modified Baker parameter for two-phase flows in a horizontal tube. $\Lambda = \sqrt{(\rho_\ell \rho_v)}$	Lb_m/ft^3
λ	Latent heat of vaporization for a liquid.	Btu/lb_m
μ	Viscosity of a fluid. μ_ℓ, refers to liquid, μ_v to vapor.	$lb_m/ft\ hr$
ρ	Density of a fluid. ρ_ℓ refers to liquid density, ρ_v to vapor density.	lb_m/ft^3
σ	Surface tension of a liquid. Also, in radiation, the Stefan-Boltzmann constant.	dyne/cm 0.173×10^{-8} Btu/hr $ft^2(^oR)^4$
Φ	Fin efficiency: the ratio of the total heat transferred from a real fin to that transferred if the fin were isothermal at its base temperature.	dimensionless
Ψ	Modified Baker parameter for two-phase flows in a horizontal tube. $\Psi = \mu_\ell^{1/3} / \sigma \rho_\ell^{2/3}$	$(ft^{5/3}cm/lb_m^{1/3}\ hr^{1/3}dyne)$

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