# COMPREHENSIVE BIOTECHNOLOGY

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# 54

# Fundamental Considerations of Fixed Film Systems

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## 54.1 INTRODUCTION

The origin of fixed film reactors for wastewater treatment is estimated to have occurred around 1871 (Lohmeyer, 1957). Since that time, fixed film reactors have been widely adopted, although

their popularity waned during the period of wide scale adoption of the activated sludge process. Rotating biological contactors (RBC), plastic packing for towers, and the acceptance of fluidized bed reactors have increased the applications of fixed film processes in the last 10 years. An important advantage of the RBC over activated sludge is the lower energy requirement, which has influenced its rapid adoption.

As a result of the new developments, there has been a renewed interest in the modelling of fixed film reactors. The interest in modelling is related to expectations for improved design and operation of the reactors for wastewater treatment. This chapter will deal with phenomenological or mechanistic aspects of fixed film modelling. The intent is to develop models to simulate fixed film reactors under conditions and in applications heretofore unexplored. The oft-used empirical approach can be used with caution for design from pilot data and numerous case histories of this type can be found in the literature (Watt and Cahill, 1980). However, empirical models can rarely provide useful extrapolations for predicting performances of widely disparate systems.

Phenomenological models are developed with attention to the conservation equations derived from thermodynamics and Newton's laws of motion. Using these tools experimental data can yield stoichiometric and kinetic expressions which describe the processes occurring in any fixed film reactor.

Three types of fixed film reactors will be discussed in the succeeding chapters in this section: (1) trickling filters, (2) rotating biological contactors, and (3) fluidized beds. Superficially, these reactor configurations appear quite different. In fact, the fluid flow patterns are significantly different. However, the fundamental processes occurring in the biofilm within these different reactor configurations are essentially the same. The heterogeneous (*i.e.* requiring two phases) reactors contain active biomass immobilized on the wetted surfaces. The immobilized biomass, herein referred to as the *biofilm*, extracts nutrients from the flowing liquid. As noted before, the flow patterns in the various reactor configurations are different and, as a result, fluid shear stress and mass transfer processes are different at the biofilm–fluid interface.

Consequently, a flow diagram of any model for a fixed film reactor would include two major components: (1) a reactor flow model and (2) a biofilm model (Figure 1). The reactor flow model will be different for every different flow configuration. The biofilm model will be the same for all fixed film reactors. The remainder of this chapter will deal with these two model components with emphasis on the biofilm component.

The goal of this chapter is to provide a tool to help the reader formulate questions regarding data presented in succeeding sections. The intent is to stimulate the reader to use this tool as a starting point toward a deeper understanding of the processes occurring within a fixed film reactor which will result in design or operational improvements in a specific wastewater treatment plant.

## 54.2 SIMPLIFYING ASSUMPTIONS

The growth of even a single population of microorganisms is a very complicated process. The task of modelling such growth requires simplifying assumptions. The assumptions introduce errors since the model will not describe all the various facets of growth. However, the model will describe the processes considered important. Continued experimentation will lead to continued improvement in the accuracy of fixed film mathematical models.

Although many microbial process models make certain simplifying assumptions, it seems important that the more general assumptions be stated explicitly at this point. More specific assumptions will be presented throughout the chapter.

### 54.2.1 Distribution of States

Biological populations are composed of individual organisms and the individual organisms are physiologically, morphologically and genetically different. More detailed analysis perhaps would reveal even more fundamental distinctions between individuals. In summary, the individuals of a population do not all exist in the same 'state', but rather in a distribution of states.

Our first simplifying assumption is that distribution of states can be ignored and the properties of the culture can be adequately described in terms of a 'typical' individual whose behavior represents an average over the distribution states.

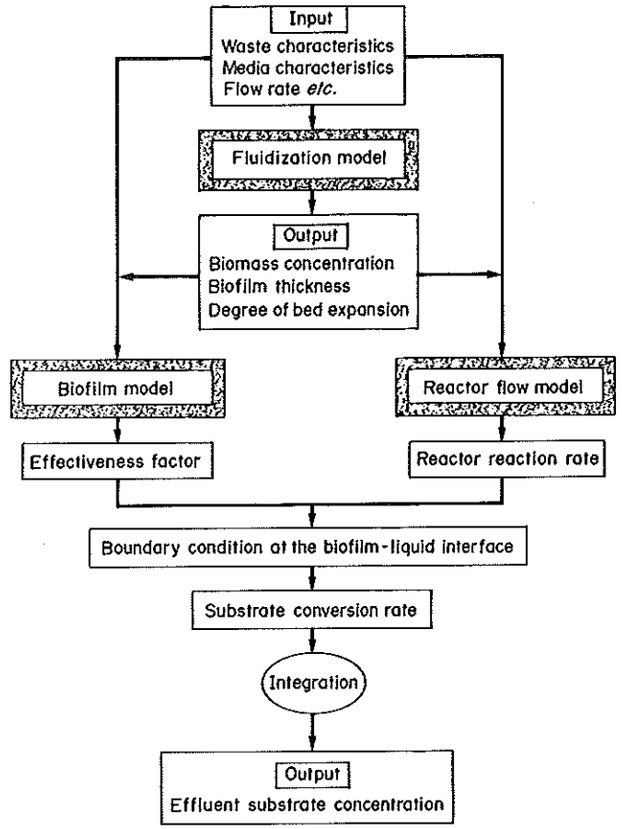



**Figure 1** Flow diagram of a model for a fluidized bed biological reactor illustrating interfacing of the biofilm model with the model of the physical characteristics of the reactor

### 54.2.2 Segregation

In microbial processes, life is segregated into structurally and functionally discrete units, *i.e.* cells. Hence, the number of individual organisms present in a population is as important for the description of the problem as biomass. Despite these considerations, we will sometimes assume that the population is only considered as biomass distributed continuously throughout the reactor. Models based on this assumption are termed nonsegregated or distributed.

If microbial growth is balanced, then increase in biomass and cell number are proportional, which possibly explains some of the success of distributed models in the past. However, microbial growth in biofilms cannot always be considered balanced without introducing large errors.

### 54.2.3 Structure

Two microorganisms having the same biomass and inhabiting the same environment may, nevertheless, have widely different properties and activities. This is the problem of state again. Even a distributed model should recognize that the average or typical organism can change in response to variations in the environment. This means that parameters other than population number and biomass must be important in describing population behavior.

For most microbial process models, biomass is the sole variable employed for describing the microbial population. Therefore, these models do not recognize any 'structure' in the biotic material. Since this procedure regards organisms and population biomass as featureless, structureless entities, these models are called unstructured. Throughout most of this chapter, unstructured models will be considered.

## 54.3 FUNDAMENTAL PROCESSES

Development of a systematic understanding of biofilm processes has been limited by the seeming complexity posed by the interaction of several contributing rate processes. The development and persistence of a biofilm may be described as a net result of the following processes: (i) transport of material from the bulk fluid to the wetted surface; materials may be soluble (microbial nutrients both inorganic and organic) and particulate (viable microorganisms, other organic, and inorganic particles); (ii) adhesion, attachment and/or adsorption of soluble and particulate material to the wetted surface or the biofilm; (iii) microbial processes within the biofilm which include growth, product formation, decay or maintenance, and death or lysis; and (iv) detachment or desorption of soluble and particulate material from the biofilm and its reentrainment in the bulk fluid.

These processes are generally occurring simultaneously although their relative rates may be quite different (Figure 2). Any of the processes could provide the rate-limiting step in the overall process of biofilm development or its continued existence.

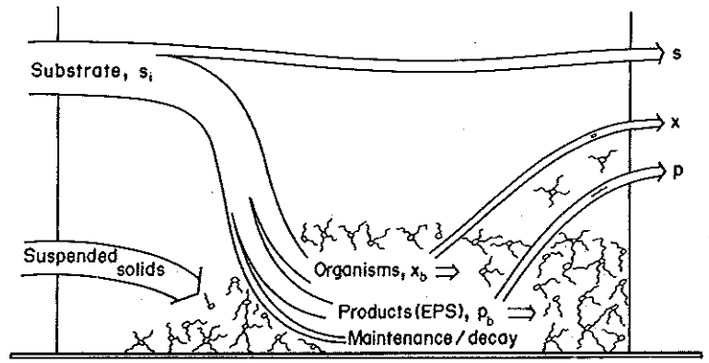



**Figure 2** Biofilm development model including transport of soluble and insoluble material to the wetted surface where attachment and microbial transformation processes are occurring. Desorption and detachment of products and cells from the biofilm are also included

### 54.3.1 Fluid Phase Transport Processes

The rate of transport of materials from the bulk fluid to the biofilm is an important factor contributing to the performance of a fixed film reactor.

#### *54.3.1.1 Soluble materials*

The transport of soluble organic and inorganic nutrients, as well as electron donors, can be the rate-controlling step in the removal of these components from the bulk fluid. Transport of soluble materials from the bulk fluid to the biofilm interface can be described adequately by well-tested empirical expressions relating transport rate to fluid flow regime, fluid phase concentration and surface roughness (as reflected by fluid frictional resistance).

#### *54.3.1.2 Particulate materials*

Transport of microbial cells, particulate and colloidal substrates, and other relatively inert particles contributes significantly to the development and continued existence of a biofilm. Transport of particles, in contrast to soluble materials, is a more complex phenomenon depending on the properties of the particle (diameter, specific gravity), properties of the fluid, and the fluid flow regime. Equations describing transport of soluble materials are used to describe transport of particulates as well, but mass transfer coefficients cannot be predicted as accurately as those for soluble components.

### 54.3.2 Interfacial Phenomena

Soluble and particulate materials are transported to the biofilm interface and are immobilized in the biofilm or reentrained in the bulk fluid. The rate of capture, or the 'sticking efficiency', is related to the biofilm surface roughness, its chemical composition and the velocity with which the particle strikes the surface. There is reason to believe that there is significant turnover of microbial cells within the biofilm resulting from the adsorption of cells from the bulk fluid and desorption of cells from the biofilm (Trulear, 1983).

### 54.3.3 Microbial Processes

The models considered in this chapter will be unstructured for the most part. As a result, we will presume that microorganisms can carry out only four fundamental processes: growth, *i.e.* increase in cellular mass or cell numbers due to reproduction processes; product formation, *i.e.* formation of intracellular or extracellular products which are excreted and attached to the cell or desorbed; maintenance, *i.e.* a process requiring energy to maintain the cellular machinery. Maintenance has not been directly observed but has been used to account for decreases in the observed growth yield, generally at low growth rates; biomass decay, *i.e.* attrition of biomass due to endogenous respiration, autooxidation, and other ill-defined processes. Biomass decay and maintenance are both used to account for the same observations. As a consequence, the two are not used in the same model; and death or lysis, *i.e.* inactivation of cells or their destruction by lysis (can be related to biomass decay).

Growth, product formation and maintenance occur at the expense of substrate and nutrients removed from the wastewater. Therefore, substrate removal rate is the net result of substrate removal for growth, product formation and maintenance. The experimental observation and quantification of the individual process rates is quite difficult. As a consequence, the wastewater treatment literature has generally ignored the fundamental processes choosing to concentrate on the more readily observed quantites such as substrate or oxygen removal rate.

### 54.3.4 Detachment

Detachment phenomena can be arbitrarily categorized as shearing or sloughing. Shearing refers to continuous removal of small portions of the biofilm which is highly dependent on fluid dynamic conditions. Under these circumstances, rate of detachment increases with increasing biofilm thickness and fluid shear stress at the biofilm–fluid interface (Trulear and Characklis, 1982). Sloughing refers to a random, massive removal of biofilm generally attributed to nutrient or oxygen depletion deep within the biofilm (Howell and Atkinson, 1976) or some dramatic change in the immediate environment of the biofilm (Bakke, 1983). Sloughing is more frequently witnessed with thicker biofilms developed in nutrient-rich environments.

Table 1 is a matrix representation of the fundamental processes and their relationship to the readily observed processes reported regularly in the wastewater treatment literature.

## 54.4 METHODS

The absence of convenient methods for measuring the biotic and abiotic components has hindered more fundamental process analyses in fixed film reactor systems. Recently, more discriminating methods for such analyses have been developed (Characklis *et al.*, 1982; Trulear, 1983). Material balances and, hence, methods are necessary for quantifying substrate, product and suspended biomass. In addition, a constitutive equation for the biofilm mass is necessary. Therefore, certain properties of the biofilm system must be determined.

### 54.4.1 Substrate and Product

Biochemical oxygen demand (BOD), chemical oxygen demand (COD) and organic carbon (OC) are nonspecific or colligative measures of organic substrate. BOD is essentially useless for any process analysis because it cannot be used in material balances. COD (in conjunction with oxygen removal rate) and OC can be used in material balances (*i.e.* they are conservative quanti-

**Table 1** A Matrix Representation for the Fundamental Microbial Rate Processes

| *Process rate* / *Fundamental process* | | *Stoichiometry* | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | *Reactants* | | | *Products* | | | | |
| *Process* | *Rate* | *Substrate* $S$ | *Nutrient* $Z$ | *Electron acceptor* e | *Biomass* $x_T$ | $x_d$ | *Product* $p_e$ | $p_i$ | *Metabolite* a |
| Growth | $\mu$ | − | − | − | + | | + | (+) | + |
| Maintenance | | | | | | | | | |
| Exogenous | $m$ | − | − | − | | | + | | + |
| Endogenous | $k_e$ | | + | − | − | (+) | + | − | + |
| Product formation | $k_p$ | − | − | − | | | + | + | + |
| Death | | | | | | | | | |
| Loss of viability | $k_d$ | | | | | | | | |
| Lysis | $k_L$ | (+) | (+) | | − | (+) | + | | |
| Observed rate | | $q_s$ | $q_z$ | $q_e$ | $\mu_n$ | | $q_p$ | | $q_a$ |

$q$ = specific production or removal rate ($t^{-1}$); $\mu$ = specific growth rate or specific biomass production rate ($t^{-1}$); $x_T$ = total biomass concentration ($ml^{-3}$); $x_d$ = inert solids concentration ($ml^{-3}$); $p_e$ = extracellular microbial product concentration ($ml^{-3}$); $p_i$ = intracellular microbial product concentration ($ml^{-3}$); $s$ = substrate concentration ($ml^{-3}$); $z$ = nutrient concentration ($ml^{-3}$); $e$ = electron acceptor concentration ($ml^{-3}$); and $\mu_n$ = net solids production rate ($t^{-1}$)

ties) but neither can distinguish between substrate and organic microbial products. Wastewaters rarely consist of a single substrate. However, a process analysis with a defined substrate (single or multiple) can provide useful insight into the biofilm processes occurring in wastewater treatment systems. Trulear (1983) and Schaftel (1982) have both used glucose as a substrate in biofilm studies because of the enzymatic analyses available for its specific detection. In addition, they used OC analysis, which measured the sum of the carbon in the glucose as well as the microbial products. The results of their studies are significant and will be discussed in other sections.

### 54.4.2 Biofilm Properties

Early fixed film studies with wastewater ignored biofilm properties and simply related process characteristics to the wetted surface area covered by the biofilm. As the need became apparent, biofilm thickness and density (dry weight per unit wet volume) were included (*e.g.* Hoehn and Ray, 1973; Trulear and Characklis, 1982). More recently, Trulear (1983) has provided a measure of structure to the biofilm by distinguishing between cellular and extracellular carbon mass within the biofilm. One of his results indicates that the biofilm may consist of as much as 90% extracellular polymer substances (EPS) expressed as organic carbon. Trulear's study was conducted axenically with *Pseudomonas aeruginosa*. Cellular carbon was estimated by acridine orange direct count (AODC) and determination of an average cell volume using epi-illuminated microscopy assuming a specific gravity (1.0) and carbon content (50%) for the cells. The difference between total biofilm organic carbon and cellular biofilm organic carbon is EPS carbon.

### 54.4.3 Suspended Biomass

Biomass, consisting of cellular mass and insoluble products, is continuously entering the reactor suspended in the influent. However, biomass is also entering the reactor fluid as a result of detachment from the biofilm. The suspended biomass can be classified into cellular and extracellular mass in the same way described above for biofilm mass.

## 54.5 STOICHIOMETRY

Stoichiometry is the application of the law of conservation of mass and the chemical laws of combining weights to chemical processes. In its broadest sense, stoichiometry is a system of accounting applied to mass and energy participating in a process involving physical and/or chemical change. Stoichiometric calculations permit a surprisingly large amount of information to be obtained from a seemingly small amount of data.

Mass balances for various components across a reactor help define the stoichiometry of the reactions occurring within it. The material balance across a continuous reactor has the following general form:

$$\begin{array}{c}\text{net rate of}\\ \text{accumulation}\\ \text{in reactor}\end{array} = \begin{array}{c}\text{net rate of}\\ \text{transport out}\\ \text{of reactor}\end{array} + \begin{array}{c}\text{rate of}\\ \text{transformation}\\ \text{by reaction}\end{array} \quad (1)$$

The net accumulation of any component in the reactor system can be described mathematically by relating the transport and transformation of its various components through their stoichiometric and rate coefficients. Roels (1980) has presented a systematic method for this type of analysis in homogeneous reactors.

The importance of a systematic mathematical process analysis has become essential in the light of recent experimental observations with fixed film systems. In almost all biofilm studies, with the exception of nitrifying biofilms, the following oversimplified stoichiometry is assumed:

$$\text{substrate} \rightarrow \text{biofilm} \quad (2)$$

The work of Trulear (1983) and Schaftel (1982) clearly indicates that the stoichiometry of the reaction is significantly influenced by other components. A composite of their work would suggest the following stoichiometry:

$$S + E + Z \rightarrow B + PI + PS \quad (3)$$

where S = substrate; E = electron acceptor; Z = other nutrients; B = biofilm mass; PI = insoluble product; and PS = soluble product.

The substrate and electron acceptor may be different in different layers of the biofilm. For example, oxygen may serve as the electron acceptor in the upper layers of a biofilm exposed to aerated media. However, the electron acceptor in the deeper, anaerobic layers may be nitrate, sulfate or an endogenous electron acceptor due to depletion of oxygen by microbial activity as it diffuses through the upper layers of the biofilms. Similarly, the upper layers of biofilm will 'see' the primary substrate while the lower layers may be exposed to products formed in other parts of the biofilm.

## 54.6 KINETICS

The biofilm is always in a dynamic, nonequilibrium state. Consequently, a stoichiometric analysis alone is not sufficient to model the behavior of a fixed film reactor. The rates of change and the process rates have to be related to the stoichiometry through the mass balance equations. The fundamental process rates discussed in this chapter will include growth, maintenance, product formation, biomass decay, adsorption and detachment. The process rate is characterized by a rate equation which is generally the result of an empirical curve-fitting procedure. The values of the rate coefficients must be determined by experiment, even if the form of the rate expression is suggested by a theoretical analysis or mechanistic model. The determination of the rate expression usually requires a study to determine the influence of concentration followed by the effects of temperature, pH, *etc.* on the reaction rate coefficients.

Rate data for biofilms are best obtained in continuous flow reactors, preferably in a CSTR for which equation (1) applies. Rate of accumulation and rate of transport are rates of change and are measured relatively easily. However, these rates cannot be correlated to fundamental system variables in any meaningful way. Therefore, these rates cannot be extrapolated or used in a predictive manner. The rate of transformation, however, is a process rate which can be used to predict behaviour in systems other than the one in which the data were collected. Generally, process rates can only be inferred from rates of change.

Process rates determine the extent of the process in a reactor with a fixed residence time. Consequently, an estimate of the process rate is necessary for process reactor design. Process rate is perhaps the most important quantity to the reactor design engineer.

The fundamental process rates are difficult to observe directly. The more readily observed process rates are nutrient (substrate) removal rate and electron acceptor (*e.g.* oxygen) removal rate (Table 1). The remainder of this section will discuss observed process rates in terms of the fundamental process rates.

### 54.6.1 Biomass Production Rate

The overall process of biofilm development is the net result of the fundamental processes of growth, decay, maintenance, product formation, adsorption and detachment.

#### *54.6.1.1 Growth*

The specific growth rate, $\mu$, of organisms can be defined as the cellular reproduction rate per total cellular mass per time ($t^{-1}$) and is, in a biofilm reactor at steady state with negligible suspended activity, measured as (Bakke *et al.*, 1984);

$$\mu = D\frac{xV}{x_b A} \tag{4}$$

where $x$ = suspended cellular biomass concentration ($ml^{-3}$); and $x_b$ = areal cellular biofilm density ($ml^{-2}$). Savageau (1969) has shown that growth rate can be related to all of its variables by a power law function. If the system is well defined and accuracy is required, this analysis can be very useful.

A special case of the power function commonly used is the saturation function first presented by Monod (1942) to describe microbial growth. The Monod model assumes that the concentration of one essential nutrient (*i.e.* the substrate) limits the growth of the microorganism as follows:

$$\mu = \frac{\mu_m s}{K_s + s} \tag{5}$$

where $\mu_m$ = maximum specific growth rate ($t^{-1}$); and $K_s$ = saturation coefficient ($ml^{-3}$). Saturation functions can also describe growth limited by more than one nutrient (Grady and Lim, 1980). The saturation model presumes that the cell is in balanced growth, a condition defined by constant biomass composition and physiological state (Powell *et al.*, 1967). The cells are, in other words, regarded as a homogeneous mass of catalytic agent for substrate conversion. Balanced growth in a chemostat is achieved at steady state. In a batch reactor, balanced growth occurs during exponential growth. In a biofilm, balanced growth cannot be defined in a rigorous manner because of the gradients in concentration, pH, *etc.* that may exist. Modelling unbalanced growth requires structured models.

The Monod model, with its limitation, has been very useful for wastewater treatment despite the variability of wastewater flow rates and composition. One reason for its apparent success may be that steady state may refer to more than 'time-invariant' states. Steady state can refer to a condition in which the derivative with respect to time (net rate of accumulation) is negligible compared to either term on the right hand side of equation (1). In fact, this may be the case of many wastewater treatment processes and may explain the usefulness of the Monod model despite its restrictive underlying assumptions. Low sensitivity requirements may be an additional explanation.

The effects of temperature, pH, substrate quality, *etc.* have to be included in the coefficients $K_s$ and $\mu_m$ when applying equation (5).

A general analysis predicting the steady state cellular areal density, $x_b$, based on the growth rate, $\mu$ (equation 4), reveals an inverse proportionality between $x_b$ and $\mu$ (Bakke *et al.*, 1984).

#### *54.6.1.2 Product formation*

Under balanced growth conditions with only one limiting nutrient, product formation rate has been related to the specific growth rate, $\mu$, and the concentration of organisms, $x$ (Leudeking and Piret, 1959):

$$r_p = k\mu x + k'x \tag{6}$$

where $k$ = growth-associated product formation coefficient ($m_p m_x^{-1}$); and $k'$ = nongrowth-associated product formation coefficient ($m_p m_x^{-1} t^{-1}$).

The first term of the equation refers to product formation related to the metabolic state of the microorganisms. In energy-rich environments, growth rate is high, as is the cellular concentration

of metabolic intermediates, which may result in 'leakage' into the bulk fluid. Consequently, the ratio of substrate energy channelled to growth *versus* product formation may be an inverse function of the growth rate.

The second term in equation (6) is independent of metabolic state and is only dependent on biomass concentration. Conceptually, this term may express the result of biomass decay, which has alternatively been modelled as endogenous metabolism, maintenance and/or lysis. The hypothesis is that there is a continuous degradation of cell material resulting in soluble or colloidal organic material which is measured as product. Energy is required to replace and/or 'maintain' the decaying cell components. Trulear (1983) has shown that this simple term can serve as a replacement for biomass decay terms used in other models. The product formation term can be related directly to observations although precision of the coefficents can be a problem (Trulear, 1983). Then $k'$ is a rate coefficient describing the transformation of biomass into soluble organic components. A portion of the soluble organics formed may serve as a secondary substrate for the microorganisms or a source of inorganic nutrients. Figure 3 graphically demonstrates the dependence of $r_p$ on growth rate and biomass concentration as expressed by equation (6).

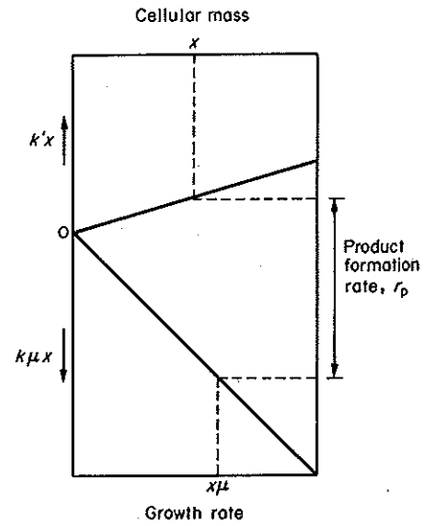



**Figure 3** Graphic product formation rate model as described by equation (6)

The product formation rate equation is attractive because it provides a simple method for predicting the soluble organic content of an effluent (substrate and product), a major concern in wastewater treatment. The rate equation (equation 6) may be unable to predict a specific product concentration because the two terms may not express the rate of formation of the same product. A more structured model is required for such predictions.

### *54.6.1.3 Extracellular polymer substances (EPS)*

At steady state, the EPS formation rate, $r_{EPS}$, can be measured as (Bakke *et al.*, 1984):

$$r_{EPS} = D\frac{pV}{p_b A} \tag{7}$$

where $p$ = bulk liquid EPS concentration ($ml^{-3}$); and $p_b$ = areal biofilm EPS density ($ml^{-2}$). $r_{EPS}$ has been related to the growth rate, $\mu$, and the areal density of organisms, $x_b$, using equation (6) (Trulear, 1983).

$r_{EPS}$ variations measured according to equation (7) but not consistent with equation (6) have, however, been observed (Bakke, 1983). Low precision in measured coefficient values (Trulear, 1983) and ignorance of qualitative EPS variations also contribute to the shortcomings of equation (6). The development of a better model in which these limitations have been eliminated depends on increased understanding of the physiological significance of EPS.

#### *54.6.1.4 Net detachment*

If the reactor influent contains suspended or particulate material, only net detachment can be discussed. The detachment processes can be classified into two categories: (1) sloughing, which refers to massive removal of large pieces of biofilm which happens at seemingly random intervals; and (2) shearing, which is the continuous removal of microscopic portions of biofilm.

Sloughing is usually observed in nutrient-rich environments and at relatively low Reynolds number. Under these conditions, biofilm thickness can become quite large resulting in oxygen-deficient and/or substrate-deficient layers deep within the biofilm. Howell and Atkinson (1976) have proposed a model which assumes that biomass decay in the deep, substrate-deficient layers of the biofilm causes sloughing.

Bakke (1983) has observed EPS desorption associated with substrate flux changes in the biofilm. For example, an RBC plant may exhibit sloughing if anaerobic digester supernatant is periodically pulsed to the system. Bakke hypothesizes that EPS, involved in diffusion regulation through biofilm density changes during load transitions, are removed from the biofilm by fluid shear forces. The magnitude of the EPS desorption has been correlated to proton flux changes across the cell membrane in symport with the substrate. An electromagnetic feedback diffusion regulation mechanism between the cell membrane and the EPS has been proposed (Bakke, 1983).

Shearing has been observed in relatively oligotrophic environments and at high Reynolds number. Shearing is probably occurring under the same conditions in which sloughing occurs but no such direct observations have been attempted. Shearing is generally attributed to fluid shear forces (Trulear and Characklis, 1982; Zelver, 1979). As long as fluid shear forces prevent the biofilm thickness from exceeding the depth of substrate penetration, detachment will significantly influence biofilm thickness. Hence, a model for predicting biofilm thickness will include a term for biofilm detachment rate which depends on fluid shear stress, $\sigma$, biofilm volume, $thA$, and biofilm density, $\varrho$:

$$r_d = k_d \sigma th A \varrho \tag{8}$$

where $k_d$ = detachment rate coefficient.

Trulear and Characklis (1982) present data indicating that detachment rate increases with increasing shear stress and increasing biofilm mass. Rittman (1982) has used their data to predict detachment rates in trickling filters and fluidized bed reactors.

#### *54.6.1.5 Biomass decay*

Biomass decay is a general term referring to the effects of endogenous metabolism, maintenance, autooxidation, and other ill-defined processes that contribute to the attrition of biomass. Biomass decay rate, like maintenance rate, is proportional to biomass concentration:

$$r_{decay} = k_{dc} x \tag{9}$$

where $k_{dc}$ = biomass decay rate.

Consequently, biomass decay rate will increase with increasing biofilm thickness and/or density. Bryers and Characklis (1982) report that biomass decay is negligible compared to biomass production processes in thin biofilms. Rittman (1982) has also calculated biomass decay rate in a fixed film system.

### 54.6.2 Substrate Removal Rate

The overall, $r_s$, and specific, $r_s^*$, substrate removal rates for biofilm reactors can be defined as follows (Bakke *et al.*, 1984):

$$r_s = D(s_i - s)\frac{V}{A} \qquad (ml^{-2}t^{-1}) \tag{10}$$

$$r_s^* = D\frac{(s_i - s)}{x_b}\frac{V}{A} \qquad (m_s m_x^{-1} t^{-1}) \tag{11}$$

where $D$ = dilution rate ($t^{-1}$); $s_i$ = inflow substrate concentration ($ml^{-3}$); $s$ = bulk liquid substrate concentration ($ml^{-3}$); $V$ = reactor volume ($l^3$); A = reactor surface area ($l^2$); and $x_b$ = biofilm cellular areal density ($ml^{-2}$).

Microorganisms consume substrate for two basic purposes: (1) to provide energy for various processes such as synthesis of biomass and products as well as maintenance, and (2) to provide materials for synthesis of cell mass and other products. The kinetic expressions describing substrate removal rates by the various fundamental processes will be discussed in the following sections.

#### *54.6.2.1 Growth*

The Monod model was developed to describe dispersed microbial growth limited by one essential nutrient. The model has been extended to describe substrate removal by biofilms by presuming it proportional to growth rate through the yield coefficient:

$$r_s = \mu \frac{X}{Y} \tag{12}$$

where $Y$ = yield coefficient ($m_x m_s^{-1}$).

The yield coefficient is a ratio of stoichiometric coefficents describing the biomass formed from the removal of a unit mass of substrate. Intrinsically, this presumes that substrate is only used for biomass formation (*i.e.* synthesis). Trulear (1983) however has measured as much as 90% extracellular organic material in biofilms, formed from primary substrate. Schaftel (1982) documented the formation of soluble product formation by biofilms and their transport into the bulk reactor fluid, even when the biofilm was entirely aerobic.

#### *54.6.2.2 Product formation*

Product formation can be accounted for by incorporating equation (6) in the material balance for substrate. The specific substrate removal rate, $r_s^*$, can be calculated as follows (Trulear, 1983; Bakke *et al.*, 1983):

$$r_s^* = \mu\left(\frac{1}{Y_{x/s}} + \frac{k}{Y_{p/s}}\right) + \frac{k'}{Y_{p/s}} \tag{13}$$

where $Y_{x/s}$ = yield of biomass from substrate ($m_x m_s^{-1}$); and $Y_{p/s}$ = yield of products from substrate ($m_p m_s^{-1}$).

Substituting numerical values for the coefficients obtained for *Ps. aeruginosa* grown on dextrose in chemostats (Trulear, 1983) yields:

$$r_s^* = 3.5\mu + 0.6 \tag{14}$$

Data obtained for *Ps. aeruginosa* grown on glucose at steady state in biofilms and dispersed in chemostats correlated well with equation (14). The biofilm cellular areal density, $x_b$, in these experiments was proportional to the substrate flux into the biofilm, $r_s$ (equation 10), at constant growth rate (Bakke *et al.*, 1984).

Too frequently, substrate removal rate is limited by mass transfer of substrate or oxygen from the bulk fluid to the biofilm or diffusion of substrate or oxygen in the biofilm. Under these circumstances, equation (13) must be modified (see below).

#### *54.6.2.3 Maintenance*

The rate of substrate removal for maintenance functions is presumed to be proportional to biomass concentration:

$$r_m = k_m x_b \tag{15}$$

Bryers and Characklis (1981) and Stathopoulos (1981) have estimated maintenance coefficients for biofilms which compare favorably to those determined in dispersed microbial growth systems.

#### *54.6.2.4 Adsorption*

Adsorption of particulate substrate, colloidal substrate and microorganisms significantly influences the performance of a fixed film reactor. The rate expressions describing each of these adsorption processes should appear at least twice in a fixed film reactor model. For example, adsorption of particulate substrate will appear as substrate removal in the substrate material balance and will contribute to increased biofilm accumulation in the biofilm constitutive equation. The adsorbed substrate will be degraded with time, at a rate probably controlled by its hydrolysis.

The net result of adsorption/desorption can be described mathematically as follows:

$$r_A = k_A x(1 - \frac{x'}{k'}) \tag{16}$$

Measurements which discriminate between adsorption and degradation of particulate substrate are difficult but have been accomplished (Banerji *et al.*, 1968). Most observations do not distinguish between adsorption and removal since removal is the major concern. However, colloidal substrate may adversely influence removal of soluble substrate (Särner, 1981).

Substrate removal rate may be mass transfer-limited when the substrate is particulate or colloidal. Mass transfer rates may be determined although predicting mass transfer coefficients may be difficult. Substrate degradation rates, however, are relatively slow compared to transport rates.

In summary, substrate removal rate is the net result of four fundamental processes: growth, maintenance/decay, product formation and adsorption. Under different operating conditions, one process may dominate over the others. For example, product formation may be the dominant process in a system with a very low substrate concentration. The plant engineer, ignorant of the fact that the unsatisfactorily high effluent carbon concentration is due to product formation rather than unreacted substrate, mistakenly presumes that increasing retention time will improve effluent quality. In most fixed film research studies related to wastewater treatment, substrate removal attributed to the various fundamental processes is not considered and, as a result, extrapolations of laboratory and pilot scale kinetic studies are often inaccurate and misleading.

### 54.6.3 Physical Processes Influencing Substrate Removal

Mass transfer, diffusion and detachment all significantly influence the overall performance of a fixed film reactor. The influence of mass transfer and diffusion may be incorporated into the substrate removal rate expression. Net detachment is an additive term in the constitutive equation for the biofilm and also appears in the mass balance for suspended biomass.

#### *54.6.3.1 Mass transfer*

The transport of any soluble component from the bulk fluid to the biofilm can be represented by the following:

$$N = k_f(C_b - C_i) \tag{17}$$

where $k_f$ = mass transfer coefficient ($lt^{-1}$); $C_b$ = bulk fluid concentration ($ml^{-3}$); and $C_i$ = interfacial concentration ($ml^{-3}$). This model presumes the two film theory (Sherwood *et al.*, 1975) for interphase transport is valid for the biofilm–fluid system. Empirical relationships are available for calculating the mass transfer coefficient, $k_f$, as a function of Reynolds number in various geometries (Sherwood *et al.*, 1975). One of the difficulties arises as a result of the nature of the interfacial surface. Most researchers prefer to depict a well-defined interface between the bulk fluid and the biofilm. In fact, some fluid may very well move through the biofilm or portions of the biofilm so that no clear interface exists. In any case, the biofilm does exhibit hydraulic roughness as indicated by the results of Picologlou *et al.* (1980). The biofilm roughness, however, is highly dependent on the microbial species within the biofilm (Trulear and Characklis, 1982). For example, *Sphaerotilus natans* is a filamentous organism which exerts a significant influence on biofilm roughness while *Pseudomonas aeruginosa* exerts little influence on biofilm roughness in its rod-shaped, single cell morphology (Trulear and Characklis, 1982; McCoy and Costerton, 1982).

Process rates in trickling filters, rotating biological contactors and fluidized beds can be rate-

limited by transport in the bulk fluid. Detecting this type of rate limitation requires varying the Reynolds number or intrinsic rate coefficients for the processes occurring in the biofilm.

#### 54.6.3.2 *Diffusion in the biofilm*

Rate of electron donor (substrate) or electron acceptor removal may be rate-limited by diffusion of reactants into the biofilm or diffusion of products out of the biofilm. For example, the rate expression for substrate removal may include an effectiveness factor as described by Atkinson and his coworkers (1974) to account for diffusion in the biofilm:

$$N = \frac{\lambda k_1 s x_b}{K_s + S} \tag{18}$$

where $\lambda$ = effectiveness factor; and $k_1$ = specific substrate removal rate ($m_s m_x^{-1} t^{-1}$).

Equation (18) is a modified version of the expression for substrate removal in equation (12). Trulear (1983) has modified Atkinson's rate expression to account for product formation in the biofilm as presented in equation (13).

By combining equations (18) and (13), an expression for substrate removal by biofilms is obtained which includes growth, product formation and the influence of diffusion.

Any model of this type suffers due to the difficulty in measuring accurate, meaningful diffusion coefficients in biofilms. Even defining a diffusion coefficient is difficult when a colligative measure of substrate is used. For these cases and other practical applications, the effectiveness factor best serves as a coefficient for modifying the substrate removal rate for the effects of diffusion.

### 54.6.4 Other Factors Influencing Kinetics

The kinetic expressions presented in the preceding sections are incomplete and suffer from many limitations. From a fundamental standpoint, additional factors may be important and should be considered.

Little is known about microbial population dynamics in a fixed film reactor despite its apparent influence on reactor performance. For example, Michels *et al.* (1979) and Otto *et al.* (1980) have shown that an organism consuming primary substrate may grow 50% faster due to efflux energy generated by organisms consuming a secondary substrate (a metabolite) excreted by the first species. Predation has been studied and has been blamed for total failure of reactors.

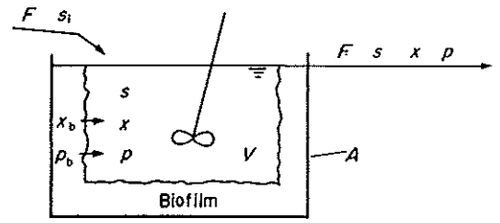
The full significance of extracellular polymer substances (EPS) is not known. However, EPS surely influences diffusion rates within the biofilm, adsorption rates within the biofilm and the physiological state of the organisms in the biofilm (Joyce and Dugan, 1970; Klimek and Ollis, 1980; Dudman, 1977).

### 54.6.5 Summary of Kinetics

Many fundamental processes are recognized as contributing to the overall performance of a fixed film reactor. In some cases, useful, quantitative rate expressions for fundamental processes are not available. A complex model, however, has little immediate relevance to wastewater treatment. Yet continued attention to fundamental aspects of the process may result in improved operation and design in future, more demanding applications.

An illustration may be instructive. Consider the fixed film CSTR in Figure 4. Steady state material balances for substrate, product and suspended cellular biomass are listed, as well as a constitutive equation for the cellular biofilm mass. Easily measured quantities are presented on the left hand side of the equations. The easily measured quantities are also the quantities of most concern to the design and operations engineer. Nevertheless, the right hand sides of the equations indicate the process rates that determine the performance of the system.

The processes discussed above occur in all fixed film reactor systems. The methods used by the observer will determine whether the fundamental processes can be resolved in any given study. For example, if sewage is used as substrate, a colligative measure of substrate is necessary and product formation cannot be considered. Nevertheless, knowing that product may be formed by the biofilm may influence interpretation of the results and subsequent decisions regarding the process.




Material balances

Substrate, s

$$\frac{F(s_i - s)}{A} = \frac{r_g}{Y_{x/s}} + \frac{r_p}{Y_{p/s}}$$

Products, p

$$\frac{Fp}{A} = r_p$$

Suspended cellular biomass, x

$$\frac{Fx}{A} = r_d$$

Constitutive equation

Cellular biofilm mass, $x_b$

$$0 = r_g - r_d$$

where $r_g$ = cellular growth rate ($m_x l^{-2} t^{-1}$)
$r_p$ = product formation rate ($m_p l^{-2} t^{-1}$)
$r_d$ = cellular detachment rate ($m_x l^{-2} t^{-1}$)

**Figure 4** A steady state fixed film CSTR analysis

## 54.7 REACTOR ANALYSIS

Reactor configuration determines the overall liquid phase concentration profiles and transport within the reactor. In addition, of particular importance in fixed film reactors, reactor geometry determines the Reynolds number and fluid shear stress at the biofilm–fluid interface. In this section, liquid phase concentration profiles will be related to reactor configurations of practical interest. Then the flux of components across system boundaries will be related to overall reactor performance.

Two fixed film reactor types will be considered: (1) continuous flow stirred tank reactor (CSTR); and (2) plug flow reactor (PFR). Figure 5 presents schematic diagrams of these two reactors and their characteristic liquid phase concentration profiles. The effluent concentration of a CSTR is the same as the reactor concentration since no spatial gradients exist, *i.e.* the reactor is completely mixed. In the PFR, there is no mixing in the longitudinal direction but mixing is perfect in the radial direction. Consequently, a unit of fluid travels through the reactor as a 'plug'.

Trickling filters without significant recycle flow can be modelled as PFRs while RBCs and fluidized beds are modelled as CSTRs. Any of the CSTRs can be converted to a PFR system by operating several of them in series. A CSTR system can be achieved with a PFR by applying a high recirculation rate. The remainder of this analysis presumes ideal CSTRs and PRFs realizing the limitations imposed by the assumption. At steady state in these reactors, the material balance simplifies to the following:

$$\text{net transport out of reactor} = \text{transformation or reaction} \tag{19}$$

The distinction between the PFR and CSTR occurs on the left hand side of equation (19). Two types of transport are possible: (1) interphase transport, as illustrated by oxygen transfer from air to the wastewater, and (2) bulk transport of materials, as illustration by the input of substrate (dissolved or suspended) in the wastewater influent.

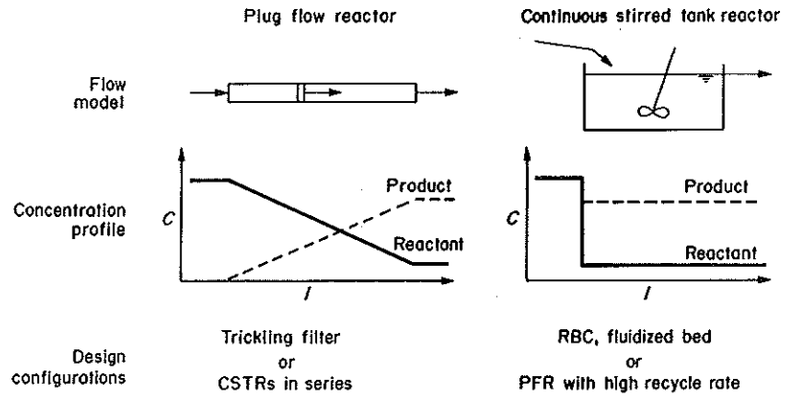



**Figure 5** Comparison of PFRs and CSTRs regarding flow scheme, bulk liquid concentration profiles and design configurations

### 54.7.1 Residence Time

Bulk transport is proportional to the volumetric flow rate across the system boundaries and can be expressed as follows:

$$D = F/V \tag{20}$$

The reactor liquid residence time, $\tau$, is the inverse of $D$ and is useful for comparing reactor configurations. At constant reactor volume and volumetric feed rate, $\tau$ required can be calculated from influent and effluent concentrations ($C_i$ and $C$, respectively) and the observed reaction rate:

$$\text{for a CSTR} \quad \tau_{CSTR} = \frac{C_i - C}{r} \tag{21}$$

$$\text{for a PFR} \quad \tau_{PFR} = \int_{C_i}^{C} \frac{dC}{-r} \tag{22}$$

where $r$ = reaction rate, *e.g.* $r = k_r C^n$ ($ml^{-3}t^{-1}$); $k_r$ = reaction rate coefficient ($l^{3(n-1)}m^{(1-n)}t^{-1}$); $n$ = reaction order (dimensionless); $C_i$ = influent concentration ($ml^{-3}$); and $C$ = effluent concentration ($ml^{-3}$). For zero order reaction, $n = 0$ and

$$\tau_{CSTR} = \tau_{PFR} \tag{23a}$$

while for all other reactions, $n > 0$ and

$$\tau_{CSTR} > \tau_{PFR} \tag{23b}$$

Therefore, all non-zero order reactions will require a larger CSTR reactor volume, as compared to a PFR, to achieve the same conversion (Figure 6). This is, however, quite an oversimplification for fixed film biological reactors as discussed below.

Figure 6 illustrates the advantage of the PFR at high reaction orders and when high effluent quality requirements exist. Other aspects, however, must be considered. For example, PFR process performance may be influenced by (1) overloading the influent region and (2) product inhibition at the exit region. Such problems do not exist in a CSTR where dilution of reactants and products occurs (Figure 5). The advantage of dilution is especially apparent in systems experiencing frequent and dramatic shock (transient) loads resulting in nutrient and/or electron acceptor (*e.g.* oxygen) limitations. These types of limitations frequently result in formation of slowly degradable products and contribute to poor effluent quality.

The 'pyramid' mode of wastewater treatment system design and operation illustrates the advantages of a combined CSTR/PFR reactor configuration. The pyramid system consists of CSTRs in series with reactor size decreasing along the reactor train length (Figure 7). Desired

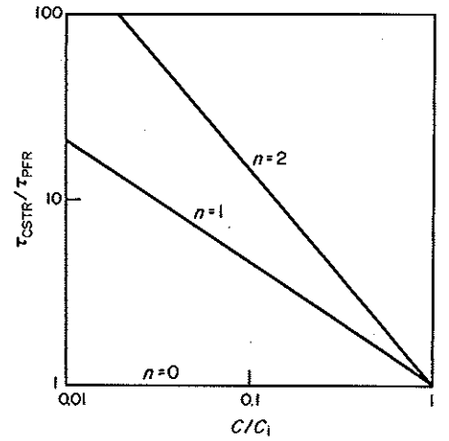



**Figure 6** Comparison of reactor detention time, $\tau$, required in a CSTR relative to a PFR to convert reactant C from inflow concentration $C_i$ to a required effluent concentration $C$ for various reaction kinetic orders, $n$

CSTR volume is commonly obtained by connecting equal size modules in parallel. The first, large CSTR dilutes the substrate while providing high nutrient and electron acceptor transfer capacity thereby ensuring desirable environmental conditions for metabolism. Each succeeding CSTR receives a smaller substrate load and, therefore, requires less dilution, nutrients and electron acceptor. The size of each stage is determined from a process analysis employing principles described in previous sections. The number of stages can be calculated from the same process analysis applied in a PFR system.

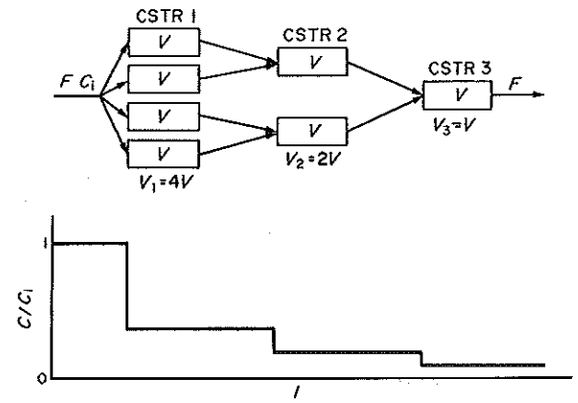



**Figure 7** The pyramid mode of wastewater treatment system consisting of CSTRs in series with reactor size decreasing ($V_1 > V_2 > V_3$) along the reactor train length, $l$

In summary, the reactor analysis is conceptually relatively simple and is based on traditional techniques of reactor engineering. In conjunction with a thorough kinetic analysis, the reactor may lead to the optimum configuration for the fixed film reactor system.

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