

FOULING OF HEAT EXCHANGER SURFACES: GENERAL PRINCIPLES

1. NOTATION AND UNITS

Two self-consistent sets of units, SI and British, are given.

		Units	
		SI	British
A	area	m^2	ft^2
E	activation energy	J	Btu
C	excess concentration at surface	kg/m^3	lb/ft^3
$C_1, C_2, C_3, C_4, C_5, C_6$	constants in Equations (A1.1) to (A6.1)	—	—
c	concentration	kg/m^3	lb/ft^3
D_r	coefficient of diffusion	m^2/s	ft^2/hr
E	Activation energy	J/kmol	Btu/lbmol
F	fraction of surface covered	—	—
h_1, h_2	fluid heat transfer coefficients on the hot and cold sides respectively	W/m^2	$\text{Btu}/\text{ft}^2 \text{h } ^\circ\text{F}$
K_d	mass transfer coefficient	s/m	h/ft
K_r	reaction rate constant	$\text{l}/\text{s } c^{(1-n)}$	$\text{l}/\text{h } c^{(1-n)}$
k	thermal conductivity of dividing wall	$\text{W}/\text{m K}$	$\text{Btu}/\text{ft h } ^\circ\text{F}$
l	thickness of dividing wall	m	ft
M	number of molecules coming in contact with a surface in unit time	s^{-1}	h^{-1}
m	constant	—	—
N	mass flux	$\text{kg}/\text{s m}^2$	$\text{lb}/\text{h ft}^2$
n	order of reaction	—	—
R	universal gas constant	J/kmol K (8314)	Btu/lbmol $^\circ\text{F}$ (1.986)
R_1, R_2	fouling or dirt resistances on hot and cold sides respectively	$\text{m}^2 \text{K}/\text{W}$	$\text{ft}^2 \text{h } ^\circ\text{F}/\text{Btu}$

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		<i>Units</i>	
		<i>SI</i>	<i>British</i>
R_B	deposit strength	depends on the final form of Equation (A6.1).	
S	ratio of number of molecules adhering to a surface to number of molecules striking surface	—	—
T	absolute temperature	K	°F
t	time	s	h
U_C	overall heat transfer coefficient for clean conditions	W/m ² K	Btu/ft ² h° F
U_D	overall heat transfer coefficient for dirty conditions	W/m ² K	Btu/ft ² h° F
w_r	rate of evaporation	kg/s	lb/h
x	foulant thickness	m	ft
y	distance normal to surface	m	ft
β	constant	—	—
ε	coefficient of eddy diffusivity	m ² /s	ft ² /h
ρ	density	kg/m ³	lb/ft ³
σ	surface tension	N/m	lbf/ft
τ	shear stress at surface	Nm ² (Pa)	lbf/ft ²
ϕ_D, ϕ_R	deposit and removal rate factors respectively	kg/m ² s	lb/ft ² h

Extra subscripts

b	bulk flow
f	fluid
s	surface or solid or saturated
t	at time t

2. PURPOSE AND SCOPE OF THIS ITEM

Fouling of heat exchangers produces inefficiencies in plant operation, including reduced heat recovery, additional energy requirements and lost production due to down-time for cleaning and maintenance. Due to uncertainties in the allowance required for fouling, excess heat transfer surface is incorporated in the equipment as a margin of safety. These factors contribute to the considerable sums of money which industry is obliged to spend each year to counteract the effects of fouling. There are, however, design and operational techniques which can reduce the extent or rate of build-up of fouling deposits but the success of these in any particular application will depend upon an understanding of the operative fouling mechanism.

This Data Item is the first of a series dealing with the fouling of heat transfer surfaces. It covers basic concepts and the consequences of the accumulation of dirt in heat exchangers. The mechanisms of fouling in different circumstances are briefly discussed.

The effects of the variables which influence the fouling process are described, leading to systematic guidance on the choice, design and operation of heat exchangers. Practical advice on living with fouling is also given.

3. INTRODUCTION

Fouling is any process which results in the accumulation of dirt or the growth of deposits on plant surfaces. In the operation of heat exchangers this is particularly undesirable since it reduces exchanger effectiveness and often leads to other operating difficulties such as high pressure drop or reduced flow rates.

Fouling is one of the least understood phenomena associated with the chemical and process industries. The need for more knowledge was revealed in a survey conducted in 1969¹. Since that time, following the steep rise in energy costs and the need for industries to be more competitive, there has been a more systematic approach to understanding fouling. Seldom is the true cost of fouling calculated but three papers^{2 3 4} illustrate the large sums of money spent each year as a direct result of fouling. Although these papers contain data obtained in 1979 the present situation is unlikely to have changed significantly. The paper by van Nostrand *et al*³ estimated annual fouling costs in a typical US refinery as about $\$10 \times 10^6$. A more recent survey⁵ estimates the total annual cost of fouling of heat exchangers in the United States at between $\$3 \times 10^9$ and $\$10 \times 10^9$ per annum.

4. PROBLEMS CAUSED BY FOULING

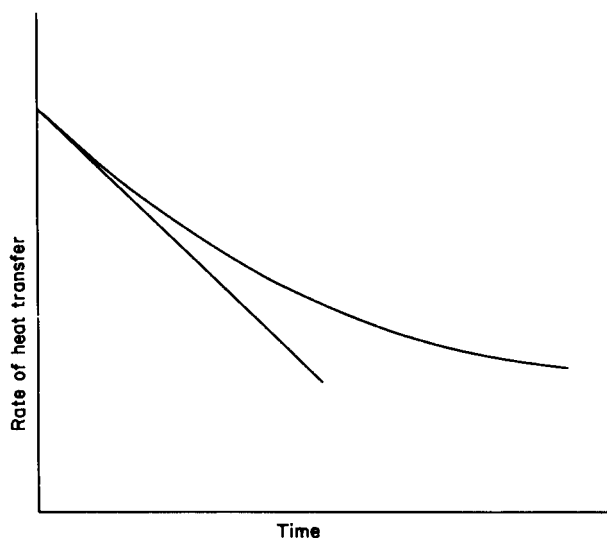
The problems caused by fouling fall into two broad areas: operating difficulties and additional costs.

4.1 Operating Problems

Problems associated with the operation of heat exchangers include reduced heat transfer efficiency and excessive pressure drop.

4.1.1 Heat transfer

The presence of dirt layers on heat transfer surfaces causes a resistance to the flow of heat from the hot fluid to the cold fluid. As operation proceeds, foulant material continues to accumulate in the exchanger and the heat transfer effectiveness is gradually reduced. Two idealised representations, straight line and asymptotic, of the reduction of heat transfer effectiveness with time are shown on Sketch 4.1.



Sketch 4.1 Reduction in rate of heat transfer as fouling progresses

Increased temperatures in the wall separating the two fluids will occur if the heat flux remains constant as the dirt layer accumulates on the cold side. Under extreme conditions this rise in temperature may lead to failure of the wall material.

Poor heat transfer performance of a heat exchanger will affect other parts of the plant in which it is located. For instance, reduced preheat in the feed to a distillation column as a result of a fouled heat exchanger could require increased boil-up in the column to remedy the shortfall in feed temperature, with consequent effects on the distillation efficiency of the column.

4.1.2 Pressure drop

Interest in heat exchanger fouling is usually focused on the limitations imposed by the deposit on the rate of heat transfer in the equipment (as outlined in Section 4.1.1). However, the deposit may cause higher pressure drops or decreased flow rates. Lower flow rate results in a lower heat transfer coefficient. In many industrial situations the pressure drop penalty may be even greater than that due to the lower thermal effectiveness experienced in fouled heat exchangers.

In general, as the deposit develops the area available for flow decreases, so that for a given mass flow rate the velocity of the fluid increases. Substantial increases in pressure drop can occur with modest reductions in flow area since pressure drop varies as the square of the velocity. Pressure drop will be further increased if the deposit has a rougher surface than the unfouled surface.

Flow maldistribution between parallel paths may increase pressure drop. If, for instance, in a shell and tube exchanger, there is maldistribution of fluid between the tubes in the clean condition, different rates of fouling are likely to occur in different tubes. This is likely to aggravate the maldistribution, giving rise to excessive velocities through some tubes and low velocities in others. The overall effect will be increased pressure drop. An estimate of these effects on pressure drop and heat transfer can be made by assuming different numbers of tubes are blocked. If half the tubes are considered inoperative, the pressure drop will be increased by a factor of around four, whereas the associated film heat transfer coefficient will only be doubled for similar conditions. Apart from the additional pumping cost the pumps may not be capable of generating the additional head.

Similar estimates of the effects of shell-side fouling may be made by assuming different reductions of the

flow area between tubes and around baffles and assessing the consequences for pressure drop and heat transfer. The problem may be severe if baffle leakage is restricted or altogether prevented.

Maldistribution of fluid between heat exchangers operating in parallel may also present similar problems to maldistribution between tubes. The true consequences of this situation may not be apparent unless individual exchangers are separately monitored.

Excessive pressure drop through a heat exchanger may mean that it has to be partially bypassed by one or other of the fluid streams in order to maintain production. The changed stream temperatures will have consequences for the effective operation of the remaining equipment in the process.

Because of the sensitivity of pressure drop to fouling, the occurrence of increased pressure drop is often the most effective way of detecting the onset of fouling before it causes a noticeable reduction in heat transfer. For this reason it is good practice to have some permanent means of measuring pressure drop across heat exchange equipment.

4.2 The Cost of Fouling

The total cost of fouling in heat exchange equipment has a number of components.

4.2.1 Additional surface

Allowance for the additional heat transfer resistance due to dirt deposition takes the form of additional heat transfer surface with resultant increased installed cost. Where the extent of the fouling is uncertain, the additional surface can increase capital cost by up to 50%. Incorporation of this additional area, unless carefully considered, may itself accelerate the fouling problem (see Section 8).

In some industries, where continuous operation is vital, a particular heat exchanger may be duplicated, so that when one exchanger has become excessively fouled it can be taken out of operation for cleaning and the second exchanger brought into service to maintain production. Duplication of equipment adds to the capital cost of the plant.

4.2.2 Corrosion

Although corrosion of equipment is a subject in its own right, the presence of corrosion on heat exchanger surfaces is likely to result in problems generally attributed to fouling. For this reason it may be necessary to specify expensive materials of construction to avoid corrosion. Depending upon the severity of the problem and the accompanying choice of material, the capital cost of an exchanger may be many times greater than its equivalent in a material such as carbon steel.

4.2.3 Operation and maintenance

If the fouling problem is not properly appreciated at the design stage, the effects of the subsequent fouling during operation may result in additional down-time and maintenance costs, over and above those anticipated in the original specification. The cost penalties for interrupted production and maintenance labour may be high unless a duplicate heat exchanger is installed. For instance, in one installation the feed preheater to a distillation column, exchanging heat with the bottom product, had to be stripped down and cleaned once a week whereas the original specification called for cleaning once every six months! In addition to the cost of maintenance, repeated dismantling and reassembly led to a rapid deterioration of the integrity of the equipment.

4.2.4 Loss of production

In many instances, where the fouling potential of the particular fluid stream is not properly recognised or inadequately allowed for in the design, frequent cleaning may be required. Unscheduled shut-down, possibly at short notice, may have a significant effect on production schedules and reduce overall output. In some instances it may be possible to bypass the particular heat exchanger while production is maintained but in others the heat exchanger will be a vital part of the plant.

4.2.5 Cleaning

The cleaning of heat exchangers involves labour costs but also may require special equipment, particularly with chemical cleaning (see Sections 8.8.1 and 8.8.2). Additional circuitry involving pumps and tanks may be required, chemicals have to be purchased and the cleaning process may produce an effluent which will require treatment before disposal. These costs can be heavy. More conventional cleaning processes, such as water jetting or rodding, will also require capital outlay in addition to labour charges.

4.2.6 Additional pumping power

One of the major problems resulting from fouling is the increased pressure drop experienced across heat exchangers (see Section 4.1.2). Additional pumping power will be required to maintain throughput under fouled conditions in comparison with operation in the clean condition whilst reduced heat transfer may increase the overall energy requirement for the process. A shortfall in energy recovery will have to be made up by increased use of purchased primary energy.

4.2.7 Utilisation of energy

In some processes there is an opportunity to utilise waste heat. For instance in domestic refuse incineration, where the heat produced by combustion may be used to raise steam which is subsequently exported. The income from the sale of the steam offsets the costs of collection, incineration and the final disposal of the ash and other non-combustible material. The gradual fouling of the steam-raising exchangers will cause a gradual reduction in the amount of steam produced and therefore a reduced income.

4.2.8 Use of antifoulants

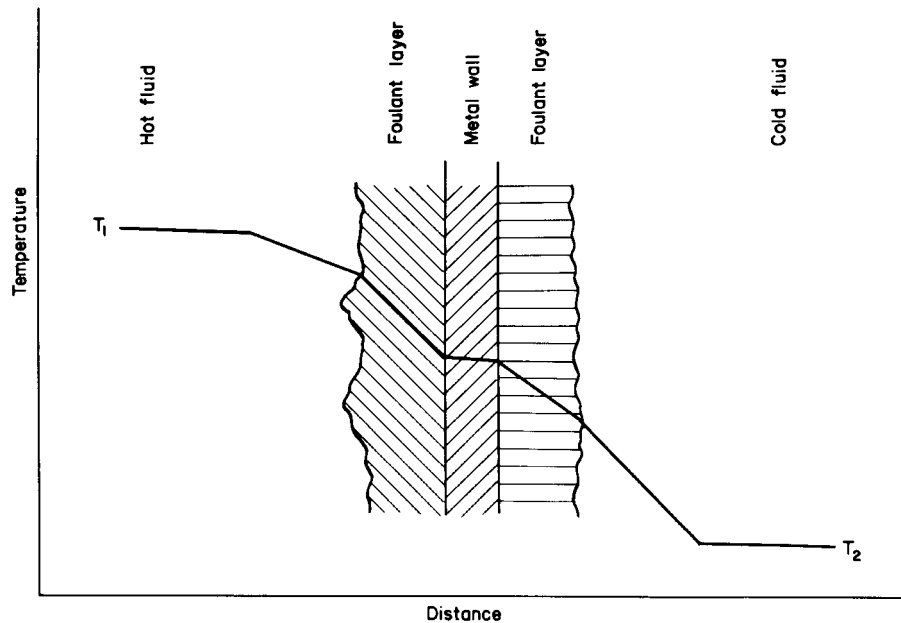
It is possible to offset the effects of fouling by adding chemical inhibitors or antifoulants to the stream responsible for the fouling (see Sections 8.6.1.3 to 8.6.2.3). Extra expenditure associated with the capital cost of the dosing equipment and the use of chemicals will occur. The use of antifoulants should result in cost savings for particular applications, otherwise it will not be appropriate. Van Nostrand *et al*³ show quite conclusively, for the crude unit in a typical petroleum refinery, that the use of antifoulant chemicals is justified. The data in Table 4.1 demonstrate the cost of antifoulants and also show the savings attained in the crude unit for a typical 100,000 barrels per day petroleum refinery and the order of the costs associated with those aspects discussed in Sections 4.2.3 to 4.2.7.

TABLE 4.1 Economic Effects of the use of Antifoulants on the Crude Unit Fouling-Related Expenses in Thousands of US Dollars³

	Energy	Throughput	Cleaning	Antifoulant	Total
Without antifoulant	1,020	3,730	35	–	4,785
With antifoulant	265	2,050	15	155	2,485
Saving	+755	+1,680	+20	–155	+2,300

5. FOULING RESISTANCE

The accumulation of dirt on the surface of a heat exchanger increases the overall thermal resistance to heat transfer between the fluid streams. The individual resistances are illustrated in Sketch 5.1 and include the resistance of the solid barrier separating the two fluids, the resistance of the foulant layer on either side of the barrier and the film resistances of the fluid in contact with the dirt.



Sketch 5.1 Idealised temperature distribution in the region of a fouled heat exchanger surface

The total resistance to heat flow across a clean heat exchanger is

$$\frac{1}{U_C} = \frac{1}{h_1} + \frac{1}{h_2} + \frac{l}{k} \quad (5.1)$$

where U_C is the overall heat transfer coefficient for clean conditions,
 h_1 and h_2 are the individual heat transfer coefficients for the hot and cold fluids either side of the dividing wall,
 l is the thickness of dividing wall,
 k is the thermal conductivity of the wall material.

Under operating conditions there will be an additional resistance to heat transfer due to the dirt on either side of the heat transfer surface.

$$\frac{1}{U_D} = \frac{1}{h_1} + \frac{1}{h_2} + \frac{l}{k} + R_1 + R_2 \quad (5.2)$$

where U_D is the overall heat transfer coefficient for dirty conditions.
 R_1 and R_2 are the fouling resistances on the surfaces exposed to the two fluids, so

$$\frac{1}{U_D} = \frac{1}{U_C} + R_1 + R_2. \quad (5.3)$$

In many older publications R_1 and R_2 are termed fouling or dirt factors, but these terms are misleading. The more consistent term, fouling resistance, will therefore be used throughout this Data Item.

The magnitude of the fouling resistance relative to the individual fluid heat transfer coefficients may have a marked influence on the size of a heat exchanger, as exemplified by the following calculations.

For a heat exchanger transferring heat from one liquid to another with individual heat transfers, coefficients of 2450 and 3940 W/m²K and a total fouling resistance ($R_1 + R_2$) of 0.0003 m² K/W, the total resistance is approximately

$$\begin{aligned} & \frac{1}{2450} + \frac{1}{3940} + 0.0003 \text{ m}^2 \text{ K/W} \\ &= 0.00041 + 0.00025 + 0.0003 \text{ m}^2 \text{ K/W} \\ &= 0.00096 \text{ m}^2 \text{ K/W}. \end{aligned}$$

For the given operating condition of thermal load and temperature difference, this fouling resistance represents an increase in the required heat exchanger area over and above clean conditions of

$$\frac{0.0003}{0.00066} \times 100\% = 45.5\%.$$

However, if the same fouling resistance is used for a gas to gas heat exchanger with individual heat transfer coefficients of 34.1 and 86.2 W/m² K the total resistance is

$$\begin{aligned} & \frac{1}{34.1} + \frac{1}{86.2} + 0.0003 \text{ m}^2 \text{ K/W} \\ &= 0.0293 + 0.0116 + 0.0003 \text{ m}^2 \text{ K/W} \\ &= 0.0412 \text{ m}^2 \text{ K/W}. \end{aligned}$$

For the given operating condition of thermal load and temperature difference this now represents an increase in the required heat exchanger area over and above clean conditions of

$$\frac{0.0003}{0.0409} \times 100\% = 0.73\%.$$

For the liquid/liquid exchanger the selected fouling resistance requires a considerable increase in the surface area in comparison with clean conditions and hence substantial extra capital cost. The same fouling resistance for a gas/gas heat exchanger represents negligible additional capital cost.

Considerable research effort has gone into the development of correlations suitable for estimating individual film heat transfer coefficients from which a reasonable estimate of U_C may be made. No such correlations exist for estimating fouling resistances. Faced with a potential fouling problem the designer of heat exchange equipment is forced to use published data on fouling resistances^{6,7}. Even with experience, unless conditions in the new design are identical to those under which the experience was obtained, there is a very real likelihood that gross errors may be introduced; the fouling allowance is either too large and leads to overdesign or, worse, the allowance is inadequate for the proposed heat exchanger duty. As discussed in Section 4.2, and quite apart from the capital cost considerations, the lack of appreciation of the true nature of the fouling problem may lead to additional operating costs associated with cleaning, maintenance and energy waste.

The extent of fouling in a heat exchanger varies with time and the condition of the fluid which in turn may result from changes in the operating conditions of the particular process. Equations (5.1) and (5.3) are statements of steady state conditions whereas the fouling process must relate to a transient condition.

When a clean heat exchanger is put on stream, the conditions exemplified by Equations (5.1) to (5.3) do not suddenly occur; a finite time, typically several weeks, will elapse before the full fouling resistances have been attained. Thereafter the fouling resistance may remain constant or, more usually, continue to increase. A clean heat exchanger will over-perform if a fouling factor has been allowed for in the design. Such a condition could lead to operating difficulties. For instance if the exchanger duty is for cooling waxy hydrocarbons, the effectiveness of the exchanger may lead to wax deposits which, if the anticipated fouling were present, would not occur. The over-performance of such an exchanger can be adjusted by the use of a bypass. The reduced velocity which follows from this procedure could accelerate the fouling (see Section 7.2) and, as a result, the final fouling may be worse than that originally estimated. Thus, if the control using the bypass results in a higher wall temperature the deposit may, through the effects of temperature, become hard and tenacious and difficult to remove even when the velocity is restored to design conditions. Had design conditions been maintained from start-up, the deposit, because of the lower surface temperature, would have been soft and kept at a reasonable thickness by the effects of the higher velocity (see Sections 7.1 and 7.2).

The film heat transfer coefficient on each side of the barrier between the fluids may be modified in two ways by the growth of dirt layers.

- (i) As the dirt layer builds up the area available for flow is reduced which, for a maintained flow rate, has the effect of increasing velocity.
- (ii) The dirt layer is likely to be rougher than the original heat transfer surface.

Both these effects will increase the film heat transfer coefficient, *i.e.* reduce the effective heat transfer resistance.

The effects may be summarised as

$$\left\{ \begin{array}{c} \text{Change in} \\ \text{overall heat} \\ \text{transfer} \\ \text{coefficient} \end{array} \right\} = f \left\{ \left\{ \begin{array}{c} \text{Change due to} \\ \text{the thermal} \\ \text{resistance of} \\ \text{the foulant} \\ \text{layer} \end{array} \right\}, \left\{ \begin{array}{c} \text{Change due to} \\ \text{the roughness} \\ \text{of the foulant} \\ \text{layer} \end{array} \right\}, \left\{ \begin{array}{c} \text{Change due to the} \\ \text{change in velocity} \\ \text{resulting from the} \\ \text{changed flow area} \end{array} \right\} \right\}$$

This expression is usually applied to the total heat exchanger surface but, strictly, it is only applicable to local conditions.

In view of the difficulties associated with the time dependence of the magnitude of the fouling factor it is usually important to assess effects at the design stage. The temperature distribution across the interfaces, and the final temperatures of the fluid streams, may be calculated for different fouling resistances from zero up to the final value expected. By such calculations it may be possible to anticipate some of the effects associated with the developing foulant layer.

6. FOULING PHENOMENA

The underlying mechanism by which a surface becomes fouled under operating conditions is more fully described in Section 9 but may be generally regarded as consisting of three stages.

- (i) The foulant or the agents which contribute to the production of the dirt layer (for example, chemical reactants or micro-organisms) approach the solid surface from the bulk fluid across the boundary layer.
- (ii) Once in the region of the fluid/surface interface, and depending upon the nature of the material involved, the foulant or fouling agents will be subject to interfacial forces and conditions associated with the flow over surfaces. The mode of heat transfer, boiling for example, may also impose special conditions at the surface which modify the surface phenomena.
- (iii) Once deposited on the surface, the material may be subject to removal forces which may compact or weaken the deposit.

Fouling can occur under static conditions as well as under operating conditions. If a heat exchanger is left full of process fluid during a shut-down it is possible that deposits will form on the surface that may be quite different from those experienced in service. A static condition may lead to accelerated corrosion fouling. More information is given in Sections 8.6.1.1 and 8.6.2.3.

The mechanisms by which surfaces become fouled under operating conditions may be classified according to the underlying process which gives rise to deposition. In particular situations, fouling is unlikely to be exclusively due to one mechanism but often one mechanism will be dominant. The mechanisms are summarised in the following sections.

6.1 Crystallisation

Before crystallisation can occur, a supersaturated solution of the depositing species must be present near the solid surface. Cooling a saturated solution containing a salt or salts with normal solubility characteristics will generally result in supersaturation and deposition on the cold surface. On the other hand, supersaturation and deposition may occur when a solution containing inverse solubility salts is heated. Crystallisation deposits can become very thick and in some instances blocked tubes have been reported.

A common example of crystallisation fouling is the deposition of the sparingly soluble hardness salts from water which may be characterised by a hard, difficult to remove, amorphous scale varying from white to grey in colour. In other instances of crystallisation of hardness salts the deposit is softer and more easily removed. The deposit may be more deeply coloured if the crystallisation fouling is accompanied by another mechanism, the deposition of particulate iron oxide, for example. The treatment of boiler feed water is primarily aimed at preventing the deposition of inverse solubility calcium and magnesium salts.

6.2 Particulate Deposition

Suspended particulate matter is common in many industrial fluid streams. In river water, particles of clay and mineral matter are carried into the river by run-off and the subsequent concentration can be high or low depending on local rainfall and ground conditions. The suspended particles, when river water is used for cooling, may be the cause of fouling of heat exchanger surfaces. In combustion processes, particulate matter derived from the mineral content of the fuel, and possibly soot particles produced by incomplete combustion, may be carried forward in the flue gas stream. Such particulate matter is a potential heat exchanger foulant. In boiler plant, fine suspensions of black magnetite or red-brown haematite particles may circulate with the boiler feed water. These particles are usually small in size and easily removed unless

some other fouling mechanism is operative which cements them to the surface. Particles produced by combustion processes in high temperature gas streams may be molten and may solidify on contact with a cooler heat transfer surface, giving rise to hard deposits which are difficult to remove.

The wide range of appearance and character of particulate deposits likely to be encountered in industrial systems can make the true origin of the particulate material difficult to establish. There are situations, however, such as boiler plant economisers where the fine black powder on the inside heat transfer surfaces is undoubtedly made up of magnetite particles.

6.3 Biological Growth

Micro-organisms originating from a process stream can be deposited and grow on heat transfer surfaces. Although fouling due to the presence of micro-organisms may occur in any suitable liquid stream, it is generally associated with cooling water, particularly open recirculation or once-through systems. Because such fouling involves living matter, the temperature range over which it can exist to any extent is limited, typically, to between 0 and 90°C. The highest incidence occurs roughly in the range 20 to 50°C. The slime layer is characterised by gelatinous hydrated material and varies in colour from almost transparent to dark green. The colour may also reflect any associated fouling such as particulate or corrosion. Another common feature of biological slime layers is that they may be filamentous and the surface may be very uneven. In general the slime is readily deformable but often the layers actually attached to heat exchanger surfaces are difficult to remove. Very thick layers of biological material are possible under certain conditions. In cooling water systems particularly, the presence of a biofilm may promote other fouling processes such as corrosion. Under a slime layer it is quite common to find pitting corrosion.

6.4 Chemical Reaction at a Fluid/Surface Interface

The deposit resulting from one or more chemical reactions between reactants contained in a flowing fluid may lead to fouling. Deposition involving chemical reaction is possible in many process streams. Examples include carbon deposition from cracking reactions occurring on the heat transfer surfaces of organic liquid vaporisers and the polymerisation of process monomer in process stream coolers. Deposits derived from chemical reactions can have a wide range of properties, from those of a loose powdery deposit of carbon to a hard, difficult to remove, layer associated with polymer formation. Chemical reaction fouling can occur over a wide range of temperatures but usually it is more pronounced at higher temperatures. Other fouling mechanisms may accompany chemical reaction fouling. The presence of the foulant layer may promote corrosion at the foulant/metal interface, particularly if the chemical foulant restricts the formation of a protective oxide layer. Polymer particles or macromolecules in suspension may be readily incorporated in the polymer being formed on the heat exchanger surface by polymerisation reactions.

6.5 Corrosion

The effects of corrosion of the heat exchange surface are also a fouling phenomenon. The origin of the corrosion may be from the process fluid itself, a constituent of it or even trace materials carried by the stream. In a sense, corrosion fouling may be regarded as reaction fouling with the chemical process involving the surface rather than just the components in the process stream. Corrosion may be accelerated because any protective oxide layer on the surface is difficult to sustain under the conditions prevailing at the interface. It is difficult to give generalised comments on the nature and characteristics of corrosion deposits since these will vary as widely as corrosion technology itself. The presence of corrosion may be indicated if the foulant layer appears to be, or to have been, part of the metal surface, or if there is an uneven metal surface below the layer.

6.6 Freezing

The deposition of a layer of solid material derived from the process fluid itself through cooling down to the freezing point reduces heat transfer. The deposition of wax from waxy hydrocarbons by cooling is often referred to as freezing but this might be more accurately classified as crystallisation fouling. Better examples would be the formation of ice in a heat exchanger during the production of chilled water or deposits formed in margarine coolers or phenol coolers. As a rule freezing fouling will occur at temperatures well below 100°C and may require temperatures close to, or below, ambient.

6.7 Mixed Fouling

Frequently two or more mechanisms may be present. Heat exchangers through which cooling water passes may be subject to biofouling, corrosion and particulate deposition. Chemical reaction fouling may be accompanied by particulate deposition and corrosion whilst changes in operating conditions, either of the heat exchanger itself or in the process plant of which it forms part, may change the nature of the fouling.

The development of leaks between the two fluid streams may also affect fouling characteristics. For example, a leak of organic liquid being cooled by biologically active cooling water may act as a biocide and reduce the incidence of biofouling derived from the cooling water.

7. GENERAL VARIABLES AFFECTING THE FOULING PROCESS

Three important variables affect the fouling process: temperature, fluid velocity and concentration of the foulant or the constituents contributing to the fouling. Furthermore, the direction of heat flux will change the temperature distribution as discussed in the next Section. Some indication of the importance of these parameters is given in the following Sections.

7.1 Temperature

As a rule, low temperatures will:

- (i) reduce the effects of chemical reaction and corrosion; usually these reactions are favoured by higher temperatures,
- (ii) reduce the effects of microbial growth if temperatures are below the optimum for growth of micro-organisms,
- (iii) avoid supersaturation conditions where inverse solubility salts are present in solution.

High temperatures will:

- (i) avoid freezing conditions so that partial solidification of the process stream at the transfer surface does not occur,
- (ii) reduce biological fouling if temperatures are above the optimum for growth of the particular species present in the system,
- (iii) avoid supersaturation conditions where normal solubility salts are present in the system.

Furthermore, temperature may affect the ageing of a foulant layer. The deposit may be hardened and become difficult to remove or, alternatively, become weaker and tend to spall under the influence of temperature

and time.

Deposit fusion may be important under certain high temperature conditions.

If there are large temperature differences within a system, particularly gas systems, thermophoresis, the movement of particles along a temperature gradient, may be a consideration.

The effects of temperature at the surface may possibly be reduced by careful attention to design and, in particular, the magnitude of individual film coefficients. By adjusting fluid velocities at the design stage, the temperature distribution across the fluid/deposit/metal/deposit/fluid interfaces may be changed. Such changes, although restricted by overall design constraints, could reduce the incidence of fouling or lengthen the time intervals between cleaning.

The temperature distribution within an exchanger is important. Unless the distribution is known, any calculations relating to overall coefficients, and hence fouling resistances, may be misleading due to incorrect temperature driving forces being used. The flow rate of cooling water, unlike that of a process stream, may often be chosen to maintain optimum temperatures at the fluid/deposit or fluid/wall interface.

The manner in which a heat exchanger is operated is also relevant since it controls the relationship between fouling resistance and time. Specified inlet temperatures will mean that the extent of the fouling determines the heat flux. The heat flux and any associated temperature distribution could affect further encrustation of the surface if temperature has an influence on the fouling mechanism. If the overall heat flux is maintained constant, local heat flux may be governed by the deposit thickness at the particular point. Such conditions can again affect temperature distribution. If, on the other hand, local heat flux is held constant, as in a nuclear reactor, the temperature will be determined by the boundary conditions.

Boiling will occur if the temperature in the deposit adjacent to the liquid rises sufficiently. The nature of the fouling process will correspondingly change.

Temperature distribution, in addition to its effect on fouling, must also take account of the material of construction. Unexpected excessive metal temperatures, perhaps resulting from the effects of the deposit under constant heat flux conditions, can lead to metal failure.

If temperature changes occur in the deposit, the condition of the deposit may be affected. In some cases this might give rise to a hardening of the deposit through chemical reaction. In food processing soft, easily removable deposits may become cooked onto the surface through the incidence of higher operating temperatures only present for short periods.

Due to the effects of differential contraction, scale may spall from heat exchangers if the temperature of operation is rapidly reduced. Although this removal mechanism may be useful from the point of view of heat exchanger cleanliness, large pieces of deposit may cause blockages downstream from the heat exchanger.

7.2 Velocity

In general, increased velocity increases the shearing action at the deposit/fluid interface. High shear forces may result in foulant removal. For instance, loose soot particles on a heat transfer surface may be readily removed by increased velocities. On the other hand, if the deposition involves mass transfer, higher velocities will increase the diffusion towards the surface in the presence of a concentration gradient. In cooling water systems, where biofouling is occurring, higher velocities may result in enhanced nutrient availability at the surface. In gas side fouling, higher velocities will result in greater particle inertia depending on particle size which, in turn, may accelerate the fouling process.