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KINETICS OF BIOFILM DETACHMENT

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ABSTRACT

In predictive biofilm modeling, the detachment rate coefficient may be the most sensitive variable affecting both the predicted rate and the extent of biofilm accumulation. At steady state the detachment rate must be equal to the net growth rate in the biofilm. In systems where organic carbon is growth-limiting, the substrate carbon utilization rate determines the net biomass production rate and, therefore, the steady state biomass detachment rate. Detachment rates, first order with biofilm thickness, fit the experimental data well, but are not predictive since the coefficients must be determined experimentally.

KEYWORDS

biofilm; detachment; modeling; *Pseudomonas aeruginosa*; substrate utilization

INTRODUCTION

The development of predictive models for biofilm accumulation and activity requires expressions for each contributing biofilm process. At steady state and negligible attachment rate, the net rate of biofilm detachment is equal to the net rate of biofilm growth:

$$Accumulation = Attachment - Detachment + Growth \tag{1}$$

$$\frac{dX_b}{dt} = R_a - R_d + \int_0^{L_f} \rho \ \mu \ dz \tag{2}$$

or,

$$R_d = \int_0^{L_f} \rho \ \mu \ dz \tag{3}$$

In a bioreactor with dilution rate greater than the microorganism's maximum specific growth rate, the detachment rate can be determined. A material balance on suspended cells in the RotoTorque shows that the detachment rate is characterized by the suspended cell concentration.

$$\frac{V\,dX}{dt} = Q(X_i - X) - A\,R_a + A\,R_d \qquad (4)$$

Assuming steady state, a sterile influent, and a negligible attachment rate, equation 4 becomes reduces to Equation 5. Equation 5 indicates the detachment rate is proportional to the effluent suspended cell concentration.

$$R_d = \frac{Q\,X}{A} \qquad (5)$$

The last equation of interest is the substrate conversion to biomass. Equation 6 assumes the substrate is the only source of carbon and energy to the biofilm, and the biofilm is at steady state.

$$(S_i - S)\,Y_{\frac{x}{s}} = (X - X_i) \qquad (6)$$

For a sterile influent, Equation 6 can be rearranged to give:

$$X = (S_i - S)\,Y_{\frac{x}{s}} \qquad (7)$$

Equation 7 can be substituted into Equation 5 to show that at steady state the detachment rate is proportional to the substrate utilization rate.

$$R_d = \frac{Q}{A}\,Y_{\frac{x}{s}}\,(S_i - S) \qquad (8)$$

PREDICTIVE MODELING

Predictive modeling of biofilm accumulation requires accurate estimation of process rates. The two primary biofilm simulation models currently in use at the Center are very sensitive to the value of the biofilm detachment coefficient. The simulation package "BIOSIM" predicts that a 50% decrease in the detachment coefficient will give a 100% increase in the biofilm thickness (Fig. 1). A turbulent flow pipeline simulation gave similar results for sensitivity to the detachment coefficient (Fig. 2).

EXPERIMENTAL SYSTEM

Experiments were conducted in a RotoTorque operated at a dilution rate of 4 h^{-1}. Glucose was the sole carbon and energy source to the *Pseudomonas aeruginosa* biofilm. Since the dilution rate was ten times larger than the maximum growth rate of *Ps. aeruginosa* on glucose, growth in suspension was negligible. A schematic of the apparatus is given in Figure 3.

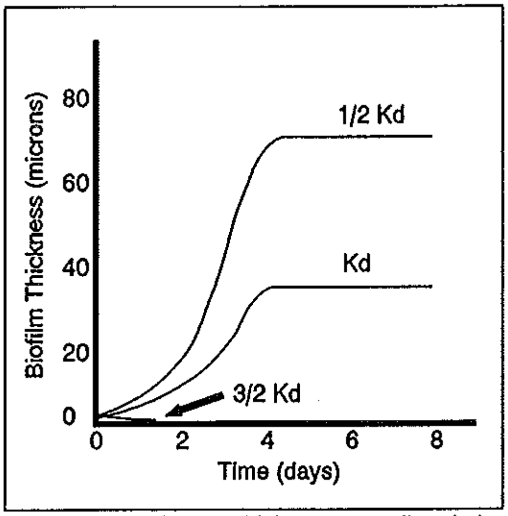

Figure 1. Biofilm thickness predicted by BIOSIM model for different detachment coefficients

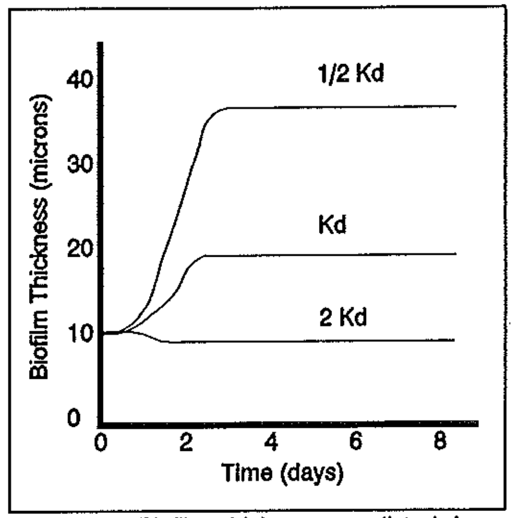

Figure 2. Biofilm thickness predicted for a turbulent flow pipe for different values of the detachment coefficient.

DETACHMENT RATE KINETICS

A first order detachment rate expression as a function of biofilm thickness is easy to utilize in predictive models and fits the data well, but does not reflect the phenomenological basis for differences in biofilm detachment rates. Biofilm thickness as a function of influent glucose concentration is given in Figure 4. Detachment rate can be modeled as a first order function of biofilm thickness (Fig. 5), but a more generally applicable correlation is with the organic carbon utilization rate. Data obtained in this research are compared with others' detachment data for *Ps. aeruginosa* in a RotoTorque (Fig. 6).

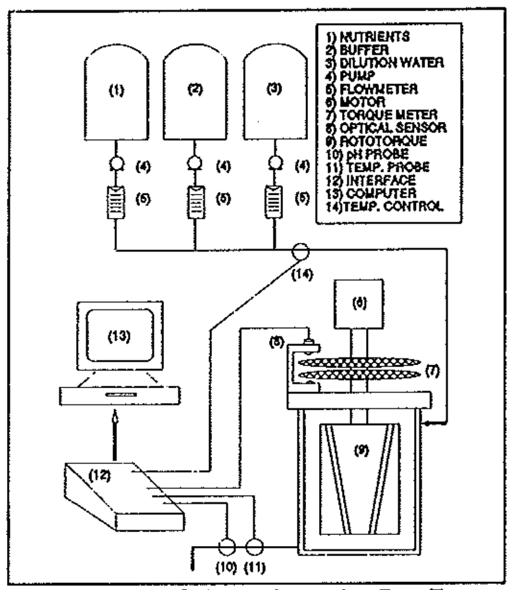

Figure 3. Schematic of RotoTorque experimental system.

CONCLUSIONS

The detachment rate is the rate-controlling process affecting biofilm accumulation in many situations, and can be modeled as a first order function of biofilm thickness. However, a more general correlation can be found by modelling the detachment rate as a first order function of the substrate utilization rate.

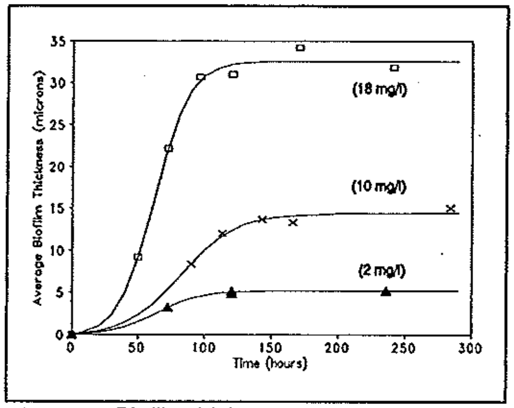

Figure 4. Biofilm thickness as a function of time and substrate loading rate.

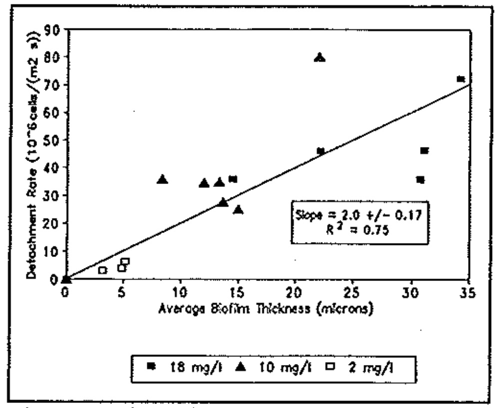

Figure 5. Detachment rate as a first order function of biofilm thickness.

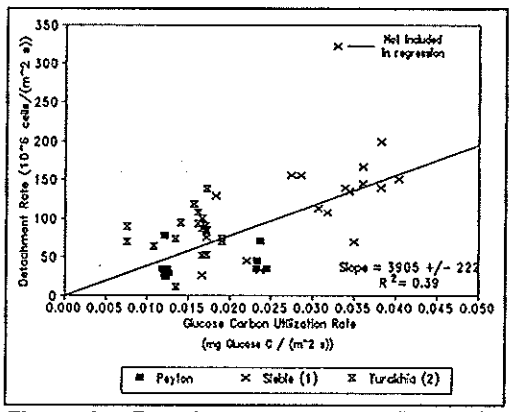

Figure 6. Detachment rate as a first order function of substrate utilization rate.

NOMENCLATURE

A = Biofilm surface Area (L^2)
Lf= Biofilm thickness (L)
Q = Bioreactor volume (L^3)
Ra= Attachment rate ($M L^{-1} t^{-1}$)
Rd= Detachment rate ($M L^{-1} t^{-1}$)
S = Effluent substrate conc. ($M L^{-3}$)
Si= Influent substrate conc. ($M L^{-3}$)
X = Suspended cell conc. ($M L^{-3}$)
Xb= Biofilm areal density ($M L^{-2}$)
Xi = Influent cell conc. ($M L^{-3}$)
Yx/s = Biomass yield from substrate ($M_x M_s^{-1}$)
V = Bioreactor volume (L^3)
z = Integration variable
μ = Specific growth rate (t^{-1})
ρ = Biofilm density ($M L^{-3}$)

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