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M. TURAKHIA , W. G. CHARACKLIS & N. ZELVER

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Fouling of Heat Exchanger Surface: Measurement and Diagnosis

M. TURAKHIA and W. G. CHARACKLIS

Institute for Biological and Chemical Process Analysis, Montana State University, Bozeman, Montana 59717

N. ZELVER

Bridger Scientific Inc., 316 South Sixth, Bozeman, Montana 59715

Fouling in heat exchange equipment results in a significant energy loss by increasing heat transfer resistance and fluid frictional resistance. This paper deals with an effective way to monitor fouling and describes a potentially useful diagnostic approach for discriminating different types of deposit in situ. Information regarding deposit type would be useful in selecting an appropriate treatment procedure. Some cautions regarding the indiscriminate use of fouling factor or fouling resistance are also discussed.

INTRODUCTION

Fouling is a term applied to formation of undesirable deposits on surfaces. In cooling systems, these deposits form on condenser tube walls increasing fluid frictional resistance, accelerating corrosion, and impairing heat transfer. Fouling includes both organic deposits (e.g., biofouling and chemical reaction fouling) and inorganic deposits (e.g., scaling, corrosion, and particulate). Biofouling refers to attachment and growth of microorganisms on surfaces, and scaling refers to crystalline fouling caused primarily by precipitation (e.g., CaCO_3 , CaSO_4 , or silicates). This paper is directed at monitoring and diagnosing fouling deposits as

well as proposing cautions when interpreting fouling data.

THE PROBLEM

Fouling of heat transfer surfaces results in energy losses. Traditionally, water quality analyses and fouling monitors have been used to predict fouling potential of heat transfer equipment, and the determination of remedial procedures is generally based on one of these measurements.

The water quality parameters (e.g., chemical analysis, selective ion electrode, and bacterial counts) define conditions in the bulk water that are generally significantly different from surface conditions where the problem exists. The fouling monitors indicate the effect of deposits on (1) frictional resistance, (2) heat transfer resistance, or (3) combined heat transfer and frictional resistance.

Moreover, frictional resistance and heat transfer resistance are closely related to specific properties of the deposit. For example, viscoelasticity and

All correspondence should be addressed to W. G. Characklis, Institute for Biological and Chemical Process Analysis, Montana State University, Bozeman, Montana 59717.

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roughness of the deposit affects fluid frictional resistance and convective heat transfer resistance, while the deposit thickness and thermal conductivity influence conductive heat transfer resistance [1].

However, no measurements yield information regarding deposit composition that may help in choosing or evaluating a particular treatment program.

This paper deals with the following:

1. An effective method to monitor fouling
2. The relative advantages and disadvantages of different monitoring methods
3. Influence of fouling deposit composition on conductive and convective heat transfer resistance
4. Precautions in interpreting *fouling resistance* data that, by definition, do not recognize the contribution of conductive and convective heat transfer resistance of the deposit
5. A concept, based on the specific properties of the deposit, that can be used as a diagnostic decision variable for choosing an internal treatment program for the control of fouling

METHODS

The experimental results presented in this paper were obtained by measuring the increase in deposit thickness, increase in heat transfer resistance, and increase in frictional resistance using a fouling monitoring system [1, 2]. The theoretical basis for the operation of the monitor and usefulness of the resulting data has been documented previously [3]. The monitor is commercially available* and has been used successfully in the laboratory and in field studies. The monitor consists of the following major components (Fig. 1):

1. A *heat transfer section* consisting of an electrically heated metal block clamped around a tube. Two thermistors are embedded in the metal block (TWHE) at two different radial distances from the center of the tube. The tube is interchangeable and can be made of any alloy. The pressure drop across the TWHE was measured by a differential pressure transducer. The reactor includes a flow meter and two temperature probes for bulk water temperature.

*Bridger Scientific Inc., 316 South Sixth, Bozeman, Montana.

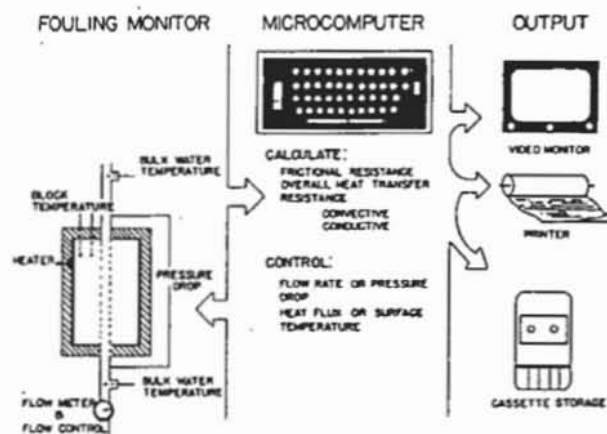


Figure 1 Components of fouling monitoring system.

2. A microcomputer serves as a complete data processing system. The microcomputer can also control flow rate or pressure drop in the tube and can control heat flux to the tube or wall temperature. Output from the microcomputer can be displayed on a television monitor and includes all pertinent measurements and calculations. The data are stored on disks.
3. A *test section* that consists of a series of removable sample tubes (5.1 cm in length) held in place to form a continuous tube. A sample tube may be removed for:
 - Estimating deposit volume, mass, and/or thickness
 - Microbial analysis (e.g., viable and total cell counts)
 - Chemical analysis
 - Scanning electron microscopy
 - Visual observations

The overall heat transfer resistance is calculated from two temperatures at different radial distances in the metal block and bulk water temperature. The change in convective heat transfer coefficient is determined from measurements of friction factor (calculated from pressure drop and fluid flow rate measurements) and its insertion in the Colburn analogy [3]. The average thickness of the deposit is estimated from the volume of the deposit. A detailed description for determining deposit volume is presented elsewhere [4].

The conductive resistance of the deposit is calculated from the difference between overall resistance and convective resistance. The thermal conductivity of the deposit is estimated from conductive resistance and the thickness of the deposit. The roughness characteristics of the deposit are estimated from Reynolds number and

friction factor measurements. A summary diagram of the fouling measurements is shown in Fig. 2.

Characklis et al. [3] have determined that thermal conductivity of the biofilm is the same as that of water by the *above measurements*. The thermal conductivity and the thickness of the biofilm were used in subsequent experiments to compare the calculated and measured overall heat transfer resistance. In most cases, the calculated value was a good estimate of the measured value.

PRESSURE DROP

Fouling of heat transfer surfaces will increase the resistance to fluid flow, as measured by the increase in pressure drop (at constant fluid velocity). Thin biofilms developed on wetted surfaces in tubes and pipes can increase fluid frictional resistance (and turbulent intensity) to flow. Large frictional resistances due to biofilm deposition are encountered and have been measured in the laboratory [4, 5] and field [6-8]. The following mechanisms can contribute to increase in the resistance to fluid flow due to *biofilm accumulation*: (i) constriction of the tube due to deposit accumulation, (ii) increased energy dissipation in the fluid due to surface roughness of the deposit, and (iii) increased drag by virtue of viscoelastic properties of the deposit.

The mechanism contributing to increase in frictional resistance depends on the type of the deposit. Generally in the case of biofilm, the biggest contributing factor is the increased roughness. The roughness effect is magnified by filamentous organisms that become established in the biofilm [5, 9]. Picologlou et al. [5] have shown constriction of a tube to be an insignificant cause of frictional resistance from biofilm formation. In contrast, constriction of tube diameter by scale deposits has been shown to be substantial [10].

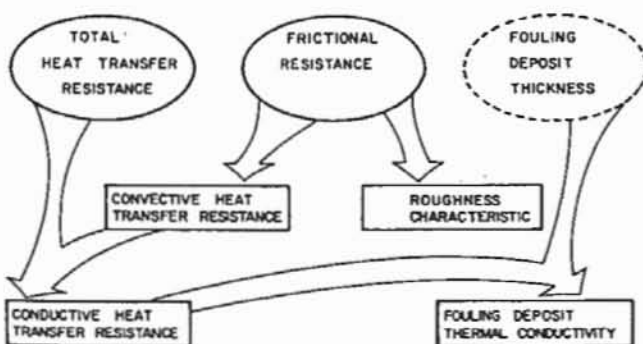


Figure 2 Summary of fouling monitoring measurements.

Table 1 Roughness Characteristics of Deposits

Type deposit	Deposit thickness, cm	Relative roughness, dimensionless	Ref.
Biofilms	0.0040	0.003	[5]
	0.0165	0.014	
	0.0300	0.062	
	0.0500	0.157	
CaCO ₃ scale	0.0165	0.0001	[1]
	0.0224	0.0002	
	0.0262	0.0006	
Combined biofilm/scale	0.0118	0.006	[18]
	0.0363	0.04	

Pressure drop alone has been used to monitor fouling and has several advantages as a fouling indicator: (1) simple and inexpensive, and (2) in water distribution systems, it monitors the quantity of most concern—head loss or loss in carrying capacity.

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

1. Some deposits, such as CaCO₃ scale, exhibit a low relative roughness (Table 1) and, hence, the pressure drop or convective heat transfer resistance (Fig. 3) remains essentially constant except as influenced by constriction of tube diameter. In our studies, CaCO₃ deposit thickness was so small that the increase in pressure drop (approximately 4%) was too small to measure with any precision.
2. Frictional resistance measurement is relatively insensitive until the fouling deposit roughness

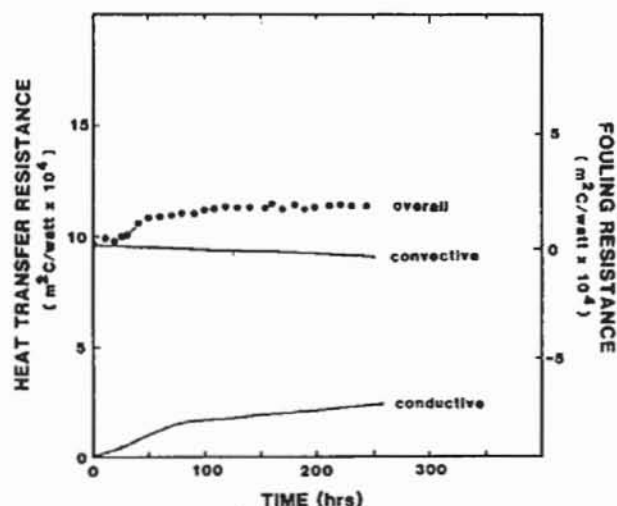


Figure 3 Progression of heat transfer resistance due to the deposition of calcium carbonate for a constant flow of 0.91 m s⁻¹ (tube alloy 70:30 Cu/Ni and Ca²⁺ = 250 mg L⁻¹).

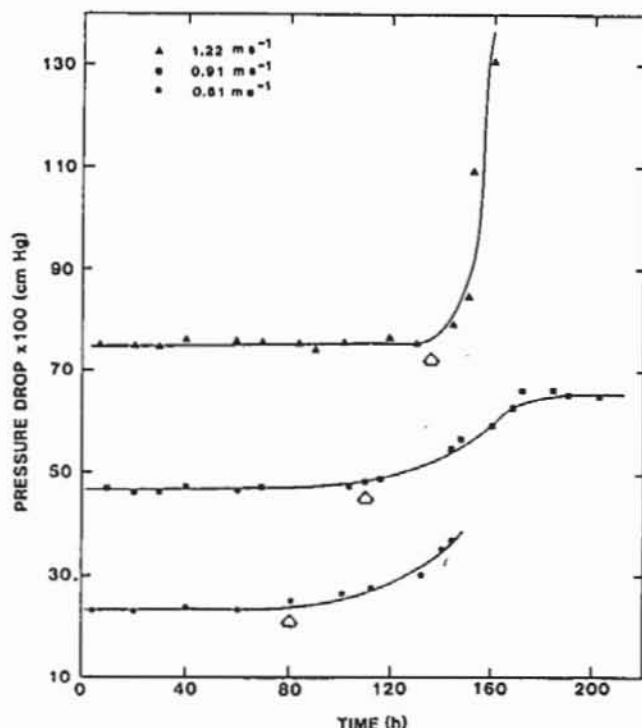


Figure 4 Progression of pressure drop due to biofilm development at different flow velocities [tube alloy titanium, $\text{Ca}^{2+} = 50 \text{ mg L}^{-1}$, total organic carbon = 10 mg L^{-1} (glucose)]. Arrows indicate the time at which the pressure drop begins to increase.

elements (or thickness) exceed a certain value, approximately the thickness of the viscous sublayer [5].

Figure 4 presents the progress of pressure drop due to biofilm accumulation on a titanium tube at varying fluid velocity (shear stress) in a laboratory experiment. The increase in pressure drop occurs at the time at which deposit thickness (and/or roughness element height) is approximately equal to the viscous sublayer thickness. Figure 5 indicates the theoretical decrease in viscous sublayer thickness with increasing Reynolds number. The experimentally determined data points (Fig. 5) represent the average measured biofilm thickness at which measured pressure drop began to increase [5, 11]. The consistency of the results is satisfactory.

OVERALL HEAT TRANSFER RESISTANCE

Fouling can also be monitored by measuring the increase in overall heat transfer resistance, which is the major concern in heat exchangers/condensers.

The overall heat transfer resistance is the sum of conductive and convective heat transfer resistance.

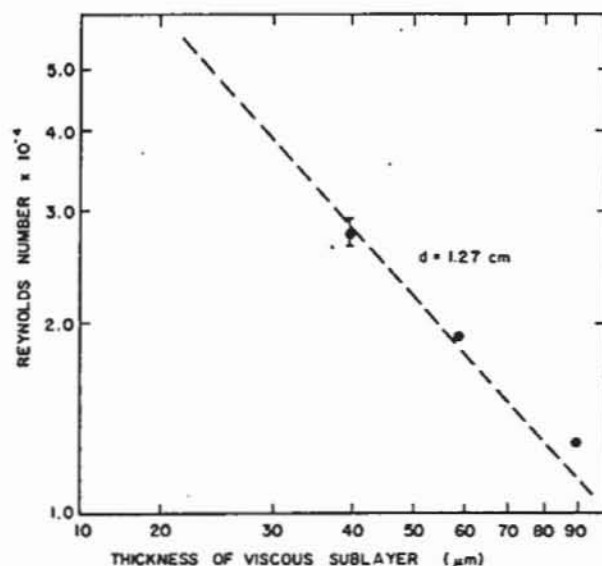


Figure 5 Changes in viscous sublayer with Reynolds number. Data points indicate the average deposit thickness at which pressure drop begins to increase.

For a clean tube, at time $t = 0$, the *conductive resistance of the deposit* is zero so that the convective resistance is equal to the overall heat transfer resistance (clean tube). At any time, $t > 0$, the relative contribution of conductive and convective resistance to overall heat transfer resistance will depend on the type of deposit accumulated on the heat transfer surface.

Results obtained in our laboratory indicate that various deposit compositions influence conductive and convective heat transfer resistance in dramatically different ways. The following observations are noteworthy:

1. In case of a CaCO_3 scale (Fig. 3), the increase in overall heat transfer resistance was largely due to the increase in conductive resistance of the deposit. This type of deposit was found to exhibit a low relative roughness, and the convective resistance was essentially constant. Hence, in this case, the effect of the deposit roughness on overall heat transfer resistance was negligible.
2. The calcium carbonate/silicate scale (Fig. 6) exhibited a higher increase in overall heat transfer resistance as compared to a calcium carbonate scale. The change in convective heat transfer resistance was significantly greater than observed in Fig. 3 for CaCO_3 deposition. We presume that silicate influences the surface characteristics of the deposit leading to increased fluid frictional resistance.
3. For a combined biofilm/scale (Fig. 7), the in-

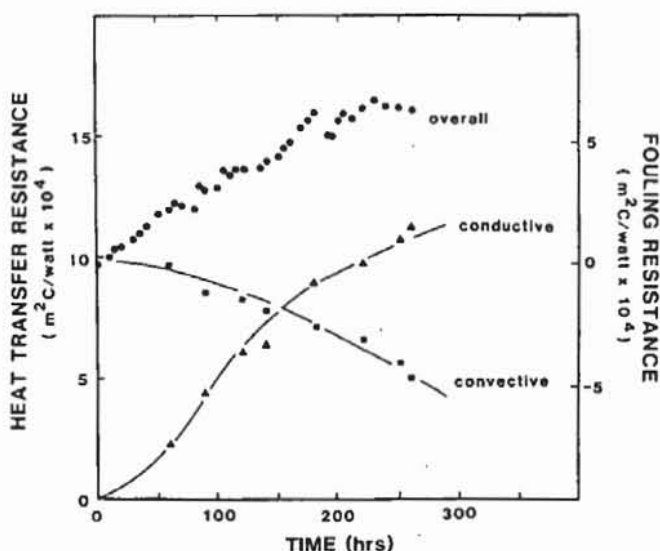


Figure 6 Progression of heat transfer resistance due to the deposition of calcium carbonate/silicate scale for a constant flow of 0.91 m s^{-1} (tube alloy 70:30 Cu/Ni, $\text{Ca}^{2+} = 250 \text{ mg L}^{-1}$, $\text{Na}_2\text{SiO}_3 = 200 \text{ mg L}^{-1}$).

crease in conductive heat transfer resistance was largely offset by the decrease in convective resistance (due to deposit roughness). Other investigators have observed the dramatic effect of biofilm on fluid frictional resistance [7, 8].

FOULING RESISTANCE

Fouling data are customarily reported in terms of *fouling resistance* or *fouling factor*, which is defined as follows:

$$R_f = U^{-1} - U_0^{-1} \quad (1)$$

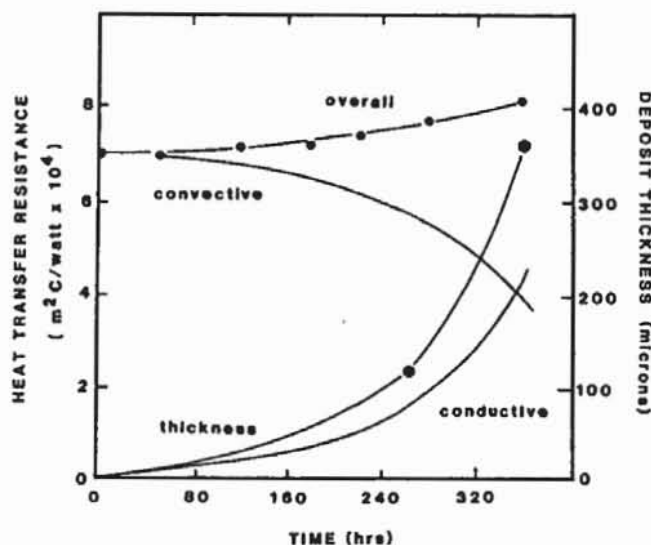


Figure 7 Progression of heat transfer resistance due to the deposition of combined biofilm/scale for a constant flow of 0.91 m s^{-1} [tube alloy 70:30 Cu/Ni, $\text{Ca}^{2+} = 250 \text{ mg L}^{-1}$, total organic carbon = 10 mg L^{-1} (glucose)].

where R_f is the fouling resistance ($\text{M}^{-1} \text{ t}^3 \text{ T}$), U^{-1} is the overall heat transfer resistance at any time t ($\text{M}^{-1} \text{ t}^3 \text{ T}$), and U_0^{-1} is the overall heat transfer resistance at time $t = 0$ ($\text{M}^{-1} \text{ t}^3 \text{ T}$).

The term *fouling resistance* is sometimes misleading and does not yield any valuable diagnostic information regarding deposit characteristics:

1. The influence of fouling on heat exchange rate in engineering design is generally determined as a *fouling resistance* describing the *thermal* (conductive) resistance of the deposit [12]. In fact, the term fouling resistance represents the *net* increase in heat transfer resistance (conductive plus convective resistance) and not thermal (conductive) resistance of the deposit.
2. The design values for fouling resistance are generally selected from tables (e.g., TEMA Standards) of questionable accuracy with vague information as to the operating condition (shear stress) and the type of deposit (scale, biofilm, etc.) for which fouling resistance values were determined. As a result, heat exchangers frequently do not meet the operating criteria for which they were designed.
3. The conductive resistance of the deposit, in *most* cases, will be higher than the fouling resistance. The extent to which it is greater than fouling resistance will depend on the roughness characteristics of the deposit accumulated on the heat transfer surface. Figure 8 shows the increase in heat transfer resistance due to accumulation of biofilm inside a tube in a laboratory experiment [3]. In terms of fouling resistance, an increase in heat transfer resistance

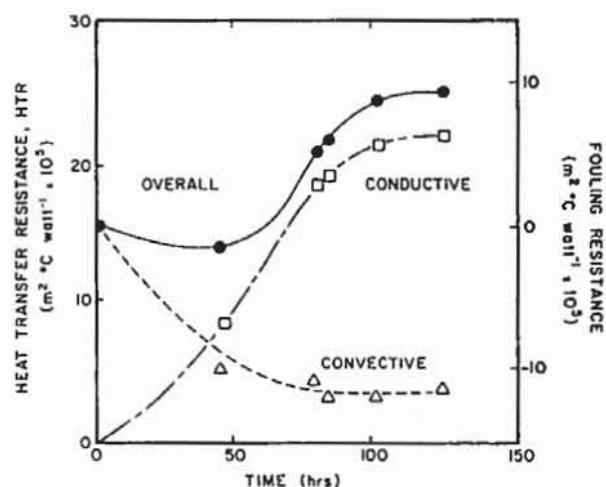


Figure 8 Relative contribution of convective resistance and conductive resistance to overall heat transfer resistance due to a biofilm deposit in a laboratory experiment.

of $0.00009 \text{ m}^2 \text{ }^\circ\text{C/W}$ ($0.00051 \text{ ft}^2 \text{ h}^\circ\text{F/Btu}$) was observed, but the increase in conductive resistance was $0.00023 \text{ m}^2 \text{ }^\circ\text{C/W}$ ($0.0013 \text{ ft}^2 \text{ h}^\circ\text{F/Btu}$), 2.5 times higher than fouling resistance.

4. The calculation of fouling resistance depends on the overall heat transfer resistance measured at a clean condition for a given fluid velocity (i.e., convective resistance). However, if the fluid velocity past the heat transfer surface changes during operation, the overall heat transfer resistance (or convective resistance) measured at the clean condition cannot be used to determine fouling resistance. These circumstances may be encountered when considering the influence of fouling deposition in emergency service water (ESW) systems. Such systems generally operate at very low fluid velocities until an emergency arises. At that point, fluid velocity changes dramatically, and the fouling deposits are partially removed. The main concern in such a system is the heat transfer rate during the emergency.
5. Most mathematical models [13-15] describing the influence of fouling processes on heat transfer are generally based on the following relationship:

$$\frac{dR_f}{dt} = \phi_d - \phi_r \quad (2)$$

where dR_f/dt is the net rate of fouling accumulation ($\text{M}^{-1} \text{ t}^2 \text{ T}$), ϕ_d is the deposition rate ($\text{m}^2 \text{ K/J}$), and ϕ_r is the removal rate ($\text{m}^2 \text{ K/J}$). This relationship expresses the deposition rate and removal rate of fouling deposit in terms of energy units rather than in terms of mass flux.

Based on Eq. (2), at constant fouling resistance, the deposition rate equals removal rate (or thickness remains constant). However, constant fouling resistance can also result when the increase in conductive resistance (or thickness) of the deposit equals the decrease in convective resistance (due to deposit roughness). In such cases, however, fouling deposit accumulation may be increasing, but its adverse affect on conductive resistance is balanced by a decrease in convective resistance. Such results would indicate that the fouling control program is not performing satisfactorily, and new measures must be taken to counteract fouling.

6. The fouling resistance model [Eq. (2)] defines fouling resistance as

$$R_f = \frac{Th}{k_D} \quad (3)$$

where Th is the thickness of deposit (L) and k_D is the thermal conductivity of deposit ($\text{MLt}^{-3}\text{T}^{-1}$). This relationship is valid only when the convective resistance remains constant (fouling resistance equals conductive resistance of deposit). Fouling, in many cases, is associated with an increase in pressure drop (or decrease in convective resistance).

7. The model [Eq. (2)] cannot predict a negative value of R_f . Yet, negative fouling resistance frequently results during initial biofilm accumulation (Fig. 8), when the increase in conductive resistance (or thickness) of the deposit is less than the decrease in convective resistance. Negative fouling resistance in the early stages of biofilm accumulation has also been observed in the field when new surfaces are initially exposed to a fouling environment. Negative heat transfer resistance can be predicted by incorporating the changes in conductive and convective heat transfer resistance of the deposit in the model [Eq. (2)]. A mathematical model simulating fouling biofilm development and its influence on conductive and convective heat transfer resistance is presented elsewhere [16].
8. Asymptotic fouling resistance can result only when conductive and convective resistance of the deposit remain constant (special case $\phi_d = \phi_r$).
9. At constant deposit (biofilm) thickness, change in density or composition of the deposit can influence the conductive resistance (fouling resistance) of the deposit.

COMBINED HEAT TRANSFER AND FRICTIONAL RESISTANCE

Heat transfer resistance or frictional resistance measurements alone cannot be effectively used to monitor fouling at a plant site since, in such cases, the deposits are rarely homogeneous.

However frictional resistance, in combination with heat transfer measurements, can yield valuable information on the progress of fouling.

FOULING DIAGNOSIS POTENTIAL

Fouling monitors measure the effects of deposition and do not yield information regarding the

composition and type of deposit. Information regarding deposit type would be useful in selecting an appropriate treatment procedure.

Recent experiments in our laboratory indicate a significant difference in fouling deposit properties as shown in Table 1 and Table 2. Fouling deposit properties can be estimated using the fouling monitor (described above), which measures the increase in deposit thickness, heat transfer resistance, and frictional resistance. A summary flow diagram describing how such a monitoring measurement is obtained is shown in Fig. 2. The type of deposit accumulating inside a heat exchanger/condenser can be determined by estimating its thermal conductivity and relative roughness using a fouling monitor if an apparent deposit thickness is known. If an apparent deposit thickness can be determined *in situ*, then *in situ* estimation of deposit thermal conductivity and deposit relative roughness can be used as a diagnostic decision variable for internal control of fouling (Fig. 9). Manual methods for determining deposit thickness have been described elsewhere [17]. A proposed method for obtaining an apparent deposit thickness *in situ* and *automatically* at regular intervals is presently under review prior to testing.

A schematic diagram illustrating the potential use of this method is shown in Fig. 9. This diagram illustrates an automatic feedback control system for implementing or evaluating an internal treatment program in a recirculating cooling tower system using an on-line fouling monitor.

SUMMARY

Fouling refers to the undesirable formation of organic and/or inorganic deposits on surfaces. These deposits can impede the flow of heat across the surface, increase fluid frictional resistance, and increase the rate of corrosion at the surface. Four types of fouling, and their combination may occur on the cooling water side of heat exchangers:

Table 2 Thermal Conductivity of Deposits

Type deposit	Thermal conductivity, $W m^{-1} ^\circ C^{-1}$	Ref.
Biofilm	0.63	[3]
Calcium carbonate	2.26-2.93	[10]
Combined biofilm/scale	1.61	[18]

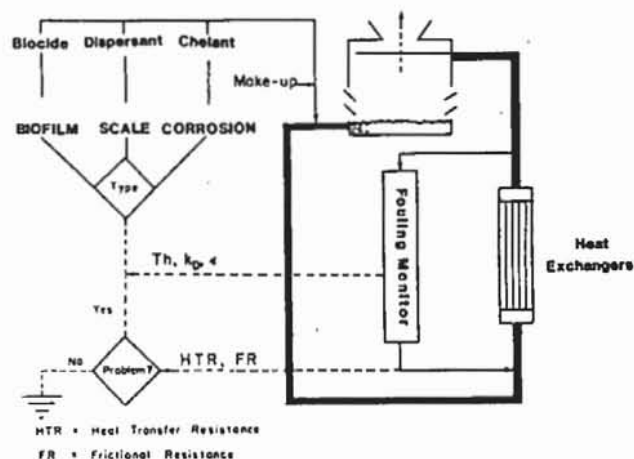


Figure 9 An illustration of the use of a diagnostic, on-line fouling monitor as a feedback control device in an open recirculating cooling tower system.

1. Crystalline fouling—precipitation of inverse solubility salts (e.g., $CaCO_3$, $CaSO_4$) on the heated surface
2. Corrosion fouling—corrosion of tube metal that results in insulating layers of oxides on the tubes
3. Particulate fouling—attachment of particulate material on the tube surfaces
4. Biological fouling—formation of biological deposits on the tube surface

Fouling can be monitored by measuring the increase in frictional resistance and/or heat transfer resistance. Each measurement indicates one effect of fouling and does not yield information on the type of deposit. At a plant site, the deposits are rarely homogeneous. In such cases, frictional resistance, in combination with heat transfer measurements, can yield valuable information on the *extent of fouling*. Results obtained in our laboratory indicate a significant difference in specific properties (*in situ* thermal conductivity and relative roughness) of the deposit. This difference suggests a method for identifying the type of deposit accumulated on the heat transfer surface at a plant site. Such diagnostic information can be extremely valuable in choosing and evaluating chemical treatment programs *in situ* (Fig. 9) at a plant site using a fouling monitor. The output from the fouling monitor will also reflect the performance of various internal chemical treatment programs.

Fouling data have been customarily reported in terms of fouling resistance. Fouling resistance, by itself, is of limited value, is sometimes misleading, and does not yield any diagnostic information

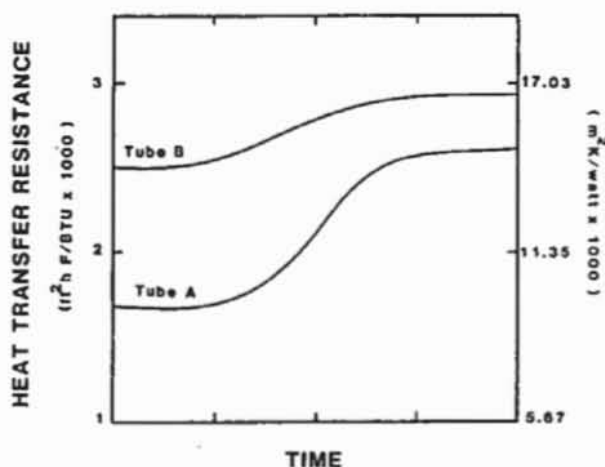


Figure 10 Hypothetical progression of fouling in two tubes (A and B) consisting of different alloys.

regarding deposit characteristics. For example, a two-tube fouling monitor was used at a plant site to test the fouling potential of two tubes, A and B, under identical environmental conditions and at constant heat flux for a given length of time. Fouling in both tubes was monitored by measuring the increase in fouling resistance. The difference in the initial conditions (U_0^{-1}) of the experiments was due to different initial wall temperatures, a result of constant heat flux across two different alloys of differing thermal conductivities. Tube A had a higher thermal conductivity than Tube B. Figure 10 shows the progression of fouling from which the data in Table 3 were obtained. At the end of the test period, tube A was fouled to a greater extent than tube B as measured by the increase in fouling resistance. However, the amount of heat transferred through tube A at the end of the test period is higher than tube B. Consequently, tube A would be a more suitable alloy because it can transfer more heat than tube B at the experimental conditions employed, despite its higher fouling resistance.

Problems of fouling are having a more dramatic effect on cost of design, construction, operation, and maintenance of heat exchange equipment. More sophisticated, yet practical, methods are necessary to evaluate, control, and monitor fouling and fouling control methods. This paper has pre-

Table 3 Heat Transfer Resistance ($\text{ft}^2 \text{ h } ^\circ \text{F/Btu}$)

Tube	Clean tube	Fouled tube	R_f
A	0.00167	0.00257	0.00090
B	0.00250	0.00294	0.00044

sented one methodology for such measurements and has provided laboratory data in support of its acceptance.

NOMENCLATURE

- k_D thermal conductivity of deposit, $\text{ML}^{-1} \text{ t}^{-3} \text{ T}^{-1}$
 R_f fouling resistance, $\text{M}^{-1} \text{ t}^3 \text{ T}$
 t time, t
 Th deposit thickness, L
 U^{-1} overall heat transfer resistance at any time t , $\text{M}^{-1} \text{ t}^3 \text{ T}$
 U_0^{-1} overall heat transfer resistance at time $t = 0$, $\text{M}^{-1} \text{ t}^3 \text{ T}$
 ϕ_d deposition rate, $\text{M}^{-1} \text{ t}^2 \text{ T}$
 ϕ_r removal rate, $\text{M}^{-1} \text{ t}^2 \text{ T}$
 ϵ relative roughness, dimensionless

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M. Turakhia is a Ph.D. candidate in chemical engineering at Montana State University. He received his B.S. in chemical engineering from Regional Engineering College, Rourkela (India) and M.S.Ch.E. from Montana State University. His research deals with the influence of calcium on microbial processes and is being conducted at the Institute for Biological and Chemical Process Analysis, Montana State University.



W. G. Characklis is Professor of Chemical and Civil Engineering and Director, Institute for Biological and Chemical Process Analysis, Montana State University. He received his B.E.S. in chemical engineering and Ph.D. (1970) in environmental engineering from Johns Hopkins University and M.S.Ch.E. from the University of Toledo. He has conducted research and consulted on topics related to industrial water problems and microbial process engineering. From 1970 to 1979, he was professor of environmental engineering at Rice University.



N. Zelter is president of Bridger Scientific, Inc., which manufactures fouling monitor systems. He received his B.A. in biology and B.S. in environmental engineering (1976) from Humboldt State University and M.S. in environmental engineering from Rice University (1979). Since 1976, he has conducted research in fouling-related problems at Rice University and the Institute of Biological and Chemical Process Analysis at Montana State University.