BIOFOULING: EFFECTS AND CONTROL

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ABSTRACT

Biofouling refers to the undesirable accumulation of a biotic deposit on a surface. The deposit may contain micro- and macroorganisms. The focus of this paper is microbial fouling biofilms which consist of an organic film composed of microorganisms embedded in a polymer matrix of their own making. The composite of microbial cells and EPS is termed a biofilm. The surface accumulation is often composed of significant quantities of inorganic materials. Complex fouling deposits, like those found in industrial environments, often consist of biofilms in intimate association with inorganic particles (1), crystalline precipitates or scale (2), and/or corrosion products (3). These complex deposits often form more rapidly and are more tightly bound than biofilm alone. These deposits are difficult to characterize at the microscale, i.e. at the cellular level.

Thus while biofilm processes, their kinetics, and their stoichiometry can be described in terms of fundamental, intensive variables, this paper must generally describe observations in terms of performance parameters (e.g. heat transfer resistance or fluid frictional resistance).

THE OPERATING PLANT ENVIRONMENT

An industrial operation contains numerous environments where corrosion and fouling processes are potentially troublesome including cooling water systems (recirculating and once-through), storage tanks, water and wastewater treatment facilities, filters, and piping. Microbial fouling and corrosion also occur on ship hulls, reverse osmosis membranes (4), porous media (e.g. groundwater or oil-bearing formation), ion exchangers (5), drinking water distribution systems (6). Biofouling has been reported in turbulent flows and stagnant waters, on smooth surfaces and crevices, and on metals, concrete, and numerous other substrata.

Biofouling frequently occurs in conjunction with other types of fouling including crystalline or precipitation fouling (e.g. scaling) and particulate fouling (frequently due to sedimentation). Microbial activity has been found in calcareous deposits, tubercles, and in deposits of particulate material resulting from sedimentation or adsorption. Increased corrosion rates are frequently reported in these circumstances.

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A recirculating cooling tower system provides an illustration of a plant environment in which fouling and corrosion can occur. The evaporative losses of water result in a concentration effect which increases nutrient concentration. The hydraulic residence time, water temperature, and surface area-to-volume are all relatively high. As a consequence, microbial growth rates and cell numbers can be very high. If the fill material is wooden, its degradation rate can be significant due to microbial degradation (fungi) or measures to control microbial activity (chlorine). In heat exchangers, scaling (under certain conditions) and microbial film development on the tubes and areas around flow obstructions can increase heat transfer resistance and (metal) corrosion rates.

FOULING: DEFINITIONS AND DESCRIPTION

Fouling is the formation of deposits on equipment surfaces which significantly decreases equipment performance and/or the useful life of the equipment. Several types of fouling, and their combinations, may occur (7):

1. biological fouling: the accumulation and metabolism of macroorganisms (macrobial fouling) and/or microorganisms (microbial fouling).

2. chemical reaction fouling: deposits formed by chemical reaction in which the substratum (e.g. condenser tube) is not a reactant. Polymerization of petroleum refinery feedstocks is an important example of this type fouling.

3. corrosion fouling: the substratum itself reacts with compounds in the liquid phase to produce a deposit.

4. freezing fouling: solidification of a liquid or some of its higher melting point constituents on a cooled surface.

5. particulate fouling: accumulation on the equipment surface of finely divided solids suspended in the process fluid. Sedimentation fouling is an appropriate term if gravity is the primary mechanism for deposition.

6. precipitation fouling: precipitation of dissolved substances on the equipment surface. This process is termed scaling if the dissolved substances have inverse temperature solubility characteristics (e.g. $CaCO_3$) and the precipitation occurs on a superheated surface.

In most operating plant environments, more than one type of fouling will be occurring simultaneously. For example, microbial fouling is not limited to processes related to biological activity. Microbial fouling also includes the combined result of microbial activity and physicochemical processes in the associated slime layer with the chemical changes at the equipment surface and chemical reactions within the bulk fluid. The interaction can enhance some of the more commonly observed phenomena such as particulate, sedimentation, and corrosion fouling. Because of its complicated composition, the accumulated material will be termed a deposit unless data is available to classify it further.

The interactions between the various types of fouling are poorly understood and, consequently, provide a challenge in diagnosis and treatment.

PROBLEMS CAUSED BY FOULING

Fouling biofilms impair the performance of process equipment. They can form on any surface in contact with a process fluid. The economic consequences of fouling are the essential reason for industrial interest in the fouling of operating equipment. To assess the importance of a fouling situation, the economic and energy penalties arising from the operation of equipment subject to fouling must be considered. The deleterious effects of fouling include the following:

1. energy losses due to increased fluid frictional resistance (e.g. in pipelines, on ship hulls and propellers, and in porous media such as oil and water wells or filters) and increased heat transfer resistance (e.g., power plant condensers and process heat exchangers). Zelver et al. (1) have documented a case of biofouling at a nuclear power plant in which heat transfer rate in a fan cooler decreased by 30% due to biofouling in a 30 day period.

2. increased capital costs for excess equipment capacity (e.g. excess surface area in heat exchangers) to account for fouling. At a Canadian power plant site, biofouling decreased heat transfer rate in a condenser by 30% over a two month period (8). The plant design had allowed for a 15% decrease due to fouling.

3. increased capital costs for premature replacement of equipment experiencing severe under-deposit corrosion. Recently, a nuclear power plant had to replace a condenser after approximately 6 years operation because of severe corrosion attributed partially to microbial activity. The condenser had a design lifetime of approximately 20 years.

4. unscheduled turnarounds or downtime, resulting in loss of production, to clean equipment which fouled at an unanticipated rate. Downtime can cost a power plant as much as $1 million per day because they must purchase the power from elsewhere to serve their customers. In oil production, downtime relates directly to the amount of product being shipped which could extend to $10 million per day.

5. quality control problems resulting from fouling of heat exchange equipment or fouling of product stream (e.g. sliming of paper mills or rolled steel).

6. safety problems. Fouling of service water systems in nuclear power plants is a major concern because it reduces the heat transfer capacity available during an emergency or during an accident. Fouling in drinking water distribution systems may lead to high concentrations of microbes in the drinking water which potentially

affect public health. Deaths due to Legionnaire's disease has been attributed in several instances to fouling in cooling towers.

The anticipated presence of significant fouling can alter the size and other design features of operating equipment. The operation of equipment subject to fouling is constrained by the need to formulate economically justifiable cleaning schedules and internal treatment programs.

An estimate of the economic consequences of fouling was presented by Pritchard (9) for fouling in Britain and suggests the cost was between $600-1,000 million per year (about 0.5% of the British 1976 GNP). Van Nostrand et al. (10) have estimated, that for petroleum refining in the non-Communist countries, the total cost of fouling is $4.4 billion per year. The costs are bound to increase with increasing fuel and material costs. Fouling in heat exchangers may cost the United States billions of dollars annually (11).

In industrial equipment, fouling of surfaces can be the main cause of progressive reduction in performance and efficiency. Accumulation of slime, dirt, and debris in the industrial environment rarely causes concern and, is the cause for the limited attention focused on fouling in the past. However, the cost of problems related to fouling are significant and must be emphasized to designers and operators of equipment.

A RATIONAL APPROACH TO SOLVING FOULING PROBLEMS

Fouling is a complex phenomenon resulting from several processes occurring in parallel and in series. The rate and extent of these processes, in turn, are influenced by numerous physical, chemical, and biological factors in the immediate environment of the substratum. Many laboratory experiments and field observations have resulted in volumes of data without deducing relationships of wide, general use. A conceptual framework for describing fouling processes would be benefical in interpreting available historical data and be invaluable in designing future experimental fouling tests. If the conceptual framework could be stated in mathematical terms, more benefits would accrue including the ability to mathematically simulate fouling processes on the computer, computer "experiments" frequently being less expensive than laboratory experiments. The simulation can be supported by a large database and a logic program to form an "expert" system.

A rational approach, as contrasted with an empirical approach, develops the conceptual framework by resorting to fundamental processes which are reasonably well understood.

A rational approach to fouling entails a process analysis which identifies the contributing fundamental processes and determines the influence of process variables on process rate and extent. The approach requires experimental measurement techniques which permit the elucidation of the specific processes. Many of these fundamental processes have been described mathematically in Characklis et al. (12). The mathematical description of the individual processes can be combined to develop models to extrapolate and generalize experimental results.

The difficulty in generalizing or extrapolating experimental fouling data is related to the complexity of the process which frequently involves heat transfer, mass transfer, momentum transfer, as well as physical, chemical, and biological processes at the surfaces. The goal of a rational approach is to elucidate the fundamental processes that contribute to the overall fouling process. Once these fundamental processes are properly understood, they are incorporated into a mathematical model of the overall fouling process. The model validation requires experiments designed specifically to investigate particular fundamental processes rather than experiments which consider only the overall deposit accumulation process. Such fundamental experiments frequently require more effort than tests which simply observe the overall fouling process, but the fundamental experiments ultimately lead to results that can be applied with greater confidence to a wider range of fouling situations.

The tools of process analysis lead to rational methods for comparing the effects of metallurgy, shear stress, heat flux, water temperature, geometry, biocide treatment, etc., on fouling processes and their influence on equipment performance. Simulation can also be used to test operating and maintenance procedures such as internal treatments and cleaning schedules (13). The process analysis technique may also lead to a more systematic method for developing and evaluating fouling control techniques, regardless of whether they employ physical, chemical, or even biological methods.

Defining Fouling *Rate* and *Extent*

Fouling biofilm accumulation can be considered the net result of the following physical, chemical, and biological processes (14):

1. transport of soluble and particulate components to the wetted substratum,
2. net adsorption of soluble and/or particulates to the wetted substratum,
3. chemical or microbial reaction at the substratum or within the deposit, and
4. net detachment, sloughing, or spalling of portions of the deposit from the wetted substratum.

The overall result is a sequence of events generally characterized by a sigmoidal-shaped progression including three identifiable periods (Fig. 1).

1. an induction period in which very small changes in accumulation are detectable,
2. an exponential increase period which is characterized as the *logarithmic rate* (or *log rate*) of accumulation and is used to represent the kinetics of net accumulation, and
3. an asymptotic or plateau period which is a criterion for the *extent* of net accumulation.

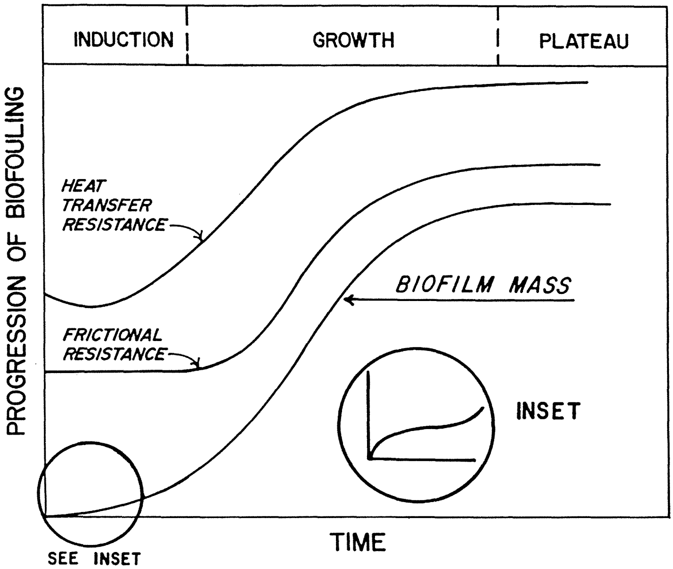

Fig. 1. The progression of biofouling is generally described by a sigmoidal function (Eq. 1) when expressed in terms of deposit accumulation, hydrodynamic frictional resistance, or heat transfer resistance. Three periods or phases can be arbitrarily defined: (i) the *induction* period during which little measurable accumulation occurs, (ii) the *log rate* accumulation period, and (iii) the *plateau* or pseudo steady state period when accumulation is constant. The plateau period represents the *extent* of deposit accumulation

Characklis (14) has described the progression of biofilm accumulation as the result of several distinct processes. Experimental methods and techniques necessary to distinguish the rate of individual contributing processes is sometimes difficult. Yet, characterization of the rate and extent of net accumulation is necessary for evaluation of many field tests in which the more fundamental processes cannot be determined.

The sigmoidal progression can be described by the logistic equation:

$$\frac{dX_f}{dt} = k\,X_f\,(1 - k'\,X_f) \qquad [1]$$

where X_f = deposit concentration (arbitrary units)
k = rate coefficient (t^{-1})
k' = saturation coefficient (arbitrary units)

Using the logistic equation, the *log rate* of biofouling deposit accumulation can be defined in terms of the rate coefficient k. The *log rate* occurs early in the progression when $k'X_f << 1$. The *extent* of biofouling deposit accumulation can be represented by $X_{f,max}$ or the coefficient k' and is determined at "steady state" when $k' = X_f$. Thus, k and k' (or $X_{f,max}$) are used in this paper as coarse indicators of system kinetics and stoichiometry to describe factors which influence net biofouling deposit accumulation. The terms *log rate* and *extent*, when used in the specific context of net biofouling deposit accumulation, are underlined to emphasize the distinction between these two characteristics of biofouling deposit accumulation. Several variables are used to represent net accumulation and can serve as the variable X in Eq. 1 including biofilm thickness, biofilm mass, fluid frictional resistance, and heat transfer resistance resulting from biofilm accumulation (15).

The rate and extent of fouling can be controlled by many process variables and can vary considerably with location and process environment. Hence, the length of the three periods (induction, exponential increase, plateau) may vary also. For example, the induction period may not be detectable in a water containing very high concentrations of microorganisms since adsorption rate will be very high. On the other hand, a very hard precipitate may form in parallel with the biofilm so that detachment rate is negligible and no plateau period is discernible. The sensitivity of the measurement technique will also influence the length of the various periods. For example, a rather insensitive technique will result in a relatively long induction period.

The deleterious effects of fouling can be experienced at drastically different levels of deposit accumulation. For example, deposition of very few cells in a computer chip manufacturing process can cause significant losses. Approximately 50% of manufactured computer chips are wasted, many because of microbial contamination. In drinking water, on the order of 1,000 to 10,000 coliform cells per m^{-3} are sufficient to disturb the operation of the distribution system. On the other hand, a biofilm thickness of 40 - 60 μm may be necessary to cause an increase in fluid frictional resistance.

Transport and interfacial transfer processes

Transport. Transport of dissolved and particulate materials from the liquid to the wetted substratum is the first step in the overall fouling process and has been described in Characklis et al. (1990a). Transport rates for soluble materials can be predicted reasonably well with accepted empirical relationships. Predicting transport rates of particulates from the bulk fluid to the wetted substratum is more difficult (12).

Deposition. Advective transport has frequently been combined with adsorption-desorption processes into a process termed deposition, primarily because techniques to distinguish between these processes are difficult. Deposition is easier to measure but is the net result of several processes. Frequently, investigators focus on advective transport rates and incorporate a "sticking efficiency" to rationalize measurements of deposition rates (12). Experimental observations, even with inert particulates (16), indicate that sticking efficiency changes as deposition alters the characteristics of the wetted substratum.

Advective transport may be the rate-limiting process in some cases of particulate fouling. However, it appears doubtful that advection will limit the rate of deposition for biofouling except in the very early stage of accumulation (i.e. the induction period in Fig. 1) or in very dilute environments.

Detachment. Detachment is a significant process, especially as the deposit becomes thicker and fluid shear stress increases (17). The detached material often deposits in other parts of the system as has been observed with corrosion products (18). Detachment processes are mostly responsible for the asymptotic phase of a typical fouling progression (Figure 1). During this phase, detachment rate is equal to the combined effects of transport, adsorption/adhesion, and reaction on deposit accumulation.

Reactions at the substratum or within the deposit

Chemical and biochemical reactions at the substratum or within the deposit can contribute significantly to the accumulation of the fouling deposit. In some cases, there will be significant interactive effects such as observed with microbially-mediated corrosion which is a combination of microbial growth and/or product formation as well as deterioration of the substratum (e.g. metal dissolution). In this case, microbial (metabolic) products may diffuse to the metal substratum and cause deterioration (corrosion) of the substratum.

Relevant reactions include microbial growth, extracellular polymer formation, endogenous respiration, and death/lysis. Microbial cells, once attached to the substratum, grow, multiply, and form products from chemical energy (chemosynthetic organisms) derived from the bulk water. In most cases, organic compounds (heterotrophs) provide the energy but reduced inorganic compounds (e.g., Fe^{++}, NH_3, $S^{=}$) can also be used (chemolithotrophs). Photosynthetic organisms can sometimes provide the organic compounds for heterotrophic growth as has been observed in recirculating cooling tower systems. The relative extent to which cells or product (primarily extracellular polymer substances, EPS) dominate the deposit will significantly influence the effectiveness of any chemical treatment in preventing or removing a biological fouling deposit. The biological deposit, an adsorptive surface, will frequently enhance the accumulation of other fouling deposits such as particulate deposits (19), precipitation deposits (20), and corrosion deposits (3).

Measurement and Simulation

Need and purpose

Experimental investigation of the fouling process is a necessary and important route to minimizing its effects on performance. If reliable fouling data can be obtained with full-scale equipment using the actual process fluids, other measurements and simulation are unnecessary. However, many of the parameters of interest vary considerably throughout the equipment and, in addition, vary with time. As a result, interpretation of operating data is difficult and measurements in the laboratory and onsite are necessary so that some measure of control is possible. Laboratory observations under carefully controlled conditions provide the framework for evaluating and interpreting field results where control of all parameters is not possible. On the other hand, field results indicate inconsistencies in the models and provide the impetus and experimental hypotheses for further laboratory work.

Laboratory tests. Laboratory tests are generally more cost effective than field tests when goals and objectives are concisely defined. The laboratory provides the proper environment for conducting defined tests which lead to useful models in terms of simulating real systems. These tests are a "starting point." Physical, chemical, and biological factors can be controlled at desired levels. Valuable information can be obtained related to design concepts such as influence of alloy (19), fluid velocity, tube geometry (e.g., enhanced heat transfer surfaces), and temperature profiles (21). The effect of water quality (chemical and biological) on these factors can also be evaluated. Operation and maintenance procedures can be evaluated. For example, laboratory tests can evaluate the effectiveness of a treatment (chemical or physical) procedure applied at varying frequency (22, 23). These tests frequently identify the operating conditions which are best for a given treatment procedure. Laboratory experimentation has also resulted in development of novel measurement techniques useful for field tests and monitoring.

Field tests. Ultimately, measurements at the process site are essential. Measurements with fouling monitors simulate the process environment and can be used to evaluate the potential for fouling as well as the effectiveness of treatment programs. Fouling monitors have been used extensively at power plant sites. For example, sidestream fouling monitors are presently capable of qualitatively simulating fouling processes in a condenser. In addition, sidestream monitors are useful for testing the effects of various design, operating, and environmental variables on fouling processes. However, in situ fouling monitors are needed for regulating fouling control programs in the condenser. More sensitive fouling monitors (sidestream and in situ) are needed to detect very thin biofilms (and/ or their effects) and to permit rapid feedback for fouling control treatments. Frequently, on site fouling tests are only conducted for several months starting from a clean tube. There may be slow processes that only manifest themselves in the fouling dynamics after longer periods of time. However, monitors installed *in situ* will supply long term data which can serve adequately for calibrating models.

How do results from fouling monitor tests relate to operation of technical scale equipment? Fouling monitors, at present, are capable of qualitatively simulating fouling processes as they occur in operating equipment. For example, an experimental program using monitors in an onsite sidestream at a nuclear power plant have resolved an important qualitative question: Is the effective chlorine dose in a condenser a product of concentration times duration? The answer is "No". Under realistic (but not necessarily representative) conditions of temperature and flow, over a realistic range of chlorine concentrations and daily exposure, accumulation of a biofouling deposit on titanium tubes is much more dependent on chlorine concentration than on duration of the treatment (13). Accordingly, by implementing higher concentrations and shorter durations, it is possible to achieve a greater degree of fouling control for the same total chlorine dosage (i.e. the product of concentration and duration), within regulatory limits. The essential qualitative result, that there is an optimal combination of concentration and duration (which is almost certainly different from the simple regulatory constraint of 2 hours per day at a dose that just meets the discharge limit), must hold true for operating condensers as well as for the test systems. The test system is similar enough to the operating condenser that there is no reason this should not be true. The experimental program also identified an optimal daily dose schedule under the conditions of the test.

Quantitatively, however, the specific values defining the optimal chlorine dosage (i.e. the most efficient combination of concentration and duration) in an operating condenser is bound to be somewhat different from that identified in a test system at that site, and will doubtless vary with the seasons and the site. Some of the problems related to seasonal variations in fouling are dependent on design of the equipment (e.g. the heat transfer capacity of a condenser) and the change in operation throughout the year (e.g. change in "heat rate", (24)). The least tractable causes of difference from season to season and from site to site are differences in substratum material, water chemistry, nutrient supply, and source microbial species. The variability owing to season and to site conditions can, of course, be taken into account by conducting measurements with a test system at that site and that time. What is not so simply accomplished is the lesser correction between the test system and the operating equipment. The key to the differences between the test system and the operating equipment is scale. For example, an operating power plant condenser tube bundle is fed by a water box, with the result that different tubes experience different temperatures and flow regimes. Each condenser tube is generally an order of magnitude longer than the test section of the fouling monitor. Because of the gradient in heat exchange rate down the condenser tube and because of the nature of the long tube as a plug flow reactor, there will be systematic differences along the length of the condenser tube with respect to wall temperature, water temperature, residual chlorine, nutrient availability, and possible other chemical changes wrought by the upstream deposit. Power plant operations personnel sometimes observe more fouling at the exit of the condenser as compared to the entrance tube region. Thus, a monitored test section can be assembled to mimic any particular short section of the tube, but the same test section cannot mimic the entire span simultaneously. Analysis of fouling deposits from a dismantled nuclear power plant condenser (admiralty brass) indicate, however, that the differences between tubes overwhelmed whatever pattern may have existed in the fouling gradient along the tubes (25).

What limits our ability to transfer conclusions from the fouling monitors to operating equipment? The extrapolation from the monitors to the operating equipment is constrained both by the amount of effort and attention that can be devoted to monitoring in an operational mode (in situ) and by the available scientific information for modifying fouling predictions to accommodate varying environmental or operating conditions. Studies with the fouling monitors at power plants (26) have been conducted in an experimental mode (sidestream) and may require considerable resources for maintaining controlled conditions. An in situ or operational monitoring program places far fewer demands on personnel and other resources as compared to an experimental monitoring program. However, operational monitoring will probably not be as precise as experimental monitoring nor can the operational monitoring be as extensive. Experimental monitoring may identify an optimal chlorination schedule empirically, while an operational monitoring program will only observe responses of fouling rates to treatment because operations will rarely be modified to observe its effect on fouling. Then a modelling effort is required to translate the results from an operational monitoring program into a recommended satisfactory treatment.

Modeling. The objective of developing a model is to determine the coefficients that describe the effects of various operating variables such as temperature, flow rate, and differences in nutrient supply on the dynamics of fouling accumulation. Then, operational monitoring will provide data to calibrate the model for the given application (season and site). This modeling objective is realistic and, with adequate representations of the component processes, will lead to control systems for optimizing biofouling control.

A mathematical model for biofilm accumulation is necessary for relating fouling monitor data to the operating equipment. For example in a power plant condenser, the "plug flow" nature of the condenser tube, the seasonal variation of fouling, and variations of fouling between different tubes in the same condenser are concerns that could be resolved by a validated mathematical model. Field tests have been used to evaluate the influence of physical factors such as substratum composition (e.g. metal alloy) and water velocity on *log rate* and *extent* of fouling. For example, the performance of different alloys has been tested at a power plant site using an instrument which simulates the heat exchange equipment (1). Field tests are also useful in evaluating the performance of contemplated changes in treatment programs and/or process modifications (17, 27). Of all factors influencing fouling, biological variables and chemical water quality appear to be most difficult to simulate and control in the laboratory. Thus, field tests are also necessary.

Measurements related to fouling

Methods for monitoring the progress of the fouling process and methods for characterizing the fouling deposit can be conveniently classified as follows:

1. direct measurement of deposit quantity and/or composition (28).
2. indirect measurement of deposit quantity by monitoring the effects of the deposit on transport processes (e.g. heat transfer and fluid frictional resistance) (15).

Direct measurement includes deposit mass and deposit thickness and are essential for several reasons. Calibration of any indirect method involves comparison with actual quantity of accumulated deposit. Direct measurements are a necessity when using mass conservation equations to establish process relationships. Direct methods are also useful in relating deposit accumulation to fluid frictional resistance and heat transfer resistance.

Indirect methods provide significant benefits including increased sensitivity. For example, organic carbon analysis of biofilm is as much as 25 times more sensitive than biofilm mass measurements (28). In this case, the specific constituent of the deposit (i.e., organic carbon) provides an excellent measure of accumulation. However, if the deposit contains a large amount of silt and sediment, organic carbon will not be representative of the total fouling deposit accumulation. Light absorbance techniques are even more sensitive than carbon analyses but have other limitations (28).

Indirect methods include monitoring the influence of deposits on heat transfer and fluid frictional resistance as discussed above. The extent of the influence of deposits on heat and momentum transfer depends strongly on deposit characteristics (e.g., composition, thermal conductivity, roughness).

FLUID FRICTIONAL RESISTANCE

Fouling deposits cause increased fluid frictional resistance by decreasing the effective diameter of tubes and by increasing the effective roughness of the substratum as described in detail elsewhere (12, 15). Frictional resistance measurement has several advantages as an indicator of fouling:

1. relatively simple and inexpensive
2. in conduit flow, porous media flow, and in ship propulsion, frictional resistance is the quantity of most concern, i.e.,head loss, loss in carrying capacity, clogging, or propulsion efficiency.

However, in some situations, frictional resistance measurements alone are of limited value and sometimes misleading:

1. Frictional resistance measurements in turbulent flow are relatively insensitive until the fouling deposit thickness exceeds a certain value, approximately the thickness of the viscous sublayer. The thickness of the viscous sublayer is inversely proportional to flow velocity in a given geometry.
2. Some deposits such as $CaCO_3$ scale, exhibit a relatively low relative roughness and have a low thermal conductivity. Therefore, frictional resistance will be relatively low even though heat transfer resistance is significant.
3. In some instances, frictional resistance is not the major parameter of interest (e.g. in heat exchangers or condensers, the major concern is heat transfer resistance).

Frictional resistance can increase significantly as a result of even a small increase in roughness. On ship hulls, a equivalent sand roughness height (densely packed) as small as 25 μm can increase drag by 8% while a roughness element of 50 μm will increase drag by as much as 22%. The drag effects become more severe as water velocity increases.

Fouling also causes increased friction losses in porous media by decreasing the effective porosity of a porous media formation, Porous media are dealt with in detail in Cunningham et al. (29).

HEAT TRANSFER RESISTANCE

Combined Heat Transfer and Fluid Friction Measurements

Overall heat transfer resistance is the sum of conductive and advective heat transfer resistance. Advective heat transfer resistance results from fluid motion and generally decreases as the fouling deposit accumulates since the "roughness" of the deposit increases turbulence in the interfacial region. Conductive heat transfer resistance results from insulating layers formed by the deposits and generally increases as the fouling deposit accumulates. The relative changes in advective and conductive heat transfer resistance will depend on the following:

- deposit thickness, deposit roughness, and deposit thermal conductivity
- fluid flow rate
- radial temperature gradient in the tube

Characklis et al. (30) have reported the influence of fouling deposits on conductive and advective heat transfer resistance in tubes in the laboratory and also in plant-scale equipment (12). If deposit thickness is measured along with overall heat transfer resistance and fluid frictional resistance, the effective deposit thermal conductivity and effective deposit roughness can be determined. Effective deposit thermal conductivity and roughness have been determined in several cases by this method (15).

Thus, frictional resistance and heat transfer resistance measurements indicate the effect of fouling on system performance and can indicate the *extent* of fouling but do not yield information on the type of the deposit. At a plant site, the deposits are rarely homogenous but are typically a combination of biofilm, scale, and corrosion products. Results obtained by Characklis et al. (19) indicate significant differences in specific properties (in situ thermal conductivity and relative roughness) between deposits which vary in composition. The different deposit transport properties have been used as a basis for a proposed method for an in situ and non-destructive method for identifying the type of deposit accumulated on the heat transfer surface at a plant site (31).

Heat Transfer Fouling Factor

Heat transfer fouling results are customarily reported in terms of fouling resistance or <u>fouling factor</u> (R_f) which is defined as follows:

$$Rf = U_f^{-1} - U_0^{-1} \qquad [2]$$

where R_f = fouling resistance (t^3 T M^{-1})
U_f = overall heat transfer coefficient for the fouled surface (M t^{-3} T^{-1})
U_0 = overall heat transfer coefficient for the clean surface (M t^{-3} T^{-1})

The use of R_f, fouling resistance, is sometimes misleading and frequently conceals valuable diagnostic information:

1. The influence of fouling on heat exchange rate in engineering design is generally expressed as the thermal (conductive) resistance of the deposit (32). In fact, measured R_f represents the net increase in heat transfer resistance (conductive plus advective resistance) and not thermal (conductive) resistance of the deposit.

2. The conductive resistance of the deposit, in most cases, will be higher than R_f. The extent to which it is greater than R_f will depend on the roughness of the deposit accumulated on the heat transfer surface. The progression of heat transfer resistance due to accumulation of biofilm inside a laboratory tubular reactor experiment (30) was observed to be sigmoidal. In terms of R_f, an increase in heat transfer resistance of 0.00009 m^2 °C/W was observed, but the increase in conductive resistance was 0.00023 m^2 °C/W, 2.5 times higher than R_f.

3. The heat exchanger design values for R_f are generally selected from tables of questionable accuracy with vague information as to the operating condition (e.g. shear stress) and the type of deposit (scale, biofilm, etc.) for which R_f values were determined.

4. The calculation of R_f is directly related to the overall heat transfer resistance (i.e., advective resistance) at clean condition (U_0^{-1}). But water velocity influences the advective resistance at clean condition and, hence, calculation of R_f. Thus, R_f at two different velocities are difficult to compare.

5. Most mathematical models (33-35) describing the influence of fouling processes on heat transfer are based on the following relationship:

$$\frac{dR_f}{dt} = r_{dep} - r_{det} \qquad [3]$$

where r_{dep} = rate of deposition (t^2 T M^{-1})
r_{det} = rate of detachment (t^2 T M^{-1})

This relationship expresses the deposition rate and detachment rate of fouling deposit in terms of energy units rather than in term of mass units. The model (Eq. 3) defines R_f as:

$$R_f = L_f / k_{Td} \qquad [4]$$

where L_f = thickness of deposit (L)
k_{Td} = thermal conductivity of deposit (M L t^{-3} T^{-1})

This relationship is only valid when the advective resistance remains constant and R_f equals conductive resistance of deposit. Fouling, in many cases, is accompanied by an increase in pressure drop or decrease in advective resistance.

At constant R_f (i.e. $dR_f/dt = 0$), the deposition rate equals detachment rate (or thickness remains constant as indicated in Eq. 4). However, constant R_f can also result when the increase in conductive resistance (or thickness) of the deposit equals the decrease in advective resistance (due to deposit roughness). The model (Eq. 3) cannot predict a negative R_f. Yet, negative R_f has been observed in numerous studies during initial biofilm accumulation when the increase in conductive resistance (or thickness) of the deposit is less than the decrease in advective resistance. Negative R_f in the early stages of biofilm accumulation has also been observed in the field when new surfaces are initially exposed to a fouling environment. At constant deposit (biofilm) thickness, change in density or composition of the deposit can influence the conductive resistance (R_f) of the deposit. Asymptotic (or steady state) R_f can only result when conductive and advective resistance of the deposit remain constant. However, biofouling deposit properties such as thickness, density, and/or roughness may be varying.

Therefore, R_f may result in ambiguities, especially as related to simplistic models. Nevertheless, R_f has been used to evaluate fouling processes in many field tests when more detailed information was not available. R_f is also used because of the numerous studies which have reported results in those terms.

However, R_f will be used more generally can also include the fluid friction resistance resulting from fouling.

DEPOSIT PROPERTIES

Fouling monitors frequently measure the increase in frictional resistance and/or heat transfer resistance. These measurements indicate the effect of fouling and do not yield information on the type of deposit. Information regarding deposit properties and composition, however, is often useful in selecting an appropriate treatment procedure.

Deposit Mass and Composition

In addition to fouling monitors, analytical methods have been developed to assess the contribution of biological and chemical processes to overall fouling deposit accumulation. As an illustration, results from physical, chemical, and biological analysis of deposits removed from fouling monitors and operating condensers at several power plant sites are illustrated in Characklis (15). Results of deposit analyses from three different sites are presented as examples in Table 1. The differences in deposit composition at different exposure times and between sites are evident.

Table 1 Comparison of deposit characteristics from fouling monitors at three power plant sites. Water velocity in the tubes containing Hudson River water (24) ranged from 1.34 - 2.23 m s^{-1} on a seasonal basis to simulate plant operating schedule. Site B, on an Atlantic estuary, used a water velocity of 2.16 m s^{-1}. Water velocity at the estuarine Canadian plant (8) was 1.97 ms^{-1}.

Exposure Time (days)	Tube Mat'l. (g/m^2)	Deposit Mass (% deposit mass)	Volatile Mass (% deposit mass)	% C	% N	% H
				(% deposit masss)		
Hudson River						
40	Titanium	1.15	6.28	4.07	0.41	1.27
61	Titanium	6.30	13.45	5.55	0.75	1.35
Atlantic Estuary						
35	Titanium	14.89	26.65	9.50	0.03	1.43
62	Titanium	37.79	26.70	10.03	1.02	1.85
Canadian Estuary						
60	Admiralty Brass	7.77	14.07	0.55	2.59	

Deposit Thickness

Deposit thickness is difficult to determine experimentally and has rarely been accomplished in field tests. However, thickness is extremely important because it is required to determine deposit density and distribution of other constituents in the deposit. In addition, the usefulness of deposit roughness depends on the thickness measurement. In some cases, the standard deviation in the thickness measurement represents an estimate of biofilm roughness (36).

Deposit Transport Properties

Industrial fouling deposits are rarely homogenous and can exhibit a wide range of chemical and microbial composition. Not surprisingly then, two deposits of equal thickness can influence heat and momentum transfer in drastically different ways since deposit thermal conductivity and relative roughness can vary widely (Table 2):

Table 2 A comparison of measured values for thermal conductivity and relative roughness of biofilm and $CaCO_3$ deposits (37).

Deposit	Thickness (μm)	Relative Roughness (---)	Thermal Conductivity (W m^{-1} °C^{-1})	Reference
Biofilm	40	0.003		(17)
	165	0.014		(17)
	300	0.062		(17)
	500	0.157		(17)
$CaCO_3$	165^1	0.0001		
	224^1	0.0002		
	262^1	0.0006		
$CaCO_3$			2.26 - 2.93	(38)
$CaSO_4$			2.31	(38)
$Ca_3(PO_4)_2$			2.60	(38)
$Mg_3(PO_4)_2$			2.16	(38)
Fe_2O_3 (magnetic)			2.88	(38)
Analcite			1.27	(38)
Biofilm	≈100		0.63	(19)

^{1}Calculated from overall heat transfer resistance assuming a thermal conductivity for $CaCO_3$ of 2.6 W m^{-1} °C^{-1}.

If in situ deposit thickness were determined, effective deposit thermal conductivity and roughness could be determined by measurement of conductive and advective heat transfer resistance, fluid frictional resistance, and engineering correlations. This *in situ* diagnostic method could be incorporated into an on-line fouling monitor. Such a diagnostic tool would find advantage as a feedback control instrument in an operating plant. As more data accumulates, deposit composition could be estimated from thermal conductivity and roughness determinations in much the same way as chemical composition is determined from "libraries" of spectral data associated with gas chromotography-/mass spectrometry.

SUMMARY

Biofouling is the undesirable accumulation of a microbiological deposit on a surface. Complex biofouling deposits found in industrial environments often consist of biofilms in intimate association with inorganic particles, crystalline precipitates, and/or corrosion products. The biofouling process is characterized by a *log rate* and an *extent*, each influenced by a variety of operating and environmental variables including water temperature, fluid velocity, etc.

A rational approach to industrial biofouling processes is necessary for several reasons including the following: 1) to determine the effects of critical variable in any given system, 2) to compare biofouling processes in different systems, 3) to develop standard practices related to design, operation, and control. Such a rational approach is only possible through proficient use of fluid dynamics, energy balances, and mass balances in the operating systems.

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