Fouling During the Use of Seawater as Coolant - The Development of a 'User Guide'

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ABSTRACT

ESDU International of London, UK has recently published a 'User Guide' [1] on fouling in heat exchange systems using seawater as the coolant. Developed over a period of eighteen months in close collaboration with a team of oil refiners, heat transfer equipment and services suppliers and universities, with valuable input from the power industry, the User Guide is a practical guide to the current state of knowledge relating to fouling in cooling systems using seawater. Its objective is to provide the designer and the operator of both onshore and offshore equipment with a practical source of guidance on the occurrence, the mechanisms and the mitigation of seawater fouling in these systems.

ESDU's collaborative 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. The seawater fouling User Guide is the second in a group, following the development of the Crude Oil Fouling User Guide issued in 2000. Work is now underway on cooling water fouling,

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

Keywords: Fouling, cooling, seawater, mitigation, cleaning, heat exchangers, plate, shell-and-tube, cooling tower, pipework.

Table 1 ESDU Oil Industry Fouling Working Party Participants, 2002/03

Refinery Operators
BP
Chevron Texaco
Exxon Mobil
Shell Global Solutions
Statoil
Total
Heat Transfer Equipment and Services
ABB Lummus Heat Transfer
Brown Fintube Company
Cal Gavin
Fluor Daniel
HTRI
Kvaerner Process
NEL
Petroval
Struthers Heat Transfer
Wellman-Graham
UKAEA
Universities
Birmingham University
UMIST
University of Bath
University of Cambridge

INTRODUCTION

Heat exchanger fouling in general is a major economic problem, accounting for 0.25% of the gross domestic product (GDP) in the highly industrialised countries [2]. Against this background, ESDU formed the industrially led

Oil Industry Fouling Working Party of oil company experts in refining technology and key engineers from companies developing fouling mitigation technologies. It was noted that some 70% of the global refining capacity was represented on the Working Party. Member companies are listed in Table 1.

A key milestone for the group was the publication in July 2000 of the ESDU Data Item ("User Guide") 'Heat exchanger fouling in the pre-heat train of a crude oil distillation unit", and associated software [3]. These tools allow process engineers and plant operators to review the impact of process conditions and equipment design changes on heat exchanger fouling and plant operation.

The work was conducted under the guidance of the ESDU Oil Industry Fouling Working Party and consisted of detailed review and evaluation of the experience of the industrial members and a literature study.

This paper follows in part the structure of the seawater fouling User Guide and summarizes some of its content.

WATER AS A COOLANT

Water is the main coolant in industry, though environmental pressures are increasingly militating in favour of the use of air rather than water. Oil refineries, chemical plants, steels mills, power plants, all use water to remove heat from their processes. Generally the water is not consumed, but simply passes through heat exchangers and returns to the source.

Seawater consumption is huge in the power generation industry. According to Keens [4], the United States power industry uses around 6700 m^3/s (106 million US gallons per minute); that is, 80% of all industrial cooling water or a third of water usage for all purposes in the USA.

Although seawater consumption is less in the process industries than in the power generation industry, its effective use is crucial, particularly in offshore processing.

In electricity utilities and process plants located in coastal zones, seawater is frequently used directly in heat exchangers and condensers.

Once-through systems using fresh water are used in locations close to rivers or lakes. However, fresh water supplies are usually not sufficiently abundant and their consumption is increasingly restricted by legislation limiting the thermal load on natural waters and the use of chemical additives for cooling water conditioning. It has, therefore, become common practice to use closed cooling water systems and to reject the heat to the atmosphere via cooling towers or to fresh water or seawater through heat exchangers.

On a world scale, fresh water represents only a small fraction of available water. The world's water resources [3] are 1.36×10^{18} m^3 of which only a small proportion is fresh water. Keens estimated the distribution of available water as follows:

Oceans	97.2%
Icecaps & Glaciers	2.15%
Atmosphere	0.001%
Ground water	0.626%
Rivers	0.0001%
Fresh water lakes	0.009%
Saline lakes	0.008%.

Fresh water conservation in process plant is often economically very important [5]. Thus, cooling with seawater, when it is readily available in the locality, makes use of the largest resource of water. Keens estimated that 42% of the water used by US power plants is seawater; however, this utilisation is likely to decrease in future because of the severe environmental pressures.

Usually, cooling with seawater is done on a once-through basis (though it is occasionally used in cooling towers). It has the following further advantages over cooling by re-circulated fresh water from cooling towers:

• With cooling towers, there is a limit on the return temperature to within around 5^oC of the wet bulb temperature and, often, once-through seawater systems give lower available temperatures and, hence, smaller heat exchangers.

• There is continuous loss of (relatively expensive) fresh water from cooling towers. Typically, 0.2% is lost as spray and about 1% as water vapour for each 5^oC of cooling in the cooling tower.

There are two possible routes to utilisation of seawater as a heat sink, namely the use of direct and indirect cooling systems. These choices are summarised below, but are described and illustrated by industrial examples in the User Guide [1].

SELECTION OF SEAWATER COOLING SYSTEM TYPE

There are three possible routes to utilisation of seawater as a heat sink:

1. Direct use of seawater; here, the seawater is pumped directly to the heat exchanger and there is direct transfer of heat (across the heat exchanger surface) from the hot medium being cooled to the seawater cooling medium.

2. Indirect use of seawater; here, heat is exchanged between the seawater and a secondary stream which could be fresh water or a mixture of fresh water and, say, glycol; this secondary stream is then used as the cooling medium. In general, for offshore use, water with typically 30% of tri-ethylene

glycol (TEG) or mono-ethylene glycol (MEG) is used as the secondary cooling medium. For onshore use, fresh water is often used if climate conditions permit.

3. Use of seawater in cooling towers. In some areas, it may be economic to utilise seawater in cooling towers; here, the heat rejection is not only to the sea but also to the atmosphere due to partial evaporation of the seawater. This obviously can make available an alternative source of cooling tower water where fresh water is expensive. It can also lead to a considerable reduction of pumping power and thermal pollution. Usually, in such systems, the seawater is cycled through the cooling tower for no more than two cycles, to minimise corrosion and fouling.

Typically, for direct cooling process applications, plate heat exchangers are used for low-pressure duties and shell-and-tube exchangers for high-pressure duties. Plate exchangers would be a common choice for cooling of the cooling medium in indirect systems.

The selection between the two most common (direct and indirect) systems is a prime design decision and needs to be considered carefully. The advantages and disadvantages of the respective systems are summarised in the User Guide.

INTRODUCTION TO HEAT EXCHANGER FOULING

Epstein [6] classified fouling mechanisms for heat exchangers into particulate fouling, crystallisation fouling, corrosion fouling, chemical reaction fouling and biofouling. Biofouling (both aerobic and non-aerobic) and corrosion fouling are the most important mechanisms for seawater cooling systems but crystallisation fouling and particulate fouling

may also be significant in some circumstances. Epstein suggested a general sequence of fouling events which may play a role in all types of fouling; the sequence is:

- initiation,
- transport of foulant,
- attachment to the surface,
- release of the deposit, and
- ageing of the deposit on the surface.

The processes of heat exchanger fouling are actually quite complex and there is an increasing need to consider these complexities in designing and operating systems. Fouling is currently accommodated in heat exchanger design as follows.

Tubular Heat Exchangers

In order to quantify the fouling propensity of the heat exchanger, it is normal to define, for tubular heat exchangers, a fouling factor, R_f . This is derived from the normal definition of overall heat transfer coefficient. It is common practice in industry to use fixed values of fouling factors for tubular exchangers, most usually those listed by the Tubular Exchangers Manufacturers Association (TEMA) [7].

In practice, however, a wide range of variation in fouling factor is observed, and the value of the fouling factor that applies will depend critically on the circumstances. Also, it should be stressed that fouling is a time-dependent phenomenon. Figure 1 [8] illustrates the various forms of variation of R_f with time that may occur. The assumption of constant values of R_f would be consistent (in the longer term) only with the asymptotic behaviour, (c). In many cases, the fouling factor would continue to increase over the period of operation of a system between cleaning either linearly (a) or with a falling rate (b). In some circumstances, the fouling layer is periodically removed and a "saw tooth"

behaviour (d) is observed. A typical example is shown in Figure 2 [9].

Compact Heat Exchangers

For compact heat exchangers, it is common practice to define a duty margin, which is the amount that the surface area has to be increased to account for fouling; this might typically be around 10-20%. Care needs to be taken about the way in which the additional area is introduced. Increasing area by increasing the number of channels would decrease velocity and may lead to an infringement of minimum velocity constraints. Alternatively, area might be increased by increasing tube length without affecting velocity but this may infringe pressure drop restraints.

For plate-and-frame heat exchangers, the following fouling factors have been suggested [10]:

Coastal seawater: 0.000 043 m^2 K/W.
Ocean seawater: 0.000 026 m^2 K/W.

However, for plate heat exchangers, the maximum excess surface area should be also limited to 20-25% of the clean surface requirements.

Power Station Condensers

For power station condensers, it is common practice to account for fouling using a cleanliness factor, which is the fraction of the clean surface heat transfer which occurs after accounting for fouling. This methodology is recommended by the Heat Exchange Institute Inc. (HEI) whose standards [11] tabulate reference values of overall heat transfer coefficients which are functions of velocity and tube diameter.

In contrast to TEMA, HEI does not make quantitative recommendations on how to allow

for the effect of fouling; HEI standards state the following: "A design cleanliness factor (FC) should be selected by the Purchaser that suitably reflects the probable operating conditions the tubes will experience in service. Non-copper bearing tube materials are more susceptible to biofouling than tubes with a high copper content".

Guidance on the use of cleanliness factor is given in the User Guide, where a comparison of stated HEI values and those calculated based on TEMA values are presented. Large discrepancies are shown between values. It is noted that to maintain high cleanliness factors, attention needs to be given to maintaining high velocities and to proper design of inlet conditions, etc.

TYPES OF SEAWATER FOULING

The most important forms of fouling occurring in seawater systems are as follows:

Crystallisation fouling. This includes the deposition of calcium carbonate, calcium sulphate and other salts that have a solubility that diminishes with increasing temperature, leading to crystallisation of deposits of the salts on the heat exchanger tubes.

Corrosion fouling. Some metals are oxidised to produce insulating layers of oxides on the tubes.

Biological fouling. A whole range of biological growths form on heat exchanger tubes in seawater. The species attached range from micro-organisms (bacteria, algae) to macro-organisms (mussels, barnacles, etc.).

Particulate fouling. Seawater may contain many types of silt, mud, sand or other finely divided particles that may settle on the heat exchanger surfaces and act as an insulating layer.

Of the above mechanisms, the ones presenting the most problems for seawater systems are corrosion fouling and biological fouling.

There are six factors that have a predominant role in governing fouling in seawater systems:

Surface temperature. The temperature at the interface between the seawater and the solid surface (that is, initially the metal but later the foulant layer) is of crucial importance. Figure 3 sketches the effect of temperature on the various types of fouling. Thus, for crystalline fouling, the deposition is small at temperatures below $60^{o}C$ but can become serious at elevated temperatures [9].

Fouling factors for corrosion fouling show a peak value as temperature increases; at low temperature, the corrosion rate increases with temperature but the corrosion requires the presence of dissolved oxygen and this dissolved oxygen content is reduced at higher temperatures due to the decreasing solubility of oxygen in water. For biological fouling, the rate initially increases with temperature [12] up to about 30-$40^{o}C$. Foulant organisms are killed at high temperature and, thus, the rate of biological fouling decreases with increasing temperature. There is less effect of temperature on deposition of silt but it should be noted that silt or mud deposits could be dehydrated at higher temperatures, which decreases their conductivity and increases the fouling factor.

Bulk temperature. The value of the bulk temperature is also important. Biological growth becomes faster as bulk temperature increases from ambient values. At high bulk temperatures the organisms may be killed; however, long residence times may be required at elevated bulk temperatures, to kill the organisms present. At the UK CEGB Abberthaw "A" power station, water temperature was increased to 85°C by reversing and throttling the flow. A time of 120 minutes was required at this temperature to kill

off mussel growth. The use of higher temperatures would increase the rate at which the mussel growth could be killed (but was not possible in this case due to problems of differential thermal expansion, Loraine [13]).

Water velocity. The relative effects of water velocity on the various fouling mechanisms are sketched in Figure 4. Water velocity generally has only a small effect on crystalline fouling at lower velocities but may tend to shear off the crystalline deposits at higher velocities. Corrosion fouling is not strongly affected by water velocity but there is a strong velocity effect in both biological fouling and suspended solids fouling. With biological fouling, the fouling rate may increase with velocity at low velocities, reflecting the need to supply nutrients to the surface which needs at least a low flow rate to sustain mass transfer.

For the same turbulence level (and hence shear rate), flow velocities in compact heat exchanger types, such as plate-and-frame heat exchangers are lower than in tubular geometries.

Oxygen concentration. As was mentioned above, corrosion fouling is strongly affected by the amount of oxygen dissolved in the water. This tends to reduce at higher temperatures. Oxygen is also necessary for the maintenance of biological fouling, though anaerobic slimes can sometimes occur at low oxygen concentrations.

Tube or plate material. The material of the tube or plate in the heat exchanger plays an important role in fouling. Alloys with more than about 60-70% copper will not support marine growth. Ferrous materials are easily oxidised. Most stainless steels are susceptible to stress corrosion cracking. Duplex high chrome nickel alloy tubing is generally not suitable for seawater duty but some suppliers claim that Superduplex nickel alloy tubing may be used for metal temperatures up to around 50°C. Titanium has excellent resistance to corrosion and usually has no

temperature limitations for use in seawater cooling systems (it can be used up to 300°C though it, too, may have stress corrosion cracking problems above 100°C), However, it is more susceptible to biological fouling, particularly if the velocities are too low. Titanium tubes are, however, able to withstand higher velocities and this allows the avoidance of biofouling by suitable increases in velocity. Cathodic protection can increase allowable operating temperatures in seawater considerably.

Upstream pipework materials. Corrosion products from upstream pipework may be transferred to the heat exchanger and create a fouling layer. Care should therefore be taken in the selection of materials for such pipework.

Solids. Superficially, high solids concentrations might be expected to reduce fouling rate. However, there is a significant risk that erosion followed by corrosion will severely damage tubes (particularly with Cu-based alloys). In seawater, sand is the most prevalent solid and erosion may be expected for sand particles with sizes greater that around 50 micrometres at concentrations more than a few hundred ppm. Titanium and Superduplex alloys are much less prone to erosion-corrosion than copper-based alloys.

It is important to stress that several fouling mechanisms frequently operate simultaneously. Thus, interaction effects may be important in many circumstances. An example here is the complex effect of flow velocity; high velocities at a given surface temperature will reduce the potential of biological fouling and silt deposition. However, in most practical applications the higher flow rates would also lead to lower surface temperatures and this may offset the decrease in biological fouling resulting from the increase in velocity (see Figure 3). This underlines the need to treat fouling problems in terms of overall system design and not just as a series of numbers (e.g. TEMA fouling factors),

which can be introduced in an arbitrary way. It is possible to also have temporarily varying fouling mechanisms. A power station on the Thames Estuary at West Thurrock, UK (fitted originally with 70-30 copper nickel tubes) suffered from non-aerobic corrosion from polluted Thames water when the flow was downstream but was affected by aerobic corrosion augmented by entrained sharp sand once the flow reversed as the tide came in (Loraine [13]).

A full description of each of the fouling mechanisms listed above is given in the User Guide. Also given are design guidelines such as preferred, minimum and maximum tubeside velocities for minimisation of corrosion fouling with various materials: these data were supplied by Working Party member companies.

MATERIALS SELECTION

The selection of materials is a crucial factor in fouling in seawater-cooled systems. Steels are not generally suitable for seawater duties; carbon steels corrode and most stainless steels suffer from stress corrosion cracking. Duplex alloys are not usually suitable, though some manufacturers claim that Superduplex alloys may be used at temperatures up to around 50°C, or even as high as 80°C with cathodic protection. Traditionally, copper based alloys were used in seawater applications. Such alloys inhibit biological fouling and, provided that the velocity is kept below the erosion/corrosion limit, corrosion is often small and acceptable. The types of copper alloy used most frequently have been:

- Aluminium brass, which has excellent corrosion resistance in clean seawater provided that the velocity is not too high. It is not recommended in contact with polluted water or water containing large amounts of suspended sand.

- 70-30 copper-nickel with 1% iron and 1% manganese which offers greater resistance to

impingement corrosion, polluted water and deposit attack, but is more expensive.

- 90-10 copper-nickel which is roughly intermediate between aluminium brass and 70-30 copper-nickel in impingement resistance.

However, there has been a recent shift towards the use of titanium rather than copper alloys for reasons that include the following:

- Advances in manufacturing technology, including the ability to weld titanium tubes, have made this material a cost-effective option.

- There are now strict environmental discharge limits on copper and these must be adhered to. It is sometimes difficult to demonstrate unequivocally that even minor levels of corrosion of copper alloy tube bundles will not give rise to a breaching of these limits.

- It is possible to operate titanium heat exchangers with much higher surface temperatures in contact with the seawater. This favours many process applications and minimises biological fouling.

- Titanium is highly corrosion resistant and this allows titanium heat exchangers to be operated at high velocity without erosion/corrosion problems. Again, this minimises biological fouling.

- Titanium has a relatively low density (4500 kg/m^3) compared to copper alloys (8600 - 8900 kg/m^3) and steels (7200 - 8000 kg/m^3) and this can be advantageous where weight saving is important (e.g. in offshore platforms).

- Titanium heat exchangers present fewer problems than copper alloy heat exchangers

for disposal at the end of their life. This is because of the lower toxicity compared to that of copper.

- The modern use of seal welded and bead crushed titanium tubes or seal welded and drawn titanium tubes has reduced the cost of heat exchanger surface, particularly when 22 SWG (0.71 mm wall thickness) tubes are used; the use of thin tubes (which is possible due to the higher Young's modulus and greater resistance to impingement attack of titanium) also offsets the smaller wall thermal conductivity of titanium, in addition to reducing materials cost. However, recently the application of similar manufacturing technology to brass and cupro-nickel tubes has allowed reduced wall thickness for such tubes also and this has offset the cost gains made using the technology for titanium tubes.

The above factors have led many refinery operators to use only titanium in seawater cooling applications. However, if such a selection is made, then it is important to make sure that the velocity is sufficient to inhibit biological fouling at the temperature of the heat exchanger surface. If the seawater flows on the shell side in shell-and-tube heat exchangers, a factor militating against increasing the velocity may be the fact that tube vibration (and consequent damage) may occur, particularly bearing in mind the fact that the wall thickness of titanium tubes is often smaller for the reasons mentioned above. Tube vibration can be minimised by attention to baffle design, for instance by using rod baffles. Bi-metallic effects due to differences in tube and baffle materials should be avoided.

SYSTEM DESIGN CONSIDERATIONS

Key Considerations

It is axiomatic that the overall cooling system should be designed taking into account the various propensities to fouling outlined above. Thus, cooling equipment should embody a number of basic features, which include:

- Construction from corrosion resistant materials.

- A minimum of dead area, i.e., regions of low velocity which could permit organisms to settle and develop, or silt to deposit. Such dead areas occur in segmentally-baffled shell-and-tube exchangers in the regions near the point of contact between the baffles and the shell. The turning shell-side flow tends to bypass these areas, making them natural zones for deposits to form. Another dead area in this case might occur near the U-bends in a U-tube exchanger.

  A variety of techniques are available for the minimisation of dead spots and the enhancement of heat transfer, and are discussed in the User Guide.

- A design that, so far as is possible, discourages surface fouling.
- A design that, as much as possible, facilitates cleaning and inspection.

The User Guide discusses the applications of tubular exchangers (including the role of enhancement technologies) and then goes on to discuss plate heat exchangers. Then, intake system design (which is common to all types of heat exchanger) is reviewed. Of course, other components of the cooling system such as pumps, distribution piping, treatment/dosing plant, control elements (measurement instruments, valves etc) and outfall are also important and should be considered carefully at

the design stage. Finally, a review is given of some overall design aspects such as the interactions between the respective sides of the exchanger and the effects of off-design operation.

Overall System Design and Operational Considerations

In the design and commissioning stages of seawater cooling systems, it should be borne in mind that:

- Any change in heat transfer coefficient or effective area on one side of a heat exchanger will be reflected in a change of conditions on the other side. Thus, enhancing the hot side coefficient or surface area (by finning) will cause the seawater side wall temperature to increase. This would have implications on the fouling behaviour (as discussed in the User Guide).

- The system will not always operate at its design conditions. Thus, startup and shutdown, controller actions, etc, may give conditions under which the propensity to fouling is significantly increased. Controller actions should not reduce the seawater velocity. The consequences of off-design conditions should be considered at the design evaluation stage.

Thus fouling should be accounted for in the design not only for a point design condition but also for anticipated off-design conditions.

Velocity-dependent and wall temperature-dependent fouling in shell-and-tube heat exchangers can be investigated at point design conditions and over ranges of operation using ESDU's EXPRESS computer program. This program, which also allows the investigation of crude oil fouling behaviour, is described in the companion User Guide on crude oil fouling in pre-heat trains [3].

MITIGATION AND CONTROL OF FOULING

There are many factors influencing fouling that 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.

Mitigation and control strategies are predominantly "on-line" processes, carried out either continuously or intermittently. A wide variety of methods have been used for fouling treatment and control and these are summarised in the User Guide. These methods can be categorised into External Treatment (which includes water softening and ion exchange), Internal Treatment (which implies the use of chemicals dissolved in the water) and Removal (which implies the use of mechanical devices for the continuous or intermittent removal of deposits).

Chemical Mitigation and Control of Fouling

A variety of chemical agents have been used to inhibit deposition in seawater fouling systems. As was stated above, the most important problem is that of biofouling and a whole variety of biocides are available to control biofouling in water systems. The principal types of biocides are as follows:

1. Oxidising agents – including chlorine, ozone and potassium permanganate.

2. Hydrolysing agents – acids and alkalis.

3. Cell poisons (heavy metals).

4. Protein coagulants – mercury and phenol.

5. Surfactants – cationic detergents.

6. Electrolytically-produced copper ions.

7. Film-forming/dispersing additives.

Of the above, types 3, 4 and 5 can be ruled out for open circuits. Phenols and heavy metals are forbidden by anti-pollution legislation, and surfactants cause undesirable foams. Hydrolysing agents (type 2) would require concentrations large enough to upset pH and promote corrosion in the circuit. Of the oxidising agents, permanganate is sometimes used in closed fresh water circuits, but would be too expensive in open circuits. Thus, the number of alternative practical systems for chemical inhibition and treatment of biofouling in seawater systems is limited. The most important systems, discussed in detail in the User Guide, are chlorine addition, ozone treatment, electrolytic copper ion addition and film forming/dispersing additives.

Mechanical Mitigation And Control Of Fouling

A number of methods for mechanical mitigation have been developed, the most important of which are discussed in detail in the User Guide. Micromesh filters treats the cooling water itself whereas flow reversal, gas rumbling, continuous transport of cleaning devices, fluidised bed heat exchangers, tube inserts, and robots treat the contaminated surfaces. Most of the commonly-used fouling mitigation techniques have been developed for the tube-side liquid in shell-and-tube heat exchangers. Even though attempts have been made to develop mechanical on-line mitigation devices for non-tubular heat exchangers, their installation has not penetrated the market.

Surface Effects and Treatments

There are a number of cases in which surfaces are naturally inhospitable to biofouling. Furthermore, there are a number of antifouling treatments in which the surfaces are coated or modified. These surface-influenced situations are discussed in the User Guide.

Miscellaneous Methods

A wide variety of alternative methods for fouling mitigation have been proposed and investigated. A brief survey is given of some of these technologies in the User Guide.

CLEANINGOF HEAT EXCHANGERS

Periodic 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 pipe-line 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.

Chemical Cleaning Methods

Chemical cleaning methods have a number of advantages over mechanical methods, namely:

- They are relatively quick. Typically, chemical cleaning would take one day whereas mechanical cleaning might take three days, principally because most mechanical methods require the unit to be isolated and removed for cleaning.

- Surfaces do not experience mechanical damage.

- Chemical solutions reach normally inaccessible areas.

- They are less labour intensive than mechanical cleaning.

- Cleaning can be performed *in situ*.

One drawback with chemical cleaning is that, since the exchanger is usually not opened, methods for validating the cleaning programme may be needed, as inaccessible areas may not be cleaned as effectively.

However, the type of cleaning process used, the procedure followed, the selection of cleaning agents and any problems associated with cleaning must be understood. These aspects are discussed in the User Guide.

Mechanical Cleaning Methods

For the application of mechanical cleaning methods, heat exchangers have to be taken off-line and dismantled. Some of the deposits may then be removed manually, for example from the water box. Steam-blasting and hydroblasting (up to 60 MPa) are probably the most common mechanical cleaning methods. However, blasting may not completely eliminate all deposits and some significant roughness can remain. Both steam- and hydroblasting are labour intensive and keep the exchanger off-line for a considerable time.

While blasting (or brushing for soft deposits) is the only available alternative for the shell side of the tube bundle, several cleaning methods can be used for the inside of straight tubes. The continuous cleaning sponge ball system, described in detail in the User Guide, can also be used as a transportable, off-line cleaning system, particularly if used with corundum-coated sponge balls. Very dirty and plugged tubes can be cleaned with drills equipped with drill bits, brushes or bit-brush combinations.

To avoid damage of the heat transfer surfaces, cleaning must be done carefully, thus increasing costs for labour and down-time.

Most mechanical cleaning methods remove not only the deposit but also the protective oxide layer. Under certain circumstances, this may create a corrosion problem. On the other hand, regular cleaning removes deposit and avoids flow conditions, which promote corrosion due to chemical reaction or stagnant flow. For very severe fouling problems, a combination of chemical and mechanical cleaning may be recommended.

The shell side of tube bundles can only be cleaned completely if the tubes are arranged in-line.

A discussion of the main methods for mechanical cleaning is given in the User Guide.

Design For Cleaning

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. Examples include connections and sensors required for chemical cleaning, drainage points for removing cleaning fluids, access for tube bundle removal, and specifying tube pitches so that bundles can be cleaned. If information on fouling, deposit nature and subsequent cleaning

requirements is available for similar situations, this should be exploited at the design stage in deciding the unit configuration.

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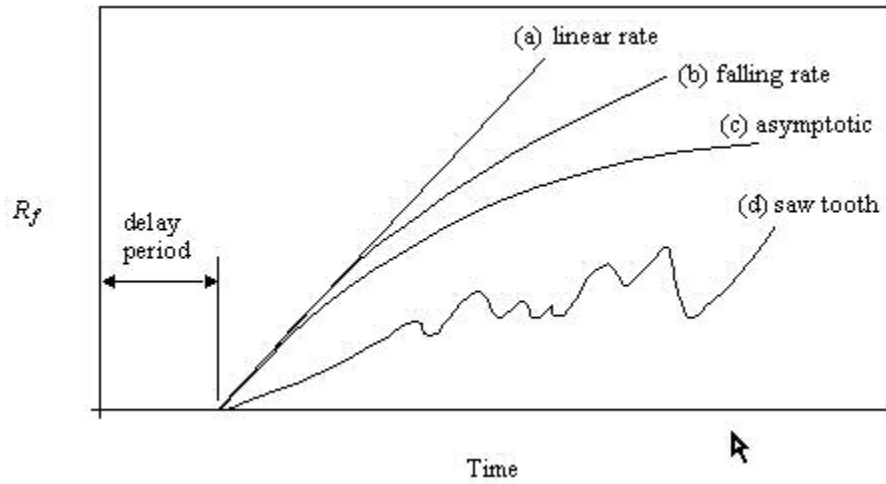`

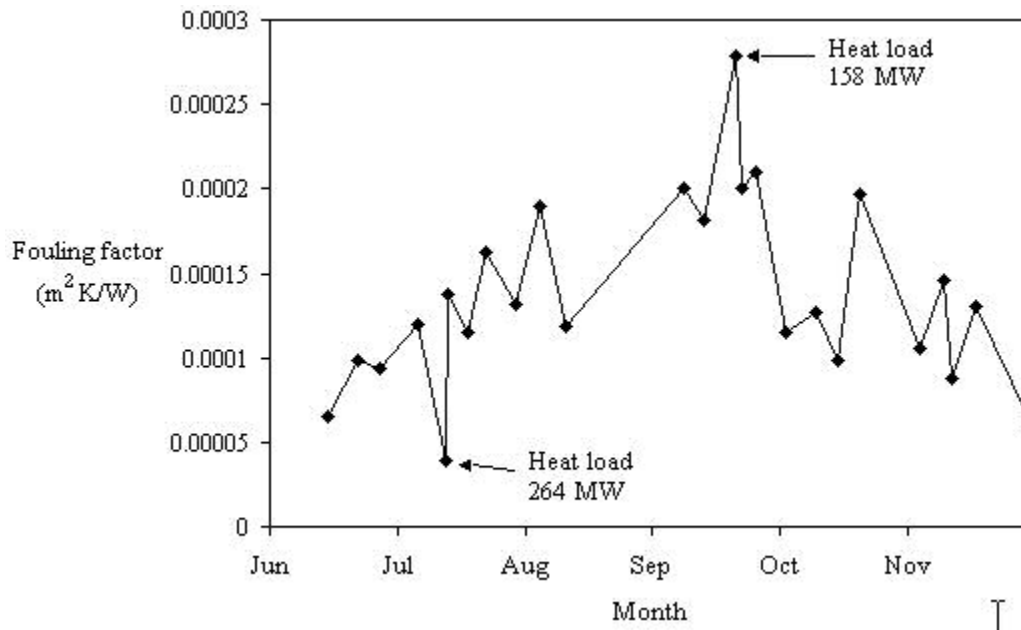Figure 1. Fouling curves showing the various possible fouling rates [7]

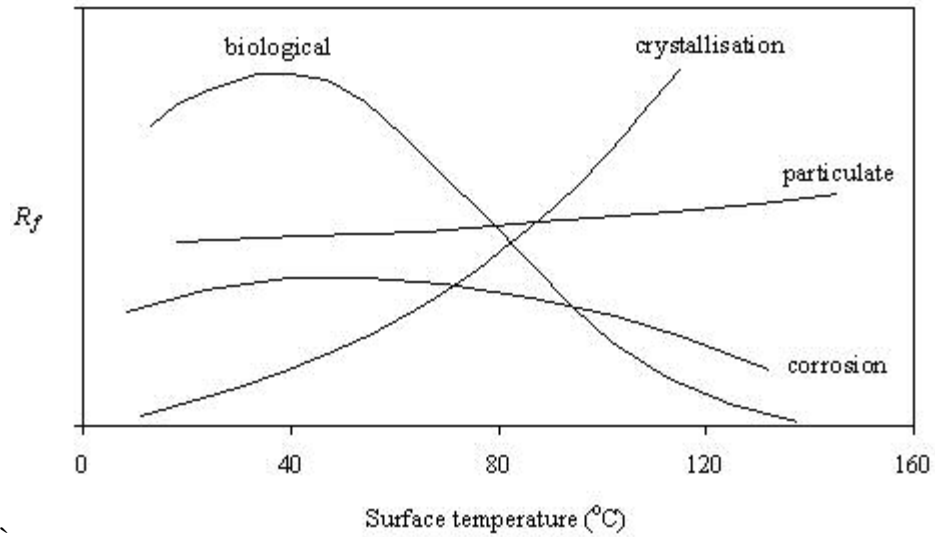Figure 2. Fouling history for power plant surface condenser [8]

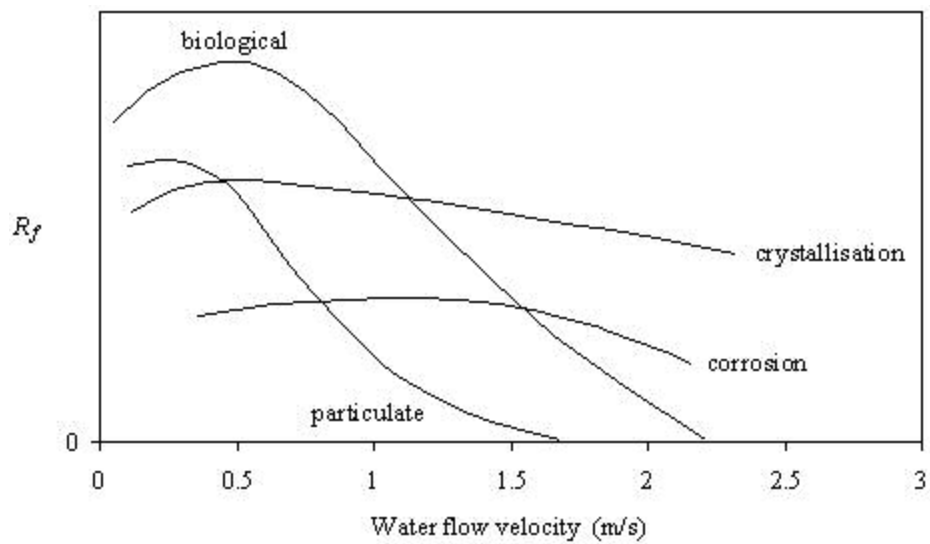Figure 3. Effect of temperature on various fouling mechanisms at constant velocity

Figure 4. Effect of water velocity on various fouling mechanisms at constant temperature