# FOULING DURING THE USE OF 'FRESH' WATER AS COOLANT- THE DEVELOPMENT OF A 'USER GUIDE'

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## ABSTRACT

IHS ESDU recently published its latest 'User Guide' to fouling in heat exchange systems, for systems with fresh water as the coolant. ESDU 07006 [1] is the third in a group, following the development of the Crude Oil Fouling User Guide [2] issued in 2000 and the Seawater Fouling User Guide [3] issued in 2004.

ESDU 07006 was developed by IHS ESDU over a period of five years under the guidance of the Oil Industry Fouling Working Party, a collaborative team of oil refiners, heat transfer equipment and services suppliers and Universities. It provides designers and operators of cooling water facilities with a practical source of guidance on the occurrence, the mechanisms and the mitigation of fresh water fouling in these systems.

IHS ESDU's Oil Industry Fouling Working Party was formed in recognition of the huge economic and environmental importance of heat exchanger fouling and the potential benefits that can accrue from better understanding of mitigation strategies. Work is now underway on reboiler and FCCU fouling.

The development of the User Guide ESDU 07006 is discussed in this paper and its technical content is summarized.

## INTRODUCTION

Heat exchanger fouling in general is a major economic problem, accounting for 0.25% of the gross national product (GNP) in the highly industrialised countries. In 1999, IHS ESDU formed the industrially led Oil Industry Fouling Working Party of oil company experts and key engineers from companies developing fouling mitigation technologies. Under the guidance of that Working Party, a range of Best Practice User Guides and computer software has been developed. These tools are now being used by plant designers and operators to understand better practical fouling problems and to design or operate equipment in such a way that fouling is minimised.

It was noted that some 70% of the global refining capacity was represented in the IHS ESDU Oil Industry Fouling Working Party member companies. Key milestone for the group were the publication of the ESDU User Guides 'Heat exchanger fouling in the pre-heat train of a crude oil distillation unit' (and associated software) and 'Fouling in cooling systems using seawater'.

Prof. Geoff Hewitt and Prof. Hans Müller-Steinhagen co-authored the crude oil, seawater and fresh water fouling User Guides for IHS ESDU. All work was undertaken under the guidance of IHS ESDU Technical Committees, namely the Oil Industry Fouling Working Party and the Heat Transfer Steering Group. Regular meetings of these Committees were held over the period of development, which provided an opportunity for members to share their knowledge and experience. This information was distilled and subsequently reviewed in interim drafts. As part of the work, a comprehensive study of the literature was undertaken and key findings were augmented by the practical experience of the industrial members. Throughout the new User Guide, over 300 selected source references are carefully noted for all key findings. Within this summary paper, for brevity only a limited number of those original sources are referenced.

This paper follows in part the structure of the fresh cooling water fouling User Guide and summarizes some of its content. Comprehensive detailed design and operating recommendations are provided in ESDU 07006.

### Definition of 'fresh water'

In ESDU 07006, 'fresh water' is defined as natural or treated water with low salt content. In this definition are included the following categories of water: cooling tower water (treated and untreated), water

containing glycol additives, river water, canal water, lake water and certain 'brackish' waters.

Fresh cooling water may be utilised in three different ways [4], as follows:

o In closed systems, where the water is circulated around the circuit without coming into contact with the environment.

o In open recirculating systems, where water is circulated around the circuit to remove heat to the environment.

o In 'once through' systems, where the water is taken directly from the natural source, used for cooling and then discharged back to the source.

Both the 'open' and 'once through' systems present problems for the environment either in terms of thermal or chemical pollution. The use of a closed loop system has many advantages but care has to be taken in operating such systems in order to realise these advantages. All of these types of system are discussed in detail in ESDU 07006.

**Introduction to Heat Exchanger Fouling**

The following sequence of events leading to fouling initiation has been proposed by Epstein [5], mass transport of foulant, formation of deposit and attachment to the surface, release of the deposit, and aging of the deposit on the surface. Epstein developed a 5 by 5 fouling matrix [5], which was adapted by Bohnet [6] to present an assessment of the extent of knowledge in the various elements, as shown in Figure 1. Bohnet [6] concludes that the least known areas are the removal and aging processes; though this assessment was published in 1987, this conclusion is still valid.

In order to quantify the fouling propensity of the heat exchanger, it is normal to define, for tubular exchangers, a *fouling resistance* to heat transfer, commonly referred to industrially as a *fouling factor*. This is derived from the normal definition of overall heat transfer coefficient in Equation [1]:

$$\frac{1}{U_o A_o} = \frac{1}{\alpha_o A_o} + \frac{R_{fo}}{A_o} + \frac{R_w}{A_o} + \frac{R_{fi}}{A_i} + \frac{1}{\alpha_i A_i} \qquad [1]$$

where $U_o$ is the overall heat transfer coefficient based on the outside surface area of the tubes, $\alpha_i$ and $\alpha_o$ are the heat transfer coefficients for the inside and outside of the tubes (based on the inside and outside area $A_i$ and $A_o$), $R_{fi}$ and $R_{fo}$ are the fouling resistances for the inside and outside of the tubes respectively, and $R_w$ is a tube wall thermal resistance.

For tubular exchangers, it is common practice in industry to use fixed values of fouling resistances in design. These values are most usually those listed by the Tubular Exchangers Manufacturers Association (TEMA) [7]. According to the original TEMA reference in 1947, these values allow heat exchangers designed using these fouling resistances to operate for "an acceptable period of time". However, the "fouling factors" given in TEMA tables, though based on the experience of people in industry, were not in general the result of systematic research.

Values recommended by TEMA for fouling resistances for tubular exchangers range from 0.000 088 to 0.000 53 $m^2 K/W$ for various types of fresh water. However, the value of the fouling resistance that applies depends critically on operating conditions. One of the many weaknesses of the TEMA Tables is the fact that they differentiate only very approximately for the effect of water quality, flow velocity and surface temperature. Figures 2 and 3 show the effect of these parameters on cooling water fouling. (Note: The results in Figure 3 are for water with chromate addition. Chromate is now rarely used.) Also, it should be stressed that fouling is a time-dependent phenomenon.

HTRI has developed an empirical prediction procedure for the fouling resistance as a function of these parameters which is proprietary to members of this organisation.

The TEMA fouling resistances are for tubular exchangers and are not applicable to other forms of heat exchanger. For compact exchangers, it is common practice to define a *duty margin,* which is defined as the amount that the surface area has to be increased to account for fouling; for plate exchangers, this might typically be around 20%. For power station condensers, it is common practice to account for fouling using a *cleanliness factor* which is the fraction of the predicted clean surface heat transfer coefficient which occurs after accounting for

fouling; a typical value for this factor for a power condenser might be 0.85.

Factors such as flow velocity and surface temperatures influence fouling in various heat exchanger types in different ways, and ESDU 07006 provides detailed guidance on these effects for tubular exchangers, compact exchangers (including plate-and-frame exchangers), power station condensers, printed circuit exchangers and spiral plate exchangers.

**Cost of cooling water fouling**

Cooling water fouling has great economic significance. In 1981, Curlett and Impagliazzo [8] estimated lifetime costs associated with cooling water fouling of between 6 million and 12 million dollars (US) for a single 600 MW power plant.

Despite the enormous costs associated with heat exchanger fouling, only very limited research has been done to determine accurately the economic penalties due to fouling and to attribute these costs to the various aspects of heat exchanger design and operation. However, reliable knowledge of fouling economics is desirable to evaluate the cost efficiency of various mitigation strategies. The total fouling related costs are composed of various elements, namely capital, energy, maintenance, production loss, increased pumping power and disposal of cleaning materials.

**Types of Fresh Water Fouling**

The prime factor governing fouling in fresh water systems is the composition of the water (that is, the chemical, biological and particulate components dissolved or suspended in the water). The types of fouling encountered in fresh water systems are:

o  Crystalline fouling (scale).

o  Corrosion fouling.

o  Biological fouling.

o  Particulate fouling (sludge)

o  Chemical reaction fouling.

Each of these fouling types is considered in more detail below, and comprehensively in ESDU 07006. Interactions between these fouling mechanisms can be complex, and are also considered in ESDU 07006.

The following factors are of importance in governing fouling by the above mechanisms:

o  Surface temperature. The temperature at the interface between the seawater and the solid surface (*i.e.*, initially the metal but later the foulant layer) is of crucial importance. The influence of temperature varies with the fouling mechanism (see Figure 4).

o  Bulk temperature. The value of the bulk temperature is also important. Again, the influence depends on the mechanism. For instance, biological growth becomes faster as bulk temperature increases from ambient values but at bulk temperatures the organisms may be killed.

o  Water velocity. The relative effects of water velocity on the various fouling mechanisms are illustrated in Figure 5. The influence of velocity varies with the fouling mechanism.

o  Oxygen concentration. Corrosion fouling and biological fouling are strongly affected by the amount of oxygen dissolved in the water.

o  Materials of construction. In a heat exchanger the tube, tube plate and baffle materials play an important role in fouling. Generally, the tube plate material for fresh water systems will be carbon steel in shell-and-tube exchangers and stainless steel in plate-and-frame exchangers.

o  Upstream pipework materials. Corrosion products from upstream pipework may be transferred to the heat exchanger and create a fouling layer.

o  Solids. Solids present in the water may deposit as a result of gravitational or intermolecular forces. For substantial concentrations of large particles a reduction of fouling rate is possible as a result of scouring of the surface by the solids.

o  Surface energy. Surface free energy is a very important parameter in fouling. The poorest

adhesion would be expected to occur on materials such as PTFE which have low surface energy.

o Heat exchanger design. Cooling water fouling and corrosion can be minimised by selection of coolers embodying design features which can combat fouling and corrosion, and using them in a way that maximises these advantages.

**Crystalline fouling**

Crystalline fouling can occur as a result of deposition of crystals formed in the bulk fluid or as result of formation of crystalline deposits on the surface itself. Crystalline deposits formed at the surface ('scales') tend to be hard and difficult to remove. The key drivers for scale formation are concentration, temperature at the heat transfer surface ('skin temperature'), bulk water temperature, pH, the existence of ion pairs capable of forming an insoluble scale compound, heat flux and velocity.

The propensity for scale formation is often expressed in terms of s*caling indices*. Detailed information on calcium carbonate ($CaCO_3$) scaling is presented in ESDU 07006 These include the *Saturation Index*, the *Langelier Saturation Index* and the *Ryznar Stability Index.* Parameters affecting $CaCO_3$ scaling in heat exchangers include the effects of supersaturation, pH, flow velocity and temperature

For calcium sulphate ($CaSO_4$) scaling a *solubility index* is used. Factors influencing $CaSO_4$ scaling are solution concentration, flow velocity, temperature and particulate matter.

An important parameter governing fouling resistances is thermal conductivity of the scales formed, but there are severe limitations to the use of scaling indices for heat exchanger applications. These limitations are discussed in ESDU 07006.

**Corrosion and fouling**

Corrosion and fouling are intimately connected. Not only do surface deposits formed by corrosion form a thermal resistance (*corrosion fouling*), but there exist interrelationships between scale, solids deposition, microbial growth and corrosion which are at the very heart of the fouling problem. Understanding

corrosion is, therefore, very important in understanding fouling. Corrosion is influenced by many factors including temperature, dissolved gases, dissolved solids, pH, water velocity and the composition and nature of the metallic surface being attacked.

There are a number of important types of corrosion which are linked to fouling as follows:

o General or overall corrosion. Here, a uniform attack over the entire exposed area of a surface occurs.

o Pitting corrosion. This is characterised by highly localised corrosion rates with little or no general corrosion in the areas surrounding the pits.

o Galvanic corrosion. This type of corrosion may occur when two dissimilar metals (the 'anode' and 'cathode' respectively) are electrically connected in the presence of an electrolyte.

o Microbiologically-induced corrosion (MIC). Micro-organisms may form colonies on the metal surface, leading to corrosive conditions in that locality.

o Stress-corrosion cracking (SCC). When a stressed metal is exposed to certain types of environment, it may become susceptible to stress-corrosion cracking at stress levels that may be significantly below the yield strength of the material.

o Hydrogen embrittlement. Hydrogen embrittlement involves the ingress of hydrogen into a metallic material with the effect of reduced ductility and load-bearing capacity, which may lead to failure at stresses well below the yield stress of the original material. The hydrogen may be produced by corrosion reactions at the metal surface. The most vulnerable materials are high-strength steels, titanium alloys and aluminium alloys.

o Under-deposit/crevice corrosion. The propensity to corrosion is highly enhanced when concentration of corrosive substances is possible under deposits, and in particular in crevices under deposits.

o Erosion/corrosion. Here, erosion of the surface (with sand particles, say) destroys protective layers and allows further corrosion reactions between the surface and the adjacent fluid.

o Graphitisation. In cases where the ferrous material used has a high graphite content (*e.g.* grey cast iron), corrosion leads to a mixture of corrosion products and free graphite on the surface.

It should be noted that the oxidation of a metal surface, while leading to a thin (fouling) layer with low thermal conductivity on the surface, is an essential component in protecting the surface from further corrosion.

Important factors in corrosion and fouling are salt precipitation, deposits, biofouling and sediment effects. Also important is *iron bacteria*; the activity of iron-oxidizing bacteria present in cooling water may lead to heat exchanger blockage.

Methods of controlling corrosion, and hence corrosion fouling, are discussed in ESDU 07006. The most important feature is attention to detail in controlling the water chemistry to deal appropriately with the nature of the water (oxygen content, chloride content, etc.) and the metals present in the circuit.

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**Biological fouling**

Biological fouling (*biofouling*) is one of the most important problems in managing cooling water systems. A distinction has to be made between 'macro' and 'micro' biofouling. Macro biofouling relates to the deposition of macro organisms such as barnacles and micro biofouling refers to the deposition of micro-organisms.

Micro-organisms which are significant in cooling water systems include bacteria (both anaerobic and aerobic), fungi and yeasts, algae, protozoa and viruses. Such micro-organisms may enter the system through the make-up water and through the action of cooling towers in scrubbing micro-organisms from

the circulated air. For micro-organisms to grow in the system, a warm environment is required and nutrients (carbon, nitrogen, phosphorus and trace elements) need to be present in the water.

In low velocity areas of cooling systems the micro-organism (slime) layer forms a film for subsequent attachment by higher organisms. In fact, the presence of intermediate organisms (for example protozoa) in the water can often indicate particularly poor microbial control; the more evidence of succession, the likelier the control is poor. Primary fouling organisms, such as barnacles, bryozoans ('moss animals') and hydroids (small, mostly colonial plant-like animals), follow almost immediately after the development of the slime film when their larval forms are present in the ecosystem. These are later joined by secondary fouling organisms, such as anemones.

The effects of various system parameters on biofouling are summarised as follows:

o Dissolved oxygen. In order for biofouling by aerobic micro-organisms to take place, the dissolved oxygen concentration must be above 3-4 mg per litre. The presence of oxygen is not necessary in the case of anaerobic micro-organisms. Typical concentrations of dissolved oxygen in open cooling systems are 10 – 12 mg per litre; thus, there is normally a susceptibility to biofouling which has to be mitigated.

o Temperature. At low surface temperatures, biofouling tends to *increase* with increasing temperature reaching a peak at an intermediate temperature, as can be seen in Figure 4. Above temperatures of 90°C, growth of micro-organisms in heat exchangers is unlikely. A pronounced maximum is found around 35 °C.

o Velocity. At very low velocities, or in stagnant water, biological growths would probably die due to lack of oxygen and nutrients, so a slight velocity is essential to promote biological fouling. Velocities of around 0.5-1.0 m/s are optimal for biological growth. However, at higher velocities, above about 1.5-2 m/s, biological deposits are likely to be sheared off or they are unable to attach themselves to the tube wall. These behaviours can be seen in Figure 5.

o Material. In seawater fouling, the heat exchanger material of construction can have a large effect on fouling. However, for fresh water systems the normal material is carbon steel and this has little direct effect.

An important feature related to biofouling is that of the occurrence of 'Legionellosis' or 'Legionnaires' Disease'. This is caused by the presence in the system of *Legionella*, which is a human pathogen. 'Legionellosis' and can vary in severity from fatal pneumonia to a flu-like condition depending upon the virulence of the bacterium and the susceptibility of the host. Infection is caused by inhalation of water droplets (aerosols) containing virulent *Legionella* bacteria. There is also evidence that the disease can be contracted by inhalation of legionella bacteria following ingestion of contaminated water. Water temperature manipulation is an important control measure for reducing the risk of *Legionella* proliferation in engineered water systems and is the primary means recommended by the UK Health & Safety Executive (HSE) for controlling growth of the organism in building water services [9]. Because of the uncertainty regarding the infectious dose and multiplication rate of *Legionella* it is prudent to consider all positive results from tests for its presence, including those where only low levels have been detected, as indicators of a potential problem within a system. The local guidance from health and safety authorities (such as the HSE in the United Kingdom) should be followed as to levels that are considered low risk and levels at or above which specific actions are recommended.

**Particulate fouling**

Most process streams (including fresh water cooling streams) contain a certain amount of suspended solids as a result of corrosion, dust intake or imperfect cleaning. Typical particle sizes vary from 1 to 20 μm, even though larger agglomerates are also possible. These particles are inevitably deposited on the surfaces of heat exchangers.

The processes involved in particulate fouling are [10]: transport of particles (diffusion, inertia, thermophoresis), adhesion (Van-der-Waals forces, surface charges) and erosion of the deposit. Particulate deposits are not very strong and increased

fluid shear can lead to their removal. This leads to asymptotic fouling behaviour. The factors influencing particulate fouling include:

o Flow velocity. The velocity of the water in the heat exchanger tubes has a significant effect on suspended solids fouling. Except at very low velocity (where there is little effect), the fouling resistance decreases continuously with increasing velocity.

o Particle concentration. The fouling resistance increases linearly with increasing particle concentration before levelling off to a constant value.

o Surface temperature. The effect of surface temperature is much less than in the case of the other fouling mechanisms. Typically, the fouling resistance increases slowly with temperature at low temperatures and more rapidly at higher temperatures.

o Heat flux. The fouling resistance passes through a maximum with increasing heat flux. This maximum decreases in amplitude and shifts towards higher heat fluxes if the wall shear stress is increased.

o Particle size. With increasing particle diameter, the asymptotic fouling resistance decreases rapidly. It should be emphasized that this result does not apply for cases where gravitational settling of particles contributes to the deposition process; in this case, deposition rate may increase with particle size.

o Suspension pH. Attachment and agglomeration of particles is mainly due to Van-der-Waals forces and electrical double layer forces. Electrical double layer repulsion is due to the charges building up on the surface of metal oxides and hydroxides in aqueous solution. The sign and magnitude of these charges depends on the pH and ionic content of the solution. The fouling resistance can pass through a maximum as a function of pH.

## Interaction between fouling mechanisms

In practice, fouling usually involves two or more of the accepted categories of fouling - namely, crystallisation fouling, chemical reaction fouling, corrosion fouling, particulate fouling and biological fouling. Thus, for example, when a heat transfer surface is exposed to natural water, corrosion fouling is frequently observed to occur together with precipitation fouling, particulate fouling, and biological fouling. The mechanism of interaction among these four categories of fouling involves surface roughening, the characteristics of the corrosion products, and the local value of the pH at the corroding surface [11]. Corrosion products formed on a surface provide surface indentations in which suspended particles and microbes may be trapped. A detailed discussion of these interaction effects is given in ESDU 07006 for corrosion and biological fouling, corrosion and particulate fouling, corrosion and crystallisation fouling, corrosion fouling and combined precipitation and particulate fouling, and particulate and crystallisation fouling.

## Materials Selection

The selection of materials is a crucial factor in fouling.  In selecting materials for water cooling systems, economic factors have to be taken into account and in this context essentially two types of system exist as follows:

o A low initial cost system, largely based on carbon steel and cast iron which will require considerable maintenance over the life of the plant.

o A system based mainly on alloy materials (such as stainless steel) which if correctly designed and fabricated will require minimum maintenance and will function reliably.

For fresh water systems, the most common material for heat exchangers is carbon steel. However, the choice of material may be governed by the process side. This contrasts with seawater applications where copper alloys and (more recently) titanium are the usual choice.

More detailed discussions of various aspects of materials are given in ESDU 07006 on tube, tube plate (or tubesheet) and baffle materials and water velocity specification.

## System Design Considerations

It is essential that cooling equipment should embody a number of basic features, such as:

o construction from corrosion resistant materials,

o a minimum of dead area, *i.e.* regions of low velocity which could permit organisms to settle and develop, or silt to deposit,

o a design that, so far as is possible, discourages surface fouling.

The most important considerations in heat exchanger design for water cooling systems are: (a) heat exchanger type; (b) modes of heat transfer and enhancement; (c) materials and working fluid; (d) biofouling and corrosion; (e) cleaning, repairing and maintaining the units.

The formation of deposits on the heat transfer surfaces causes an increase of the frictional pressure drop due to increased surface roughness and restricted cross-sectional flow area.

For tubular exchangers, the following important design considerations should be borne in mind:

o On the shell-side (and in particular in conventional segmental baffled shell-and-tube exchangers) there are dead zones, and these zones are ones in which the propensity to fouling is much higher.

o Often, and particularly in condensers in power generation systems, there is a need to minimise the pressure drop on the hot side. Using shell-side condensation and including 'steam lanes' to minimise pressure drop and to collect the incondensible gases, it is possible to reduce pressure drop on the hot side of condensers to a much lower value than would be feasible if the condensation were on the tube-side.

o Where the hot side fluid is corrosive, it may be preferable to have it flowing inside tubes made of

an appropriate (often expensive) material. This may avoid the need to use costly material for the heat exchanger shell. Such tube-side leakage may also result in the transfer of (dangerous) tube-side fluid to a vulnerable site.

o   Where the hot side fluid is at high pressure, it may be more economic to place it on the tube-side; this allows the shell to be designed for lower pressures, thus saving capital cost. In this case, the consequences of tube failure leading to over-pressurisation of the shell should be carefully considered.

Modification of a heat transfer surface or heat exchanger configuration in order to increase the heat transfer coefficient can influence the fouling propensity by two means (often acting together) as follows:

o   Direct effects. Here, the modification directly influences the fouling process. For instance, by increasing turbulence and mixing near the wall, the fouling propensity may be reduced (as may be the case in heat exchangers with twisted tubes). Alternatively, if the modification leads to the creation of dead zones in which foulant may collect, this may increase the fouling propensity (as may occur with some forms of finned surfaces).

o   Indirect effects. Here, enhancement of heat transfer (on either the cold side or the hot side of the heat exchanger) may lead to velocity increases (due to reduction of the size of the heat exchanger) and also to changes in the wall temperature in contact with the water.

The effects of shell-side configuration and enhancement of the shell-side and tube-side heat transfer coefficient are discussed in ESDU 07006. Also discussed are design considerations for other types of heat exchanger, namely plate-and-frame, plate-and-shell exchangers, spiral plate, printed circuit and fluidised beds.

## Mitigation and Control of Fouling

There are many factors influencing fouling which need to be addressed at both the design and operational stages. These include operation at the appropriate velocities and temperatures, avoiding dead zones in heat exchangers and ensuring that proper screening of the input water is achieved. Even when all these factors are properly addressed, fouling (and particularly biofouling) may still occur and it may be appropriate to seek mitigation, control and cleaning methodologies to maintain this fouling at acceptable levels. The principal methods of mitigation are:

o   Chemical methods. Chemical treatment methods can be employed to combat scaling, particulate fouling, corrosion fouling and biofouling

o   Mechanical methods. Mechanical methods include strainers and filters, micro-mesh filters, reversal of flow direction, passing devices through the tubes and turbulence promoters.

o   Anti-fouling coatings.

A miscellany of other techniques have been proposed. These are reviewed in ESDU 07006.

## Cleaning of Heat Transfer Surfaces

Periodical cleaning of heat exchangers will be necessary, even if the heat exchanger is well designed and the fluid treatment is effective. Additionally, conditions in the heat exchanger may deviate from the design conditions due to changes in flow rates and temperatures, plant failures, ingress of air and bacteria, changes in the fluid composition or up-stream corrosion, which all may promote fouling. If a heat exchanger or pipeline develops deposit formation, this can be the start of a whole series of problems. Corrosion processes may take place under the deposit, fouling rates may be increased due to the surface roughness of the deposit or irregular behaviour of the exchanger may be observed due to build-up and removal of deposits. It is, therefore, advantageous to remove non-protective deposits soon after the on-set of their formation. Heat exchangers may be cleaned by chemical or mechanical methods or by a combination of both.

If exchangers are likely to experience fouling and therefore require cleaning, it is important to incorporate features into the design and location of the units so that they can be readily cleaned.

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| | Initiation | Transport | Attachment | Removal | Aging |
|---|---|---|---|---|---|
| Crystalline | Scant | Comprehensive | Comprehensive | Scant | Poor |
| Corrosion | Comprehensive | Comprehensive | Scant | Scant | Poor |
| Biological | Scant | Poor | Poor | Poor | Poor |
| Particulate | Scant | Comprehensive | Comprehensive | Poor | Poor |
| Chemical reaction | Scant | Poor | Scant | Poor | Scant |

Legend: Comprehensive knowledge / Scant knowledge / Poor knowledge

Figure 1. Assessment of the State of Knowledge of Fouling Mechanisms [6]
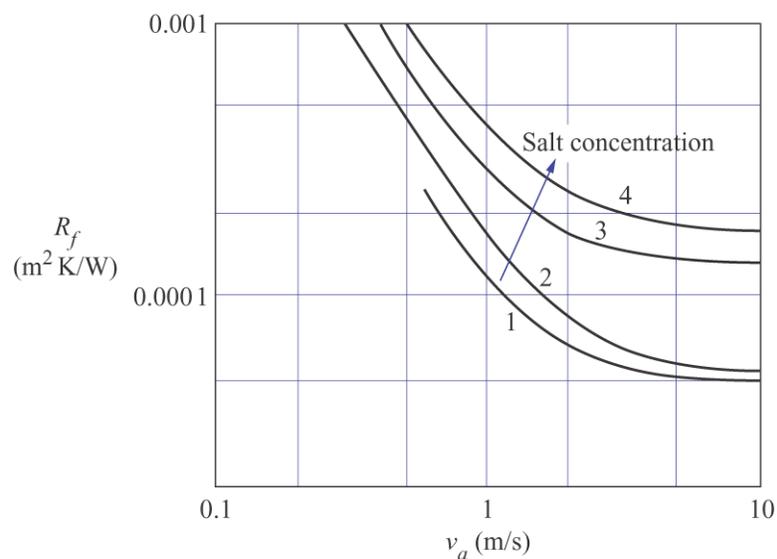
Figure 2. Fouling resistance $R_f$ in shell-and-tube heat exchangers as a function of flow velocity, $v_a$, and water quality. Depositing salt concentration increasing (and hence water quality decreasing) from 1 to 4
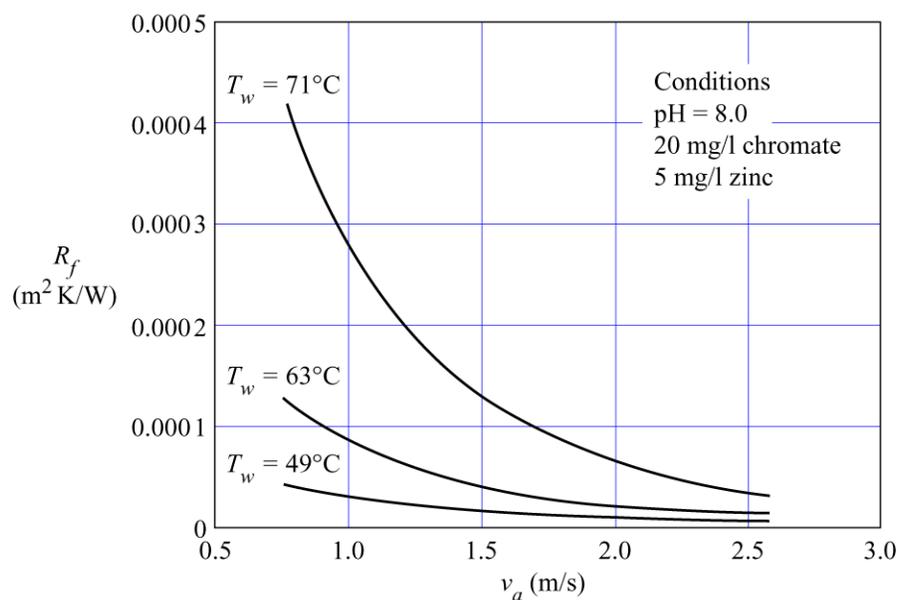


Figure 3 Fouling resistance $R_f$ in shell-and-tube heat exchangers as a function of water flow velocity, $v_a$, and surface temperature, $T_w$ [12]
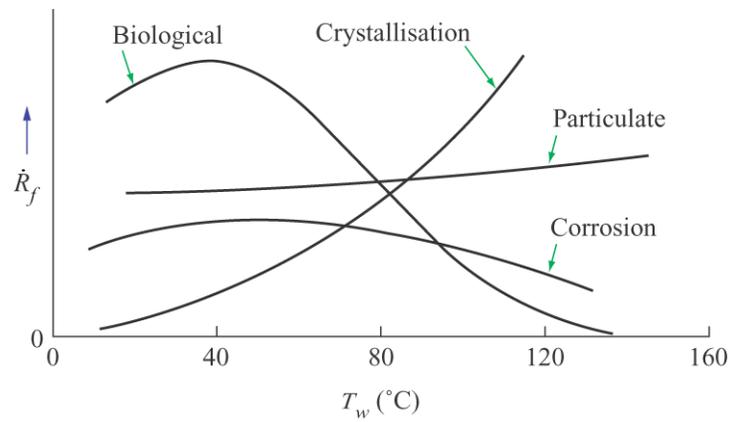
Figure 4. Effect of surface temperature, $T_w$, on fouling rate $\dot{R}_f$ due to various individual fouling mechanisms at constant water flow velocity
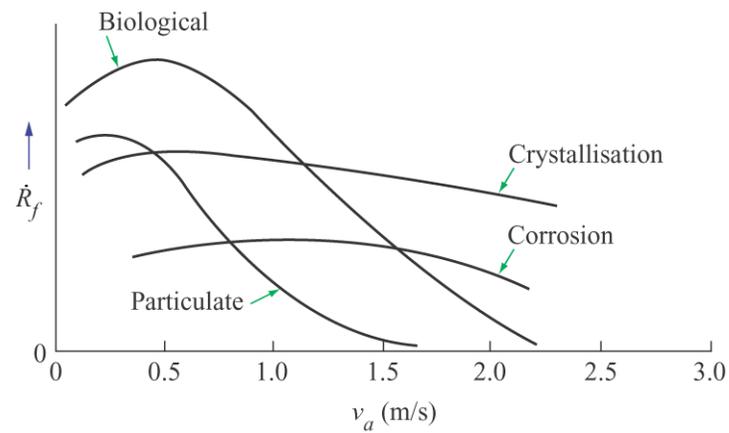


Figure 5. Effect of water flow velocity, $v_a$, on fouling rate $\dot{R}_f$ for various individual fouling mechanisms at constant temperature