1. Draw a figure for concentration change in a batch reactor. In the first order reaction case, the concentration decreases exponentially. In the zero order case, the concentration decreases linearly. Then, my question is what happen in the case of n-th order reaction?

2. Consider a river heavily polluted by ammonium nitrogen. In the aerobic condition, nitrification takes place and when DO becomes low, denitrification takes place. Please draw a figure of changes in DO, NH3-N, NO2-N, NO3-N along the river flow.

3. Most of the reactions in water environment are the results of the activities of microorganisms which are contained in water and in sediment. If we walk on a gravel in a river, we notice that the surface of the gravel is covered with biofilm and has sticky surface than a virgin stone. As shown in the Figure 1, we assume a reaction of a certain substance by biofilm which grows on the surface of a stone in a river. In figure 1, C_b is concentration of the substance in river water, δ is the thickness of the concentration boundary layer, C_s is the concentration on the surface of biofilm. We assume the gravel has a uniform biofilm over a flat surface and concentration is a function of only x.

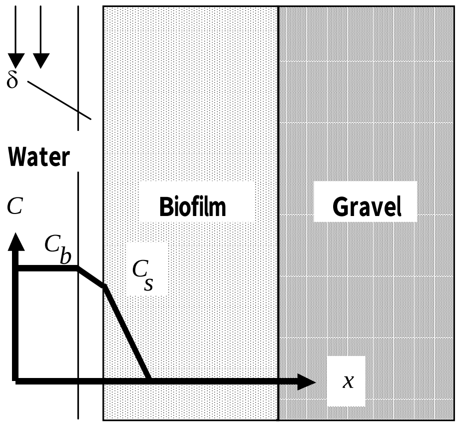

Figure-1

1) Assuming that J_B is the solute flux consumed by the biofilm at the biofilm surface and that the unit is J_B [kg・s^{-1}・m^{-2}], please explain that the solute flux can be given by $J_B = D\frac{(C_b - C_s)}{\delta}$, where D is the molecular diffusivity.

2) What are the factors affecting the thickness of the concentration boundary layer?

3) Show that the diffusion equation inside the biofilm can be written as

$$D_e \frac{d^2C}{dx^2} = r$$

where D_e is the effective diffusivity inside the biofilm and r is the removal rate of the substance by a unit volume of biofilm.

4) Which is larger, D_e or D? Explain with reason.

5) The following question should be answered with the assumption of r to be a zero order reaction in terms of C. Consequently, $r = r_0$.

(5-1) Consider a case where the substsnce is just consumed completely at the interface of the biofilm and the stone. Please show that $C_{crit} = \frac{r_0 d^2}{2D_e}$ where C_{crit} is the critical C_s in this case, and that $J_B = r_0 d$.

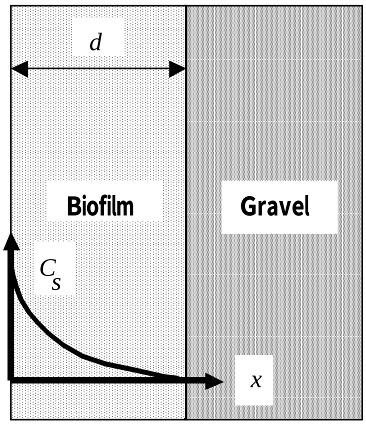

Figure-2

(5-2) If $C_s > C_{crit}$, show that the solute flux is a constant and can be expressed as $J_B = r_0 d$.

(5-3) If $C_s < C_{crit}$, the substance is consumed completely in the middle of the biofilm and the concentration of the substance becomes zero at this position as shown in figure 3. In this case, the biofilm which is located rear side do nothing for the reaction. Show that the solute flux in this case can be written as $J_B = \sqrt{2C_s D_e r_0}$.

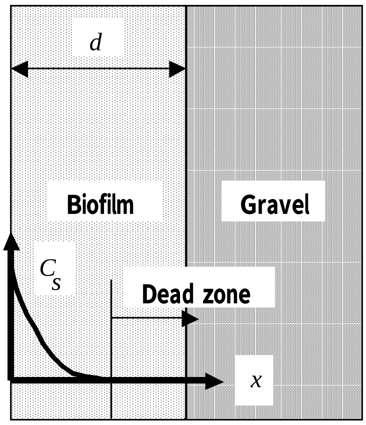

Figure-3

(5-4) Draw a graph in which the relationship between C_s and J_B. Show that the overall reaction rate by biofilm attached to the river stone is 1/2 order reaction, even if the intrinsic reaction rate is a zero order reaction.

6) The following question should be answered with the assumption of r to be a first order reaction in terms of C. Consequently, $r = kC$. In the first order reaction case, the dead zone, as considered in the case of zero order reaction is not observed. Show that the concentration profile inside the biofilm can be expressed as

$$C = \frac{\exp\left(-\sqrt{\frac{k}{D_e}}d\right)C_s}{\exp\left(\sqrt{\frac{k}{D_e}}d\right)+\exp\left(-\sqrt{\frac{k}{D_e}}d\right)}\exp\left(\sqrt{\frac{k}{D_e}}x\right)+\frac{\exp\left(\sqrt{\frac{k}{D_e}}d\right)C_s}{\exp\left(\sqrt{\frac{k}{D_e}}d\right)+\exp\left(-\sqrt{\frac{k}{D_e}}d\right)}\exp\left(-\sqrt{\frac{k}{D_e}}x\right).$$

Please calculate J_B.

7) Please give a comment on the concentration dependency of the removal rate in a real river.