

BIOENGINEERING REPORT

Fouling Biofilm Development: A Process Analysis

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Summary

Biofilm development at a surface is the net result of several physical, chemical, and microbial processes including the following: 1) transport of dissolved and particulate matter from the bulk fluid to the surface; 2) firm microbial cell attachment to the surface; 3) microbial transformations (growth, reproduction, etc.) within the biofilm resulting in production of organic matter; 4) partial detachment of the biofilm due primarily to fluid shear stress. This report presents a framework for analyzing the interrelated processes contributing to biofilm development. Some of the available rate and composition data are presented so that the relative process rates can be compared.

INTRODUCTION

The term fouling refers to the undesirable formation of inorganic and/or organic deposits on surfaces. These deposits can impede the flow of heat across the surface, increase the fluid frictional resistance at the surface, and increase the rate of corrosion at the surface. In any case, energy losses result.

Several types of fouling and their combinations may occur in heat exchangers: 1) crystalline or precipitation fouling, 2) corrosion fouling, 3) particulate fouling, 4) chemical reaction fouling, and 5) biological fouling or biofouling. Biological fouling results from a) development of a biofilm consisting of microorganisms and their products (microbial fouling), b) deposition and growth of macroorganisms such as barnacles (macrobial fouling), and c) assorted detritus. Although many different macroorganisms such as barnacles and mussels have been identified in fouling communities, this report will concentrate on microbial fouling on the controversial premise that it always precedes colonization of the surface by macroorganisms. Consequently, control of microbial fouling results in control of macrobial fouling.

Development of a systematic understanding of biofouling from field observations has been limited because of the interaction of several con-

TABLE I
Effect and Relevance of Biofilms on Various Rate Processes

Effects	Specific process and result	Concerns
Heat transfer reduction	Biofilm formation on condenser tubes and cooling tower fill material, <i>energy losses</i>	Power industry, chemical process industry, U.S. Navy, solar energy systems
Increase in fluid frictional resistance	Biofilm formation in water and wastewater conduits as well as condenser and heat exchange tubes. Causes increased power consumption for pumped systems or reduced capacity in gravity systems, <i>energy losses</i>	Municipal utilities, power industry, chemical process industry, solar energy systems
	Biofilm formation on ship hulls causing increased fuel consumption, <i>energy losses</i>	U.S. Navy, shipping industry
Mass transfer and chemical transformations	Accelerated corrosion due to processes in the lower layers of the biofilm. Results in <i>material deterioration</i> in metal condenser tubes, sewage conduits, and cooling tower fill	Power industry, U.S. Navy, municipal utilities, chemical process industry
	Biofilm formation on remote sensors, submarine periscopes, sight glasses, etc., causing <i>reduced effectiveness</i>	U.S. Navy, water quality data collection
	Detachment of microorganisms from biofilms in cooling towers. Releases <i>pathogenic organisms</i> (e.g., <i>Legionella</i> in aerosols)	Public health
	Biofilm formation and detachment in drinking water distribution systems. Changes <i>water quality</i> in distribution system	Municipal utilities, public health
	Biofilm formation on teeth, causes <i>dental plaque and caries</i>	Dental health
	Attachment of microbial	Human health

TABLE I (continued from previous page)

Effects	Specific process and result	Concerns
	cells to animal tissue, causes <i>disease</i> of lungs, intestinal tract, and urinary tract	
	Extraction and oxidation of organic and inorganic compounds from water and wastewater (e.g., rotating biological contactors, biologically aided carbon adsorption and benthal stream activity), <i>reduced pollutant load</i>	Wastewater treatment, water treatment, stream analysis
	Biofilm formation in industrial production processes <i>reduces product quality</i>	Pulp and paper industry
	Immobilized organisms or community of organisms for conducting <i>specific chemical transformations</i>	Chemical process industry
	Fouling biofilm accumulation <i>reduces effectiveness</i> of ion exchange and membrane processes used for high quality water treatment	Desalination, industrial water treatment

tributing rate processes. Mechanistically, fouling biofilm accumulation may be described as the net result of the following:

Transport of material from the bulk fluid to the surface and attachment to the surface. Materials can be soluble (microbial nutrients and organics) or particulate (viable microorganisms, their detritus, or inorganic particles). Also, suspended particles of sufficient mass may control films by "scouring" action.

Microbial metabolism within the film. Microbial growth in the biofilm and extracellular polymers produced by the microorganisms contribute to the biofilm deposit and promote adherence of inorganic suspended solids.

Fluid shear stress at the surface of the film. Such forces can limit the overall extent of the fouling deposit by reentraining attached material.

Surface material and roughness. Surface properties can influence micromixing near the surface and corrosion processes. Some metal surfaces may release toxic components into the biofilm inhibiting growth and/or

attachment. Some metals produce loosely held oxide films under the biofilms. When the oxide film sloughs, the biofilm is also removed.

Fouling control procedures. Chlorine, the most commonly used chemical, oxidizes biofilm polymers causing disruption and partial removal. Inactivation of a portion of the microbial population also occurs. Altered biofilm "roughness" and decreased viable cell numbers will influence "regrowth" rates of the biofilm. Mechanical cleaning can physically remove portions of the attached film.

The most common method of controlling biofilm accumulation is periodic or continuous chlorination. Chlorine dosage and application schedules are governed typically by observation of back pressure in a steam condenser, operator experience, or visual observation.

Recently in the United States, concern over toxicity from hypochlorous acid, or its reaction products, has resulted in federal regulations which limit the allowable concentration of free available chlorine in cooling water discharges. The impact of the limitations is unknown but will vary significantly with location. At present, there is no sound basis for assessing the impact of these regulations. This dilemma along with a host of other biofilm problems and applications has stimulated research in biofilm processes (Table I).

PROPERTIES AND COMPOSITION OF BIOFILMS

Microorganisms, primarily bacteria, adhere to surfaces ranging from the human tooth and intestine to the metal surface of condenser tubes exposed to turbulent flow of water. The microorganisms "stick" by means of extracellular polymer fibers, fabricated and oriented by the cell, that extend from the cell surface to form a tangled matrix termed a "glycocalyx" by Costerton, Geesey, and Cheng.¹ The fibers may conserve and concentrate extracellular enzymes necessary for preparing substrate molecules for ingestion, especially high molecular weight or particulate substrate frequently found in natural waters.

The biofilm surface is highly adsorptive, partially due to its polyelectrolyte nature, and can collect significant quantities of silt, clay, and other detritus in natural waters.

Physical, chemical, and biological properties of biofilms are dependent on the environment to which the attachment surface is exposed. The physical and chemical microenvironment combine to select the prevalent microorganisms which, in turn, modify the microenvironment of the surface. As colonization proceeds and a biofilm develops, gradients develop within the biofilm and average biofilm properties change. Changes in biofilm properties that occur during biofilm development must be considered when attempting to predict the effect of biofilms on fluid and heat

transport in turbulent flow systems. These changes have been largely ignored in past studies.

Physical Properties

Relevant *thermodynamic properties* of biofilm are its volume (thickness) and mass. In turbulent flow systems, wet biofilm thickness (T_h) seldom exceeds $1000 \mu\text{m}$.² The biofilm dry mass density (ρ_{Th}) can be determined from the wet biofilm thickness if the biofilm mass (ρ_{Th}) is known. ρ_{Th} reflects the attached dry mass per unit wet biofilm volume and measured values in turbulent flow systems range from 10 to 50 mg/cm^3 . ρ_{Th} increases with increasing turbulence² and increasing substrate loading^{2,3} as indicated in Figures 1 and 2. The increase in ρ_{Th} with increasing turbulence may be caused by one of the following phenomena: 1) selective attachment of only certain microbial species from the available population; 2) microbial metabolic response to environmental stress; 3) fluid pressure forces "squeeze" loosely bound water from the biofilm.

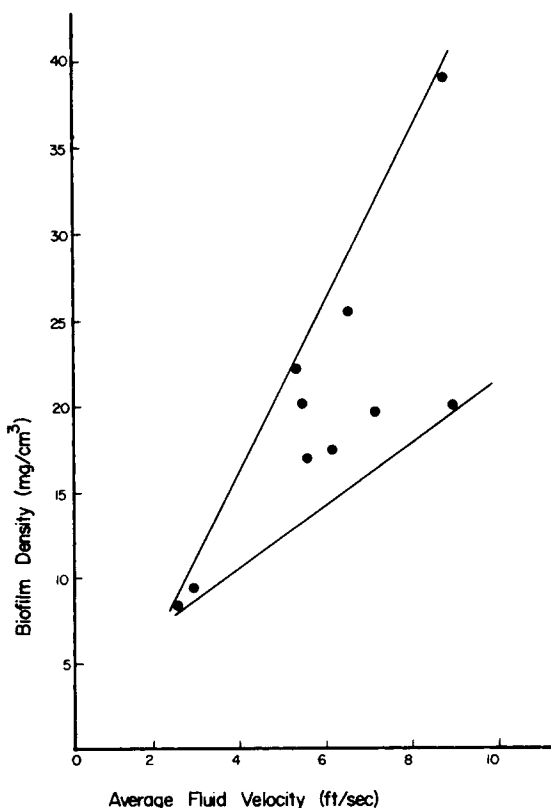


Fig. 1. Influence of fluid shear stress on biofilm density. (●) Ref. 2.

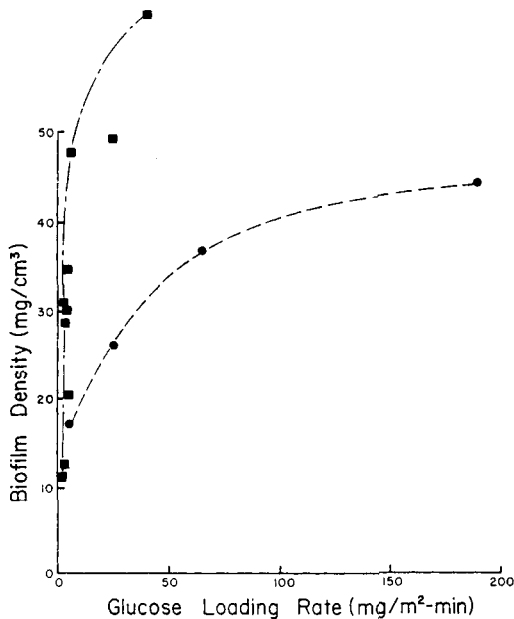


Fig. 2. Influence of glucose loading rate on biofilm density. (●) Ref. 2; (■) Ref. 51.

The relatively low biofilm mass densities compare well with observed water content of biofilm.⁴⁻⁶

The *transport properties* of biofilm are of critical importance in quantifying effects of biofilms on mass, heat, and momentum transfer. Diffusion coefficients for various compounds through microbial aggregates have been reported in the literature,⁷ mostly for floc particles (Table II). Matson and Characklis⁷ report variation in the diffusion coefficient for glucose and oxygen with growth rate and carbon-to-nitrogen ratio. In biofilms, the diffusion coefficient is most probably related to biofilm density. *In situ* rheological measurements indicate that the biofilm is viscoelastic with a relatively high viscous modulus as indicated in Table III.⁵ Reported biofilm thermal conductivities are presented in Table IV. As expected from reported water content, biofilm thermal conductivity is not significantly different from water.

Chemical Properties

Inorganic composition of biofilms undoubtedly varies with the chemical composition of the bulk water and probably affects the physical and biological structure of the film. Calcium, magnesium, and iron affect intermolecular bonding of biofilm polymers which are primarily responsible for the structural integrity of the deposit. In fact, EDTA is effective in detaching biofilm.⁵ In heat exchangers, corrosion products and inert

TABLE II
Experimental Diffusion Coefficient Measurements from the Literature (Ref. 7)

Reactant	Diffusivity (10^{-5} cm ² /s)	$D_{\text{H}_2\text{O}}/D_{\text{H}_2\text{O}}$ ($\times 100\%$)	Biomass type	Growth system	Procedure	Reference
Oxygen	1.5	70	Bacterial slime	Rotating tube	Reaction products analysis	10
Oxygen	0.21	8	Fungal slime	Fluidized reactor	Nonlinear curve fit	11
Glucose	0.048	8	<i>Zooglea ramigera</i>	Fluidized reactor	Nonlinear curve fit	12
Glucose	0.06–0.6	10–100	Mixed culture	Fluidized reactor	Two chamber	13
Oxygen	2.2	90	Nitrifier culture	Fluidized reactor	Two chamber	14
Ammonia	1.3	80				
Nitrate	1.4	90				
Oxygen ^a	0.4–2.0	20–100	Mixed culture	Fluidized reactor	Two chamber	15
Glucose ^a	0.06–0.21	10–30				15

^a Tests were conducted under a variety of experimental conditions.

TABLE III
Viscoelastic Properties of Biofilm Developed at
40°C at a Fluid Shear Stress of 3.3 N/m²; Glucose
Was Growth-Limiting and Was Applied at 6.2 mg/
m²/ min (Ref. 5)

Elastic (storage) modulus	59.5 N/m ²
Viscous (loss) modulus	118 N/m ²

suspended solids can adsorb to the biofilm matrix and influence its chemical composition. Table V reports the range of inorganic composition observed in selected biofilms.

The organic composition of the biofilm is strongly related to the energy and carbon sources available for metabolism. Classical papers^{8,9} have demonstrated the effect of environment and microbial growth rate on the composition of the cells and their extracellular products. For example, nitrogen limitation can result in production of copious quantities of microbial extracellular polysaccharides. Table VI presents data on the composition of biofilms developed in the field and in the laboratory. In terms of macromolecular composition, Bryers²⁵ has measured protein-to-polysaccharide mass ratios ranging from 0 to 10 (polysaccharide concentration in terms of glucose and protein concentration based on casein) with increasing biofilm accumulation. Other chemical analyses of biofilm have been reported by Bryers and Characklis.²⁶

TABLE IV
Thermal Conductivity of Biofilm and Other Selected Materials Relevant to Biofouling of
Heat Exchangers

Material	Thermal conductivity (W/m K)	Temperature (°C)	Reference
Biofilm	0.68 ± 0.27	28.3 ± 0.3	4
	0.71 ± 0.39	26.7 ± 0.3	
	0.57 ± 0.10	28.3 ± 0.3	
Water	0.61	26.7	16
	0.62	28.3	
Carbon steel	51.92	0–100	17
Steel	46.86	18	18
Stainless steel (type 316)	16.30	0–100	17
Aluminum 5052	138.46	20	17
	205.85	100	18
Cupronickel 10% 706	44.71	0–100	17
Copper	384.	18	18
Titanium (commercial pure)	16.44	0–100	17
Glass	0.6–0.9	—	16

TABLE V
Chemical Properties of Biofilms Obtained from Fouled Surfaces
Experiencing Excessive Frictional Losses (Ref. 6)

	Reference				
	19	20	20	21	5
Water	87	85.6	90	95	96
Volatile fraction	2.5	2.7	1.9	2.4	3.2
Fixed fraction	10.5	11.7	8.1	2.6	0.8
Si (as percent fixed fraction)		7.0	11.8	12.5	
Fe		18.5	7.9	1.4	
Al		7.5		3.9	
Ca		1.0	5.6		
Mg		2.5		3.2	
Mn		59.5	56.3	4.9	

Biological Properties

The organisms which colonize the attachment surface will strongly influence biofilm development rate and biofilm chemical and physical properties. However, organism-organism and organism-environment interactions undoubtedly shift population distributions during biofilm accumulation. Several investigators have observed succession during biofouling.^{27,28}

The first visible signs of microbial activity on a surface are usually small "colonies" of cells distributed randomly on the surface. As biofilm development continues, the colonies grow together forming a relatively uniform biofilm. The viable cell numbers are relatively low in relation to

TABLE VI
Chemical Composition of Biofilms Obtained in the Field and Laboratory Emphasizing the
Primary Constituents (C,N,P)

Source	Percent dry weight						Reference
	Carbon (C)	Nitrogen (N)	Phosphorus (P)	Fixed solids	C/N	C/P	
Biofilm power plant condenser	6.4-13.8	0.5-3.0	—	—	2-27	—	22
Biofilm laboratory reactor	42.8	10.0	—	—	4.3	—	23
Biofilm laboratory reactor	19.0	9.2	1.8	20	2.1	10.5	5
<i>E. coli</i>	50.0	14.0	3.0	—	3.6	16.7	24

the biofilm volume (10^4 – $10^8/\text{cm}^3$ biofilm) occupying only 1–10% of the biofilm in dilute nutrient solutions.⁵ Costerton²⁹ and Jones, Roth, and Sanders³⁰ present photomicrographs which corroborate these data in natural and laboratory systems.

In many cases, filamentous forms emerge as the biofilm develops further. *Hyphomicrobium*, *Sphaerotilus*, and *Beggiatoa* are frequently identified. The filamentous forms may gain an ecological advantage as the biofilm develops since their cells can extend into the flow to obtain needed nutrients or oxygen which may be depleted in the deeper portions.

Major questions remain unanswered regarding biofilm properties and their influence on processes of interest and include the following:

- 1) Are the physical and chemical properties of the biofilm dependent on the microbial species in the biofilm? To what extent? How specific is the relationship between the predominant microbial species and the immediate environment of the surface?
- 2) How much do biofilm properties influence the effect of biofilms on energy losses (i.e., fluid frictional resistance and heat transfer resistance)?
- 3) How do biofilm properties change when biocides are applied on a continuing basis?
- 4) How does inorganic content of the water influence biofilm properties?

RATE PROCESSES CONTRIBUTING TO BIOFILM DEVELOPMENT

The physical, chemical, and biological transformations of interest in biofilm development are completed in a certain period of time. For biofilm development, a specified change may signal the shutdown of manufacturing operations and the beginning of cleaning operations. The time required for this specified change is inversely proportional to the *rate* at which the process occurs. Thus the rate is the most important quantity

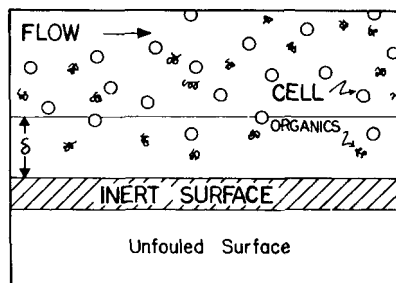


Fig. 3. A clean surface exposed to a turbulent flow of fluid containing dispersed microorganisms, nutrients, and organic macromolecules. δ refers to the viscous sublayer thickness.

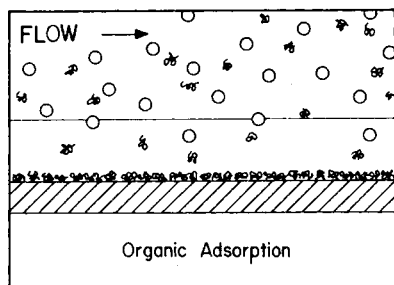


Fig. 4. Transport and adsorption of organic molecules on a clean surface.

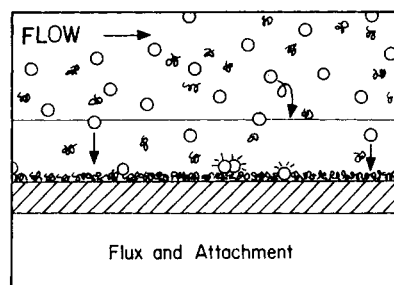


Fig. 5. Transport and adhesion of microbial cells to the conditioned surface.

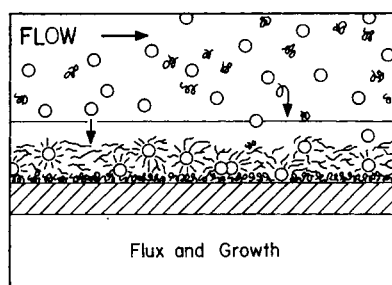


Fig. 6. Continued transport and adhesion of microbial cells as well as growth and other metabolic processes within the biofilm.

in process analysis. If the process consists of a number of processes in series, the slowest step of the sequence exerts the greatest influence and *controls* the overall process rate. This step is called the "rate-determining step" or "rate-controlling step."

In this discussion, biofilm development will be considered to be the net result of the following physical, chemical, and biological processes: transport of organic molecules and microbial cells to the wetted surface (Fig. 3); adsorption of organic molecules to the wetted surface resulting in a

“conditioned” surface (Fig. 4); adhesion of microbial cells to the conditioned surface (Fig. 5); metabolism by the attached microbial cells resulting in more attached cells and associated material (Fig. 6); detachment of portions of the biofilm (Fig. 12).

Transport to the Wetted Surface

When a clean surface is immersed in natural water, transport controls the initial rate of deposition (Fig. 3). In very dilute suspensions of microbial cells and nutrients, transport of microbial cells to the surface may be the rate-controlling step for long periods of time. Biofilm development in open ocean waters or distilled water storage tanks may be illustrative of these cases. Transport of molecules and particles smaller than 0.01–0.1 μm is described satisfactorily in terms of diffusion. In turbulent flow, the diffusion equation must be modified to include turbulent eddy transport. Transport of such small molecules and particles is relatively rapid compared to transport of larger particles. Consequently, adsorption of an organic film is reported to occur “instantaneously” in many cases, as schematically illustrated in Figure 4.

Larger particles develop a sluggishness with respect to the surrounding fluid. As the particle approaches the wetted surface, eddy transport diminishes and the viscous boundary layer exerts a greater influence. For soluble matter and small particles, diffusion can adequately describe transport in the viscous sublayer.^{31–33} For larger particles, other mechanisms must be considered to explain experimental observations.

Within a turbulent flow regime, larger particles suspended within the fluid are transported to the solid surface primarily by fluid dynamic forces. Particle flux to the surface increases with increasing particle concentration. However, particle flux is also strongly dependent on the physical properties of the particles (e.g., size, shape, and density) and is influenced by many other forces near the attachment surface.

Microbial cells (0.5–10.0 μm effective diameter) can be transported from the bulk fluid to the wetted surface by several processes including the following: diffusion (Brownian), gravity, thermophoresis, taxis, fluid dynamic forces: inertia, lift, drag, drainage, and downsweeps.

Transport mechanisms

Particles in turbulent flow are transported to within short distances of the surface by eddy diffusion. Particles are propelled into the viscous (or laminar) sublayer under their own momentum. Turbulent eddies supply the initial impetus and frictional drag slows down the particle as it penetrates the viscous sublayer.^{34,35} For microbial cells, the inertial forces are very small because of their small diameter and density (in relation to water).

If the particle is traveling faster than the fluid in the region of the wall,

the *lift force* directs the particle toward the wall.³⁶ This would normally be the case if particle density is greater than fluid density and the particle is moving toward the wall. *Frictional drag forces* can be significant, especially in the viscous sublayer region. The drag force slows down the particle as it approaches the surface and is proportional to difference between particle velocity and fluid velocity.

If the mass density of the particle, ρ_p , differs substantially from the fluid density ρ , the *gravity force* may be significant. For microbial cells in turbulent flow, the gravity force is generally negligible. *Thermophoresis* is only relevant when particles are being transported in a temperature gradient.³¹ If the surface is hot and the bulk fluid is cold, the thermophoretic force will repel the particle from the surface. *Eddy diffusion* may be instrumental in dispersing particles in the turbulent core region, thus maintaining a relatively uniform concentration in that region. However, eddy diffusion will not be significant in transporting particles to the wall. *Brownian diffusion* contributes little to the transport of microbial cells ($> 1.0 \mu\text{m}$ diam) in turbulent flow. Certain microbes are capable of *motility* or *taxis* through their own internal energy. Velocities as high as $4 \times 10^{-4} \text{ cm/s}$ ¹ have been observed. Taxis could possibly be a significant transport process within the viscous sublayer. For particles in liquids, the *fluid drainage force* is significant.³¹ The drainage force describes the resistance the particle encounters near the wall due to the pressure in the draining fluid film between the two approaching surfaces. This force is quite large for a microbial cell as it approaches the wall.

Recent published research on the structure of the viscous sublayer in turbulent flow indicates that “*downsweeps*” of fluid from the turbulent core penetrate all the way to the wall.^{37,38} Particles in the bulk fluid are transported all the way to the wall by these convective downsweeps. Aside from lift, this is the only fluid mechanic force directing the particle to the wall. Downsweeps are apparently quite important in terms of particle transport to the wall in turbulent flow.

For a Reynolds number of 30,000 in tube flow, the bursts resulting from the downsweeps have the following characteristics: burst diameter, 0.11 cm; average axial distance between bursts, 0.50 cm; and mean time between bursts, 0.006 s. Minimum transport rate of particles would be observed when particle diameter approximates $0.1 \times 10^{-4} \text{ cm}$ under constant fluid flow conditions. At this diameter, *Brownian diffusion* starts exerting a significant effect. Particle flux in the pipe for a bulk fluid particle concentration of $10^4 \text{ particles/cm}^3$ is approximately $0.1 \text{ particles/cm}^2 \text{ s}$.

Influence of surface roughness

Surface roughness significantly influences *transport rate* and *microbial cell attachment* for several reasons including the following: 1) increases

convective mass transport near the surface, 2) provides more “shelter” from shear forces for small particles, and 3) increases surface area for attachment. If surface roughness elements are larger than the viscous sublayer, the roughness can be measured quantitatively by hydraulic methods. If surface roughness elements are smaller than the viscous sublayer (i.e., microroughness), measurements of roughness are difficult to quantify and interpret. Browne³⁹ reports that particle deposition from gases is very sensitive to roughness too small to affect fluid frictional resistance.

Consequences of transport rates on biofilm development

When a “clean” surface first contacts water with biological activity, organic substances and microbial cells must be transported to the surface before biofilm development can begin. Consequently, the rate of transport determines the length of the “induction” period, i.e., the initial period during which no macroscopic effects of the biofilm are evident. In very dilute solutions (e.g., open ocean), the rate of transport may control the overall rate of biofilm development for long periods. Rate of transport is proportional to the concentration difference between the bulk fluid and the surface. In dilute solutions, this difference is small. The flow regime (zero, laminar, or turbulent) also significantly influences transport rates and should be defined carefully in any experimental system used for biofilm studies. Surface characteristics are also critical to the repeatability and applicability of the results because a rough surface will increase transport and attachment rates. Which rate controls—rate of transport or rate of adhesion?

Summary

There is a need for more information on transport of particulate material from a turbulent fluid to a wall. Especially relevant to this discussion is the rate of transport of microbial cells in aquatic systems where inertial forces are relatively small. Other questions that might be addressed include the following:

- 1) How do microbial cell properties influence transport rate?
- 2) How does particle flocculation influence transport rate?
- 3) At what concentration do particle interactions influence transport rate?
- 4) Does surface roughness influence particle transport rate? Can the influence be predicted from friction factor measurements?

Adsorption of Organic Molecules to the Wetted Surfaces

Figure 3 illustrates an initially clean surface exposed to turbulent flow of a fluid containing dispersed microorganisms, nutrients, and organic

TABLE VII
Maximum Rate and Extent of Molecular Fouling

Maximum rate (nm/min)	Maximum accumulation (nm)	Maximum accumulation ($\mu\text{g COD}/\text{cm}^2$)	Surface	Reference
0.15–0.45	30–80		Pt ^a	40
0.004	7.1		Ge ^b	41
0.044	77.3		Ti ^b	
0.01 ^c	13.5 ^c	1.5	glass ^c	25
0.22 ^c	22.5 ^c	2.5	glass ^d	

^a Immersed in quiescent Chesapeake Bay water (3–4°C) containing 2.3 mg carbon/L, salinity between 9 and 16‰, and pH between 7.9 and 8.2.

^b Gulf of Mexico water (22°C) flowing past the surface at a fluid shear stress of 7.1 N/m². Salinity was 34‰. Carbon concentration not reported.

^c Medium consisted of sterile 1:1 w/w trypticase soy broth–glucose mixture (34°C; pH 8). The glass surfaces were immersed in tubes placed in a mechanical shaker. Carbon concentration was approximately 80 mg carbon/L.

^d Medium was effluent (30°C; pH 8) from a chemostat (10–20 mg/L COD, 3 mg/L polysaccharide) with no primary substrate remaining. Microorganisms were present (approximately 10⁶ cells/mL) but no cells attached during the period of interest. Fluid shear stress was 3.8 N/m².

^e Estimated from measurements of chemical oxygen demand (COD) adsorbed per unit area. Assumed COD of protein is 0.855 mg COD/mg protein and protein density is 1.3 g protein/cm³.

macromolecules. Microorganisms select their habitats on the basis of many factors, including the nature of the wetted surface (material of construction and surface roughness). Adsorption of an organic monolayer occurs within minutes of exposure as shown in Figure 4 and changes the properties of the wetted surface. Investigations have shown that materials with diverse surface properties (e.g., wettability, surface tension, electrophoretic mobility) are rapidly conditioned by adsorbing organics when exposed to natural waters with low organic concentrations. These organic molecules are usually polysaccharides or glycoproteins. Loeb and Neihob⁴⁰ and DePalma, Goupil, and Akers⁴¹ have measured adsorption rates of organic molecules in seawater, and Bryers²⁵ has observed adsorption rates in a laboratory system. Rates and extent of adsorption in these investigations are presented in Table VII. Maximum accumulation from molecular fouling is less than 0.1 μm . The rate of molecular fouling can be considered instantaneous since it is much greater than the rate of microbial fouling. Based on "thickness" measurements, molecular fouling can have no significant effect on fluid flow or heat transfer. Nevertheless, the surface properties resulting from adsorption of an organic film may affect the sequence of microbial events which follow.

Costerton, Geesey, and Cheng¹ have discussed the pronounced specificity of some bacteria that attack only a particular animal host tissue and suggest that specificity may be explained by the specificity of the

host-tissue glycocalyx. It remains to be seen whether a surface, wetted by the adsorption of organic molecules indigenous to that environment, will be initially colonized by a *specific* microbial cell.

Brash and Samak⁴² present experimental evidence that significant turn-over occurs in molecular (proteinaceous) fouling films on polyethylene. Protein molecules in the bulk fluid are continuously exchanging with absorbed proteins. This suggests that dispersed microbial cells and their associated extracellular material may be continually exchanging with bio-film material at the wall.

Adhesion of Microbial Cells to the Wetted Surface

Previous research^{43,44} suggests the existence of a two-stage adhesion process: 1) reversible adhesion followed by 2) an irreversible adhesion. Reversible adhesion refers to an initially weak adhesion of a cell which can still exhibit Brownian motion but is readily removed by mild rinsing. The adhesive forces which hold the cell at the wall during reversible adhesion probably include the following: a) electrostatic, b) London-van der Waals, c) interfacial tension, and d) covalent bonding. Conversely, irreversible adhesion is a permanent bonding to the surface, usually aided by the production of extracellular polymers. Cells attached in this way can only be removed by rather severe mechanical treatment. Marshall²⁷ and Corpe⁴⁵ have implicated polysaccharides and glycoproteins in irreversible adhesion (Fig. 5).

Most of the research on cell adhesion has been conducted at very low fluid shear stress or in quiescent conditions.⁴⁶ These conditions suggest that sedimentation or diffusion may control the rate of adhesion. Also, there is yet to be a demonstration of reversible adhesion in turbulent flow.

In turbulent flow, the *net* rate of adhesion is the quantity most easily measured. The net rate of adhesion is the difference between the rate of adhesion and rate of detachment. Detachment results from several forces including the following: fluid dynamic forces, shear forces, lift (upsweeps), and taxis. Upsweeps are analogous to the downsweeps discussed above. Upsweeps result in turbulent bursts which move away from the surface into the bulk flow. Upsweeps generate a lift force normal to the surface which can influence detachment. Drag or viscous shear forces act in the direction of flow on attached cells and are approximately 1000 times greater than the lift forces acting on attached cells. Note that although viscous shear may dislodge a particle, unless a lift force is present, the particle will presumably roll along the surface until another surface adhesion site is found.

The nature of the surface is an important factor affecting adhesion. Wettability or critical surface tension, is the property used most frequently to describe surface characteristics in microbial attachment studies.^{47,48} In seawater, cell attachment increases with increasing critical

surface tension of the surface (including glass, copper, polyethylene, Teflon) with the exception of the copper surface on which fewer cells attached.⁴⁷ The copper may inhibit cell attachment by inhibiting a metabolic process necessary for attachment. Even so, there are many examples of biofouling on cupronickel condenser surfaces.⁴⁹

The presence of multivalent cations (especially Ca^{2+} , Mg^{2+} , and Fe^{3+}) also influences the attachment process, possibly by altering surface characteristics or by bridging cellular anionic polyelectrolytes to anionic polyelectrolytes adsorbed on the wetted surface.

Other questions of relevance still remain including the following:

- 1) Is an adsorbed organic layer a prerequisite for cellular attachment to a surface?
- 2) Is there a significant interchange between cells on the surface and cells in the bulk fluid?
- 3) What types of compounds serve as "glue" for firm cellular attachment?
- 4) Is the adsorption process "species specific", i.e., is there a high degree of specificity in the organism-surface interaction?
- 5) How does the attachment process differ after the formation of a "monolayer" of cells?

Metabolism by the Attached Microbial Cells

Restricting our discussion to chemosynthetic organisms, the attached microbial cells assimilate reduced organic or inorganic compounds, nutrients, and oxygen or some other electron acceptor. The process yields energy with which the cells reproduce, maintain their internal structure, and form extracellular products. Therefore, *growth*, *maintenance*, and *product formation* are *fundamental processes* carried out by microbial cells in the presence of sufficient nutrients (Table VIII). If nutrients are depleted, or toxic substances are present, *death* and *lysis* may occur.

The rates of the fundamental microbial processes are difficult to measure. Consequently, the *observed rates* (last row, Table VIII) are usually rate of substrate (the growth-limiting nutrient) removal, electron-acceptor (usually oxygen) removal, biomass production, or product formation.

The stoichiometry of each fundamental process can be measured in certain laboratory systems (e.g., chemostats). The rows in Table VIII qualitatively represent the stoichiometry of each fundamental process (– refers to reactant and + refers to product).

Analysis of rate and stoichiometry of processes within a biofilm are frequently complicated by significant mass transfer resistances in the liquid or diffusional resistances within the biofilm.

Trulear and Characklis³ have observed substrate removal rate in an experimental biofilm reactor. The substrate removal rate increases in proportion to biofilm thickness up to a critical thickness beyond which

TABLE VIII
A Matrix Representation for the Fundamental Microbial Rate Processes

Fundamental process		Reactants			stoichiometry →					Products	
		Substrate s	Nutrient z	Electron acceptor e	Biomass		Product			Metabolite a	
Process	Rate				x_T	x_d	p_e	p_i			
Growth	μ	-	-	-	+		+	(+)			+
Maintenance exogenous	m	-	-	-			+				+
endogenous	k_e		+	-	-	(+)	+	-			+
Product formation	k_p	-	-	-			+	+			+
Death											
loss of viability	k_d				-			+			
lysis	k_L	(+)	(+)		-	(+)	+				
Observed rate		q_s	q_z	q_e			μ_n	q_p			q_a

q = specific production or removal rate (time⁻¹)
 μ = specific growth rate or specific biomass production rate (time⁻¹)
 x_T = total biomass concentration (mass/length³)
 x_d = inert solids concentration (mass/length³)
 p_e = extracellular microbial product concentration (mass/length³)
 p_i = intracellular microbial product concentration (mass/length³)
 s = substrate concentration (mass/length³)
 z = nutrient concentration (mass/length³)
 e = electron-acceptor concentration (mass/length³)
 μ_n = net solids production rate (time⁻¹)

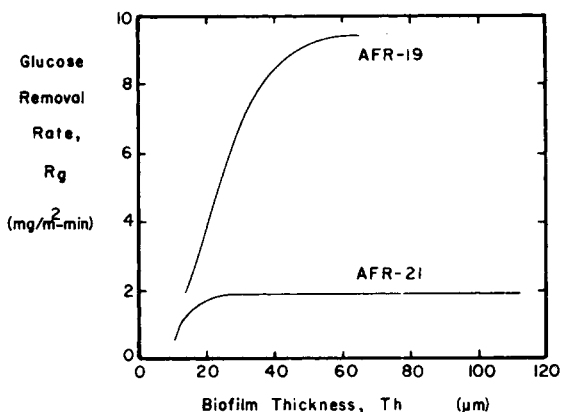


Fig. 7. The influence of biofilm thickness and glucose loading rate on glucose removal rate by a biofilm. Glucose loading rate was $9.9 \text{ mg/m}^2 \text{ min}^{-1}$ for AFR-19 and $2.0 \text{ mg/m}^2 \text{ min}^{-1}$ for AFR-21 (Ref. 51).

removal rate remains constant (Fig. 7). The critical, or "active," thickness is observed to increase with substrate concentration. This behavior is confirmed by other investigators^{2,23,50} and is attributed to nutrient diffusional limitations within the biofilm. Once the biofilm thickness exceeds the depth of substrate (or oxygen) penetration into the biofilm (Fig. 8), the removal rate is unaffected by further biofilm accumulation.

Observed substrate removal rate cannot be used to distinguish between growth, maintenance, product formation, and death. It seems clear from other data²⁵ that product formation (primarily polysaccharide) is significant in the early stages of biofilm formation. Maintenance requirements or biomass decay become important as the biofilm gets thicker and substrate does not entirely penetrate the biofilm. These other process rates

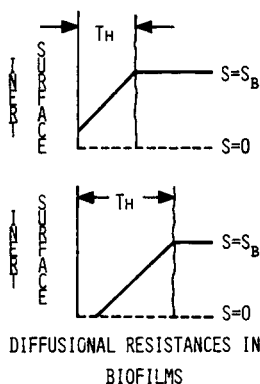


Fig. 8. As biofilm thickness increases, beyond the depth of substrate (or oxygen) penetration, substrate (or oxygen) removal rate becomes independent of biofilm thickness.

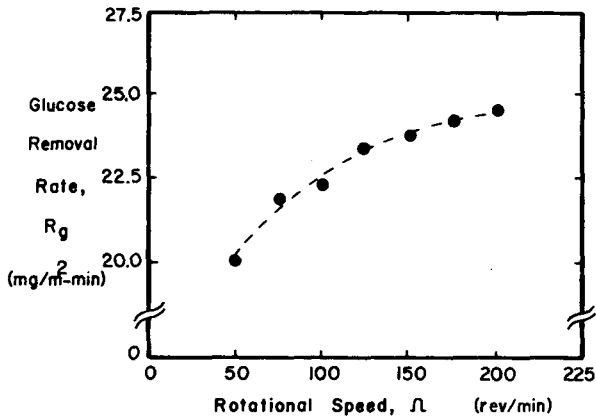
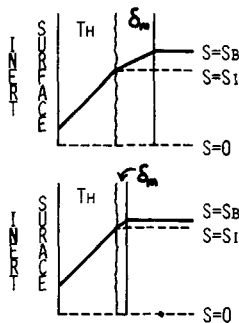


Fig. 9. Influence of rotational speed on glucose removal rate by a biofilm in an annual reactor (Ref. 51). AFR-18; $T_h = 112 \mu\text{m}$.

have not been measured and are critical for determining stoichiometric coefficients and predicting biofilm development rates.

The substrate removal rate is also dependent on fluid velocity (Fig. 9). At low fluid velocities, a relatively thick mass transfer boundary layer (δ_m) can cause a liquid phase diffusional resistance which decreases substrate concentration at the liquid–biofilm interface and thereby decreases substrate removal rate (Fig. 10).

A general mathematical model for microbial processes in a continuous stirred tank reactor (CSTR), based on material balances, is presented in Table IX. The model considers microbial activity in the bulk fluid as well as the reactor surfaces. Figure 11 is a diagrammatic representation of the model.



LIQUID PHASE RESISTANCES

Fig. 10. The mass transfer boundary layer (δ_m) decreases with increasing fluid velocity past the biofilm interface resulting in a higher effective substrate concentration at the biofilm–fluid interface (S_i).

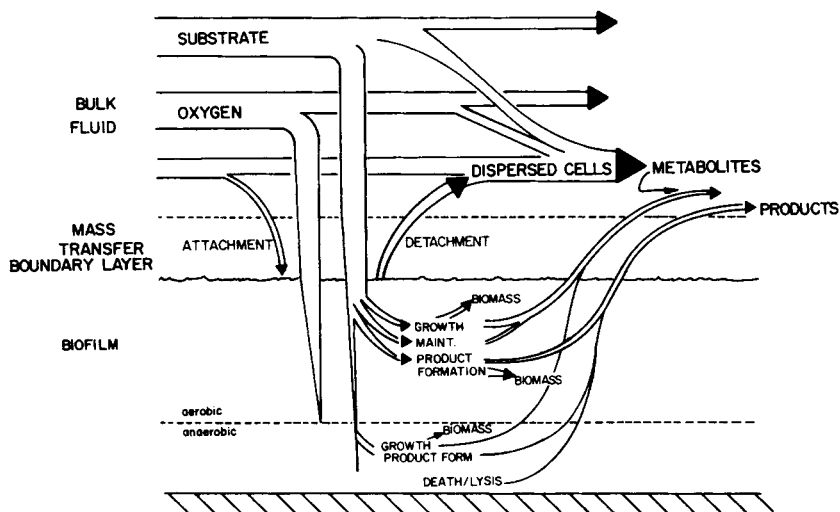


Fig. 11. Diagrammatic representation of the mathematical model for biofilm development described in Table IX.

TABLE IX
Mathematical Representation of Microbial Processes, Including Biofilm Formation,
Occurring in a CSTR (see Fig. 11)

Substrate material balance

$$V(ds/dt) = F(s_i - s) - NA - (\mu - m)xV/Y_x$$

Suspended biomass material balance

$$V(dx/dt) = F(x_i - x) + \mu xV - R_A A + R_D A$$

Accumulation of biofilm

$$dB/dt = NAY_B - R_D A + R_A A - R_E B$$

Accumulation of total reactor biomass

$$dM_t/dt = V(dx/dt) + dB/dt = F(x_i - x) + \mu xV + NAY_B - R_E B$$

A = wetted surface area (length^2)

B = biofilm mass (M_B)

F = volumetric flow rate ($\text{length}^3/\text{time}$)

m = maintenance coefficient (time^{-1})

M_t = total reactor biomass (mass)

N = substrate flux into the biofilm ($M_s/\text{length}^2 \text{ time}$)

R_A = rate of suspended biomass adsorption onto the biofilm ($M_s/\text{length}^2 \text{ time}$)

R_D = rate of biofilm detachment ($M_B/\text{length}^2 \text{ time}^{-1}$)

R_E = rate of biofilm decay (e.g., lysis, endogenous respiration) (time^{-1})

$s(s_i)$ = (input) substrate concentration (M_s/length^3)

t = time (time)

$x(x_i)$ = (input) suspended biomass concentration (M_x/length^3)

Y_B = yield coefficient for biofilm ($M_B M_s^{-1}$)

Y_x = yield coefficient for suspended biomass ($M_x M_s^{-1}$)

V = reactor volume (length^3)

μ = specific growth rate of suspended biomass (time^{-1})

Other questions of concern regarding microbial processes in the biofilm include the following:

1) Are the observed high biofilm yields in the early stages of biofilm development due to extracellular polymer production? What type of polymer predominates (polysaccharide, protein)? This point may be critical in assessment of biofouling control measures (e.g., chlorination) if they are to be used in the early stages of biofilm formation.

2) Is the Frank-Kamenetskii relationship¹⁴ useful as a criterion for determining the "critical" biofilm thickness at which diffusion of oxygen in the biofilm becomes rate-limiting for substrate removal? When oxygen limitation occurs, do sulfate-reducing bacteria, strongly implicated in corrosion, become prominent?

3) Can an effectiveness factor model adequately describe substrate removal in a time-varying (i.e., dynamic) system? Can the parameters in the model be quantified?

4) Do biofilm transport properties (i.e., diffusion coefficient, rheological properties, thermal conductivity) and physical properties (density) change significantly as the biofilm develops?

Detachment of Biofilm

As the biofilm grows thicker, the fluid shear stress at the biofilm interface generally increases. Also, as biofilms grow thicker, the potential for substrate, oxygen, or nutrient limitation in the deeper portions is great. These limitations may weaken the biofilm matrix and cause detachment (Fig. 12). Trulear and Characklis³ report that the biofilm detachment rate increases with increasing biofilm mass (Fig. 13). Trulear⁵¹ also reports that detachment rate increases with fluid shear stress (Fig. 14).

Techniques for determining strength of adhesion and strength of deposit are necessary to further understanding of the detachment process. Other questions regarding detachment also arise including the following:

1) Is there detachment of cells from the surface simply as a result of cell reproduction, i.e., the daughter cells peel off into the fluid?

2) How is the strength of deposit affected by anaerobic layers deep in the biofilm?

3) How does detachment rate change with fluid shear stress and biofilm thickness? Can detachment rate (i.e., cells in suspension) be used to monitor biofilm accumulation? Under what circumstances?

4) How do biocides influence strength of deposit or detachment rate?

Overall Rate of Biofilm Development

In summary, biofilm development is the net result of several processes occurring in series and parallel (Fig. 15). The development of a biofilm is adequately described by a sigmoidal-shaped curve (Fig. 16). The slope

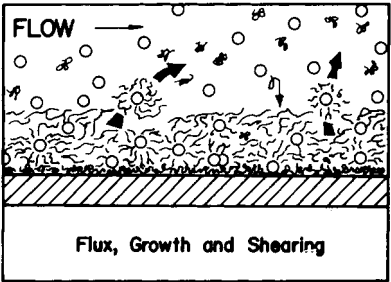


Fig. 12. Transport, adhesion, and growth increase the accumulated mass of the biofilm while detachment processes decrease the attached mass.

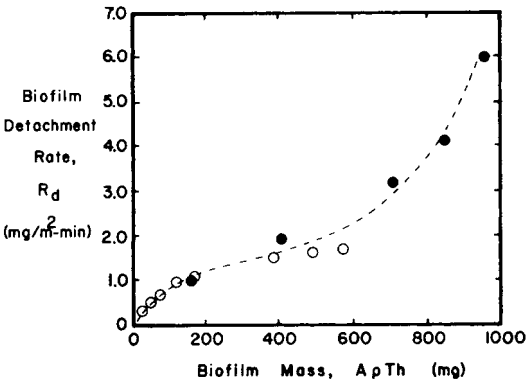


Fig. 13. Influence of biofilm mass on biofilm detachment rate at a constant fluid shear stress (Ref. 51). (●) AFR-23, (○) AFR-26.

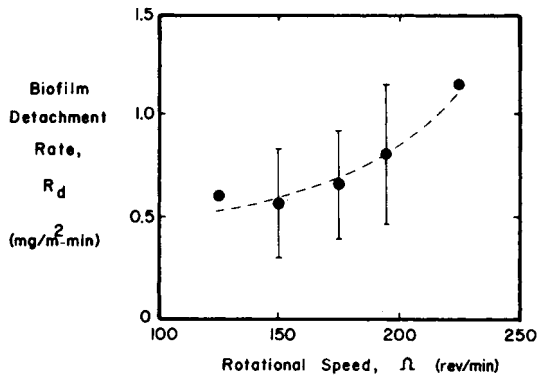


Fig. 14. Influence of fluid shear stress on biofilm detachment rate at a constant attached biomass (Ref. 51). Mass = 150–160 mg.

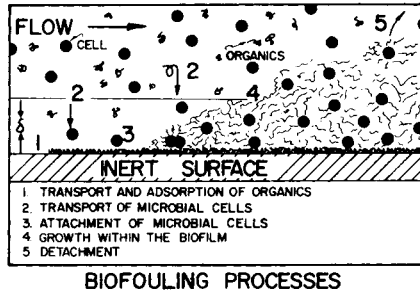


Fig. 15. A summary diagram of processes contributing to biofilm accumulation.

of this curve at a particular time is the *net biofilm development rate* and is also plotted in Figure 16. The rate increases to a maximum value corresponding to the sigmoidal inflection point and then decreases to zero. Net biofilm development rate is expressed as follows (Table IX):

$$dB/dt = NAY_B - R_{DA} + R_{AA} - R_{EB} \quad (1)$$

where NAY_B is the attached biomass production rate and R_{DA} is the biofilm detachment rate, R_{AA} is the adsorption rate of cells, and R_{EB} is the endogenous respiration rate. At steady state, thickness remains constant.

The effect of fluid velocity on the plateau (or steady state) biofilm thickness is illustrated in Figure 17 for various substrate loadings. At high substrate loadings, increasing fluid velocity increases biofilm detachment rate which minimizes the plateau biofilm thickness. However, at low

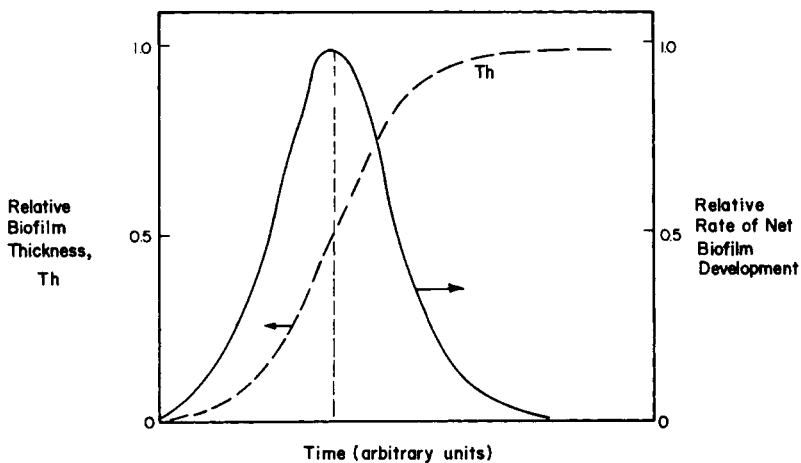


Fig. 16. Progression of net biofilm development is described by a sigmoidal-shaped curve. Net biofilm development rate is the slope of the sigmoidal-shaped curve at any time.

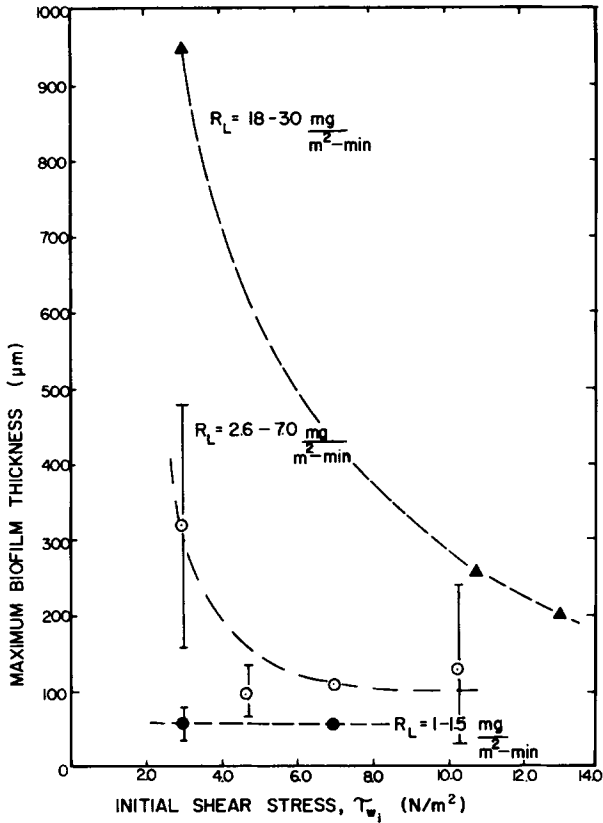


Fig. 17. Influence of fluid shear stress and substrate loading on plateau (or maximum) biofilm thickness (Ref. 2).

substrate loadings, fluid velocity seems to have no measurable effect on the plateau thickness. Trulear and Characklis³ have demonstrated that plateau biofilm mass exhibits a maximum when fluid velocity is increased. At low fluid velocities, mass transfer limits the rate of biofilm production. Therefore, increasing fluid velocity increases substrate flux into the biofilm and net biofilm development rate increases. As fluid velocity continues to increase, biofilm detachment rate becomes the dominant process and net biofilm development begins to decrease.

EFFECTS OF BIOFILMS ON FLUID FRICTIONAL RESISTANCE

Increase in fluid frictional resistance due to biofilm accumulation when flow rate is maintained constant causes an increase in pressure drop and power requirements for pumping as shown in Figure 18.² Conversely, if pressure drop is held constant, flow capacity is reduced. Figure 19 in-

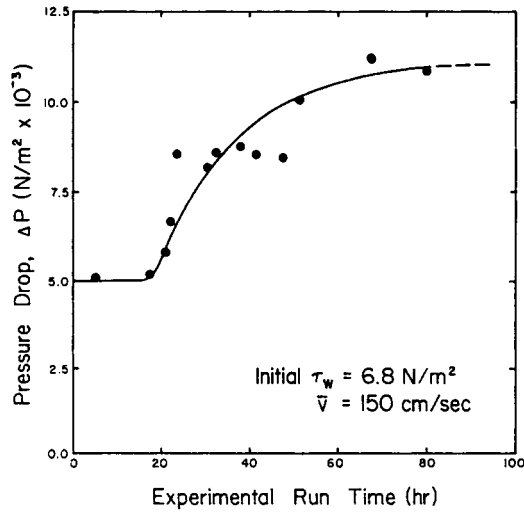


Fig. 18. Change in pressure drop with time due to biofilm formation. Experiment was conducted at constant fluid velocity (Ref. 2).

indicates that flow capacity was reduced to 42% of the original capacity in a 100-h laboratory experiment.²

Frictional resistance can be represented by a dimensionless friction factor given by

$$f = 2.0 \frac{d}{L} \frac{\Delta p}{\rho_f \bar{V}^2} \quad (2)$$

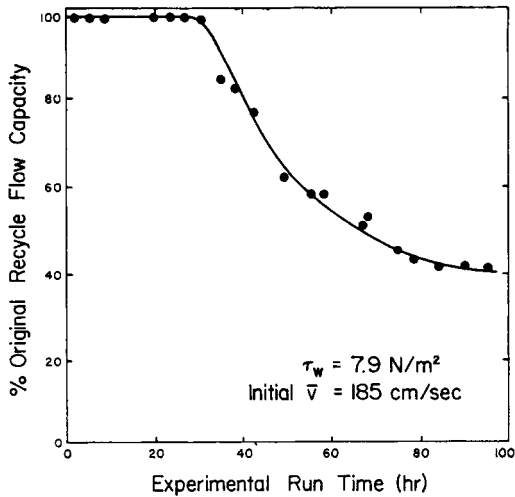


Fig. 19. Change in volumetric flow rate with time due to biofilm formation. Experiment was conducted at constant pressure drop (Ref. 2).

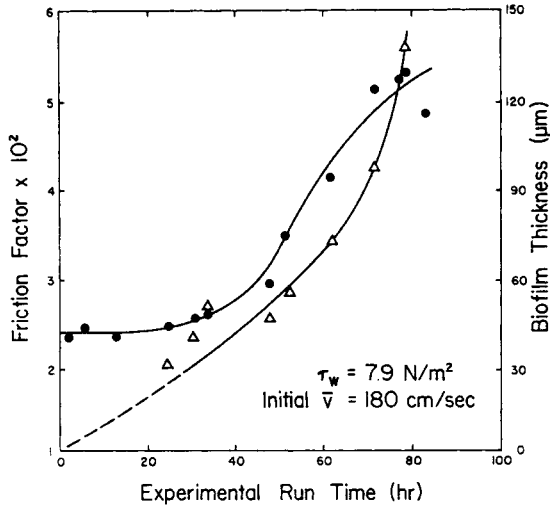


Fig. 20. Change in (●) friction factor and (Δ) biofilm thickness with time for an experiment conducted at constant pressure drop (Ref. 2).

where f = friction factor (dimensionless), d = tube diameter (length), ρ = fluid density (mass/length³), $\bar{V}$ = average fluid velocity (length/time), Δp = pressure drop along length L (mass/length time²), and L = length between pressure ports (length).

The change in friction factor and biofilm thickness with time is shown in Figure 20 for a laboratory tubular reactor. Dehart⁵² has observed similar behavior in a tubular reactor in the field (Fig. 21).

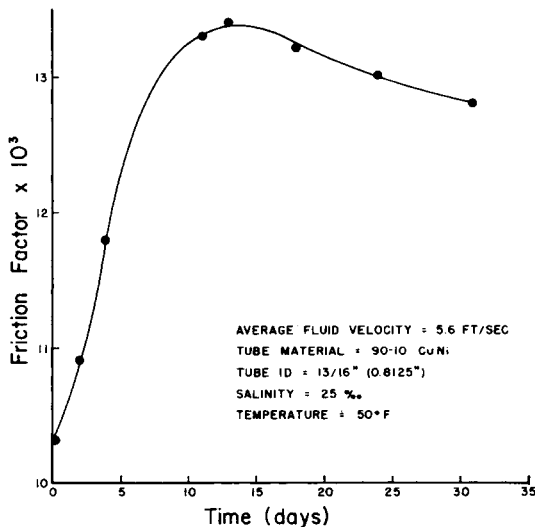


Fig. 21. Change in pressure drop due to biofilm formation at a field location (Ref. 52).

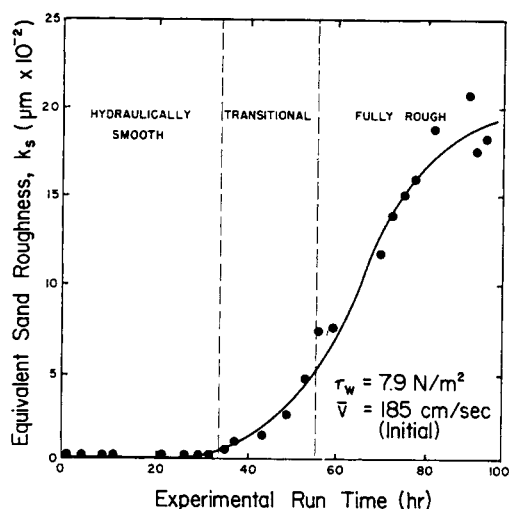


Fig. 22. Change in equivalent sand roughness with time due to biofilm formation. Experiment was conducted at constant pressure drop (Ref. 2).

The friction factor is related to the Reynolds number and the equivalent sand roughness k_s through the empirical Colebrook–White relation. This equation correlates friction factor to Reynolds number for various “commercially rough” pipes throughout the hydraulically smooth, transition, and fully rough regimes. The Colebrook–White equation solved for the equivalent sand roughness k_s yields

$$k_s = \left(\frac{d}{2}\right) 10^{(0.87 - 0.50f^{-1/2})} - \left(\frac{18.70}{\text{Re } f^{1/2}}\right) \quad (3)$$

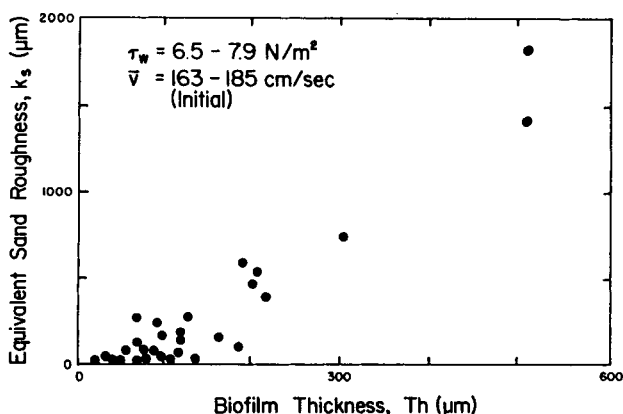


Fig. 23. Change in calculated equivalent sand roughness with biofilm thickness for several experiments conducted at constant pressure drop (Ref. 2).

where d = tube diameter (length), $Re = \bar{V}d/\nu$ = Reynolds number (dimensionless), and ν = kinematic viscosity (length²/time). This expression can be used to compute an equivalent sand roughness for the biofilm from a measurement of the flow rate and pressure drop. Figure 22 indicates the progression of k_s with time and Figure 23 presents the change in k_s with biofilm thickness for the range of shear stress investigated by Zelter.²

Determination of the flow regime (smooth, transitional, or fully rough) depends on the magnitude of k_s relative to the size of the viscous sublayer (δ_1):

$$\delta_1 = (10d/Re) (f/2)^{-0.5} \quad (4)$$

More specifically, when $k_s < \delta_1$ the pipe is considered hydraulically smooth; when $14\delta_1 > k_s > \delta_1$ the flow is in the transitional regime; when $k_s > 14\delta_1$ the flow is in the fully rough regime.⁵³

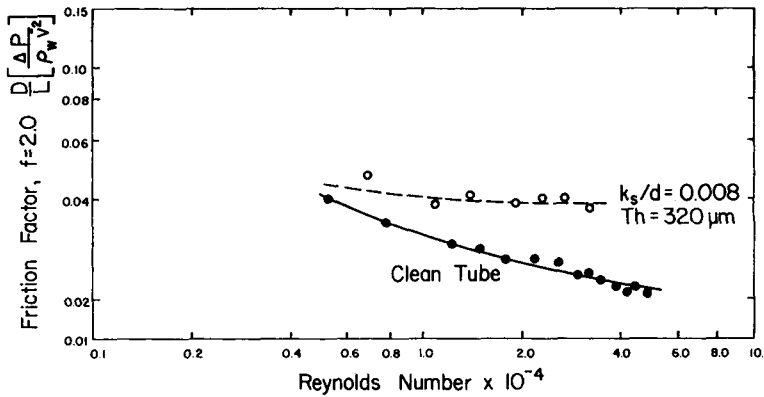
Frictional resistance of biofilms grown under constant pressure drop (i.e., constant shear stress) have been compared to the frictional resistance of pipes with a rigid roughness as given by the Colebrook–White equation. The following was observed:

- 1) Frictional resistance due to biofilms shows a similar dependency on Reynolds number as frictional resistance due to commercially rough pipe surface.
- 2) Frictional resistance is dependent on biofilm thickness.
- 3) Frictional resistance does not increase above the hydraulically smooth pipe value until a critical biofilm thickness is attained.

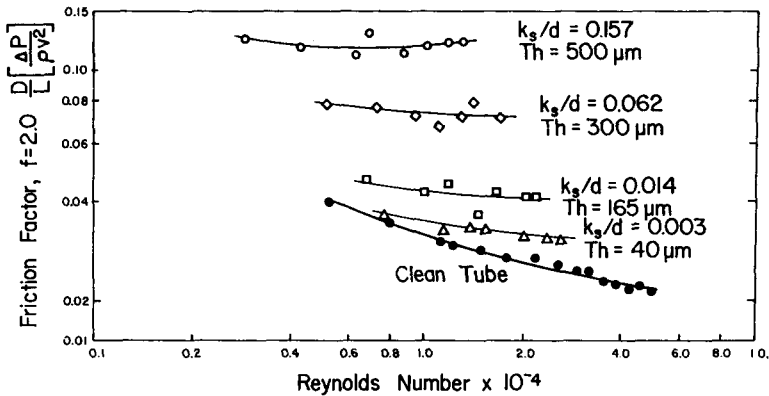
The Blasius–Stanton or Moody diagram⁵⁴ can be used to compare frictional resistance due to biofilm with frictional resistance of rigid rough surfaces. The Blasius–Stanton diagram is a plot of friction factor versus Reynolds number for a series of pipes with different equivalent sand roughness; the friction factor in a pipe with a rigid rough surface depends on both the relative roughness and the Reynolds number.

The relationship between friction factor and Reynolds number for a fouled circular tube is presented in Figure 24(a). The friction factors and Reynolds numbers presented have not been corrected for the pipe constriction resulting from the biofilm. This figure shows the dependency of friction factor on Reynolds number is the same as for a tube with a rigid rough surface within the range of Reynolds number investigated (5000–48,000). These data were obtained by reducing, in steps, the shear stress from its initial value in a given experiment and calculating friction factor and Reynolds number at each step. The shear stress was reduced from the initial condition to minimize detachment of biofilm during the experiment.

Figure 24(b) indicates the relationship between friction factor and Reynolds number within a single experiment at different stages of biofilm development; friction factor increases with biofilm thickness. The rela-



(a)



(b)

Fig. 24. Change in friction factor as function of Reynolds number and roughness: (a) due to biofilm formation; (b) at different stages of biofilm development (Ref. 2).

tionship between biofilm thickness and friction factor for all of Zelter's experiments at a wall shear stress from 6.5 to 7.9 N/m² is shown in Figure 25. Friction factor is dependent on biofilm thickness after a critical thickness (Th_c) approximately equal to the thickness of the viscous sublayer (δ_1) is attained.

Conceptually, Th_c corresponds to the stage of biofilm development at which surface irregularities protrude through the viscous sublayer. Until this stage, the biofilm lies completely within the viscous sublayer ($k_s < \delta_1$) and friction factor does not increase (the tube is hydraulically smooth). For a wall shear stress of 6.5–7.9 N/m², the viscous sublayer is approximately equal to 40 μm ; this compares well with the observed $Th_c = 30$ –35 μm for the same wall shear stress range.

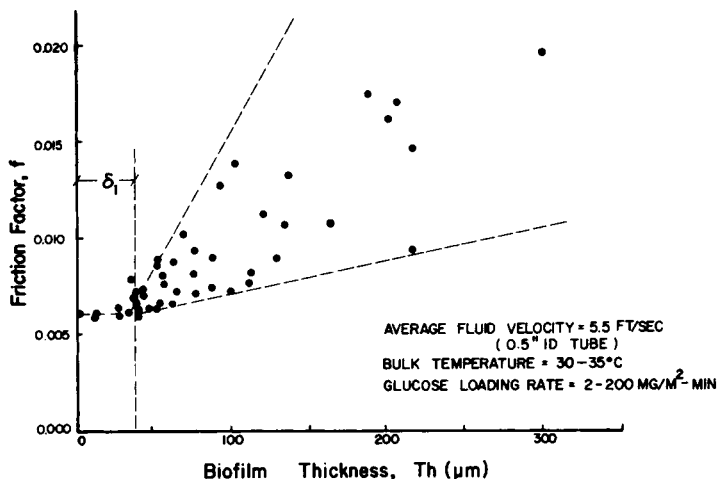


Fig. 25. Influence of biofilm thickness on friction factor in a circular tube 1.27 cm i.d. (Ref. 2). Results of several experiments at widely varying glucose loading rates indicating viscous sublayer thickness.

Although the frictional resistance effects of biofilm can be adequately described by formulas and concepts suitable for rigid rough surfaces, the conclusion should not be drawn that indeed the biofilm presents a rigid rough surface to the flow. Such a notion is an oversimplification and cannot account for all experimental observations.⁵⁵

Finally, frictional resistance measurements provide a relatively simple method for determining liquid mass transfer resistance in some biofilm systems since frictional resistance and liquid mass transfer resistance are related.⁵⁶

EFFECTS OF BIOFILM ON HEAT TRANSFER RESISTANCE

Biofilm development and resulting fluid frictional resistance have been discussed and both influence heat transfer. Changes in heat transfer resistance arise from the combined effects of increased biofilm thickness (conductive heat transfer) and increased frictional resistance (convective heat transfer).

Conductive heat transfer can be related to biofilm thickness and its effective thermal conductivity. Experimental biofilm thermal conductivity determinations indicate no significant difference from that of water at the same temperature (see Table IV). This is not surprising since biofilm is approximately 98–99% water.

Convective heat transfer results from fluid mixing or motion and can be related to momentum transfer or frictional resistance. Colburn⁵⁷ correlated convective heat transfer in tubes to friction factor and properties

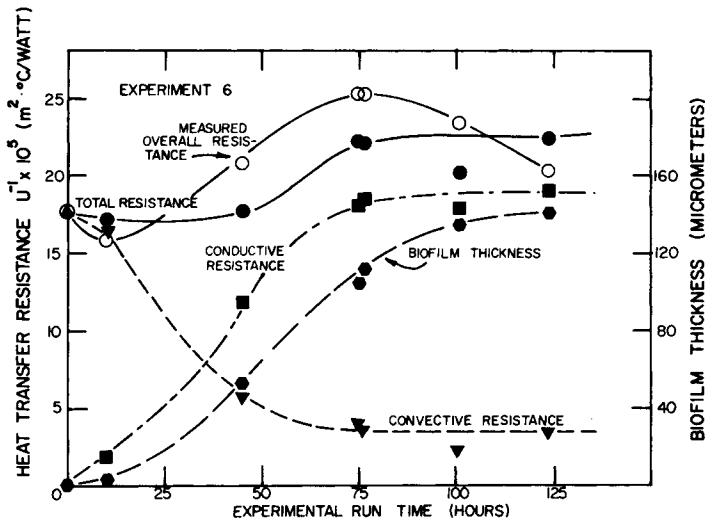


Fig. 26. Changes in convective and conductive heat transfer resistance as a result of biofilm development (Ref. 4).

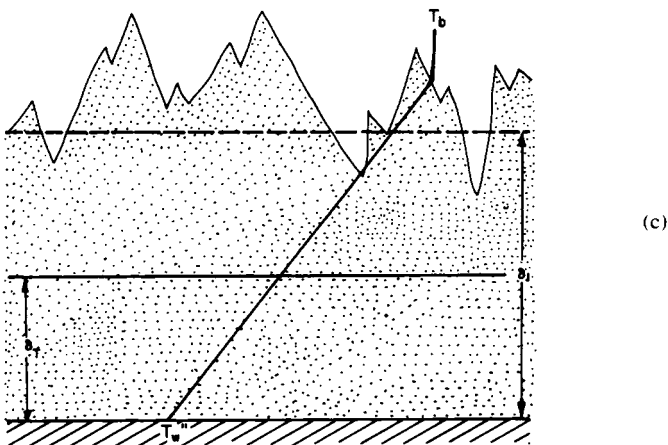
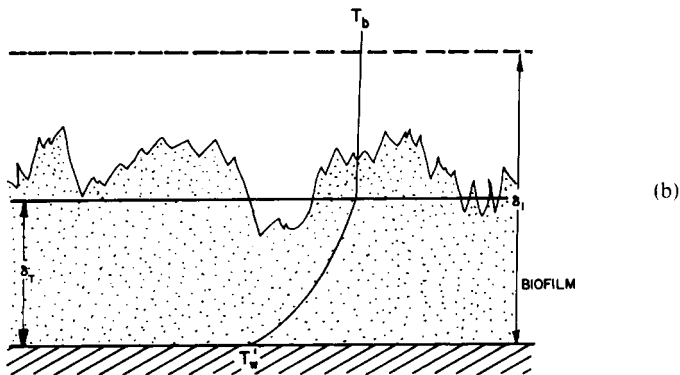
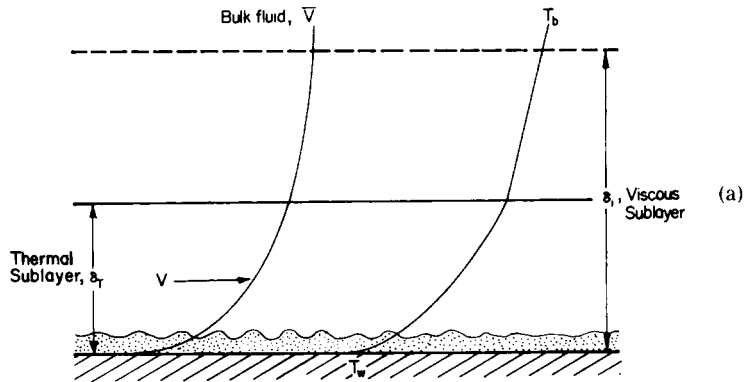
of the fluid. The Colburn relationship is only useful when the biofilm is thicker than the viscous sublayer.

Overall heat transfer resistance due to biofouling film development can then be calculated if the following are known: 1) biofilm thickness and biofilm thermal conductivity, 2) frictional resistance, and 3) wall temperature and bulk temperature.

Figure 26 describes a typical experiment conducted by Nimmons⁴ in a tubular reactor and illustrates the relative effects of conductive and convective heat transfer resistance on overall heat transfer resistance.

Heat transfer resistance was consistently observed to decrease upon initial exposure to the fouling fluid in Nimmon's experiments. He hypothesized the following sequence of events to explain his observations. As a clean heat exchanger [Fig. 27(a)] is exposed to the fluid, a microlayer of organics and microbial cells forms. The conductive thermal resistance is relatively insignificant for a thickness of a few micrometers and the fouling layer remains within the viscous and thermal boundary layers. However, the biofilm layer produces a microroughness increasing convective heat transfer. Assuming the biofilm thermal conductivity is equal to that of water, the effect of the biofilm on conductive heat transfer would be equal to a stagnant water film of the same thickness. As long

Fig. 27. Hypothesized thermohydrodynamic changes occurring near a heat transfer surface as biofilm develops: (a) thin biofilm causes no changes in friction factor but "microroughness" decreases convective heat transfer resistance; (b) biofilm becomes thick enough to significantly influence conductive heat transfer but not friction factor; (c) biofilm is sufficiently thick to increase friction factor and Colburn relationship is valid.



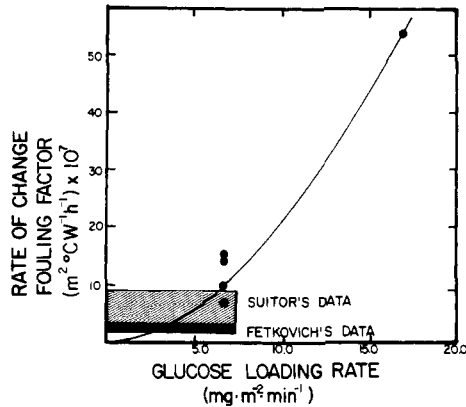


Fig. 28. Influence of substrate loading rate on heat transfer fouling factor (Ref. 4). The ranges measured by others are indicated for comparison (see Table X).

as the biofilm thickness is less than the viscous sublayer thickness, changes in convective heat transfer are not accompanied by changes in friction factor [Fig. 27(b)]. When the roughness elements are of sufficient height to project beyond the viscous sublayer and into the turbulent zone, an increase in friction factor and a further decrease in convective heat transfer resistance are observed. At this point the Colburn relationship may be used to determine the convective heat transfer coefficient [Fig. 27(c)]. Based on this hypothesis and his experimental data, Nimmons estimated the thermal boundary layer to be approximately 10–15 μm . The expected value is 22 μm . The viscous sublayer thickness calculated from hydrodynamic considerations was 44 μm as compared to 40 μm based on the observed onset of increased frictional resistance.

Nimmons computed the fouling factor R_F for his system and Figure 28 indicates its strong dependence on input substrate (glucose) concentration. Ranges of R_F measured in natural seawater systems are also included in Figure 28 for comparison purposes. Table X describes the experimental systems for Nimmons (data points), Ritter and Suito,⁵⁸ and Fetkovich et al.⁵⁹ Neither carbon nor nutrient concentrations were determined in

TABLE X
Description of Experimental Systems for R_F Measurements Reported in Fig. 28

	Nimmons (Ref. 4)	Ritter and Suito (Ref. 58)	Fetkovich et al. (Ref. 59)
Surface	Al 6061-T6	Titanium	Cupronickel
Surface temperature ($^{\circ}\text{C}$)	39–45	26–38	21
Fluid velocity (cm/s)	81	60–120	90–180

the latter two studies. However, carbon concentrations are estimated at between 0.5 and 10 mg/L.

Kirkpatrick, McIntire, and Characklis⁶⁰ have modeled the heat and mass transfer occurring in a heat exchange tube as a biofilm develops. In a typical heat exchanger, results indicate a significant decrease in heat transfer. For systems of interest, the biofilm is relatively uniform over the length of the heat exchange tube. In tubes with combined heat and mass transfer, the biofilm thickness varies appreciably with fluid temperature. The assumed relationships between temperature and biofilm development rates in their model have been partially verified by Stathopoulos.⁶¹

SUMMARY

Biofilm processes have been discussed in terms of the more fundamental physical, chemical, and biological processes which contribute to the biomass accumulation at a surface. The purpose was twofold:

- 1) to present a framework for analysis of the rate of biofilm development, extent of biofilm development, and influence of biofilms on energy losses;
- 2) to stimulate fundamental investigations on topics related to biofilm processes.

Biofilms are emerging as a most critical factor affecting natural aquatic systems, water distribution systems, wastewater treatment systems, heat exchangers, fuel consumption by ships, and even human disease. More attention must be directed to their behavior. Some topics that require more attention include the following:

- 1) Physical, chemical, and biological properties and structure of biofilms as a function of water quality and hydrodynamic characteristics.
- 2) Mathematical models relating process rates to bulk water concentrations, surface characteristics, and microbial species.
- 3) Population dynamics within the biofilm and its relationships to the microbial populations in the bulk water as well as water quality.
- 4) Methods to inhibit, control, or prevent biofilm accumulation which are compatible with environmental quality.
- 5) Methods to enhance biofilm accumulation and activity in terms of substrate removal for fixed-film wastewater treatment systems.

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