7
Aerobic Treatment with Biofilm Systems

7.1
Biofilms

Biofilms are small ecosystems usually consisting of three layers of differing thickness, which change in thickness and composition with location and over time (Meyer-Reil 1996). In the *first phase* of colonization, macromolecules are adsorbed at clean solid surfaces (proteins, polysaccharides, lignin; Wingender and Flemming 1999), because they are transported from the bulk liquid to the solid surface faster than the microorganisms are. As a consequence of this adsorption, the coverage of the solid surface with water is reduced. During the *second phase*, microbial cells attach to this prepared surface. Frequently, they do not form closed layers of uniform thickness, rather they form small attached colonies, which may spread by growth and further attachment. Usually, these cells are supplied with substrate and oxygen and are able to grow at their maximum rate. During this process, they produce organic molecules, which diffuse through the cell wall and to *e*xtracellular *p*olymeric *s*ubstances (EPS) catalyzed by exoenzymes. These EPS molecules are necessary for the formation of a stable biofilm (Wingener and Flemming 1999). In the *third phase*, the biofilm may consist of bacteria and EPS, the thickness of which is a function of growth rate and depends on the stability of the biofilm and the shear stress of the flowing water (Van Loodsrecht et al. 1995). At lower shear stresses, eukaryotic organisms (protozoa, insects, their eggs and larvae) typically establish themselves. All these organisms live in a community. Materials such as substrates and oxygen are transported into the biofilm by diffusion and convection and the products are transported out of the biofilm.

Oxygen may reach only into the exterior part of the biofilm, resulting in a growth of aerobic microorganisms such as nitrifying bacteria and protozoa. Nitrate and nitrite produced in this layer are reduced by anoxic metabolism within a middle layer, resulting in an anaerobic interior layer directly at the solid surface, where acetic acid and sulfate may be reduced (Marshall and Blainey 1991; Fig. 7.1).

Heterogeneous biofilms grow on the sides of ships and on buildings near the water's edge, inside human and animal mouths and within inner organs. They frequently cause damage to these surfaces (biocorrosion) and must be removed. In the area of environmental biotechnology, however, they can be utilized to advantage in certain bioreactors, such as:

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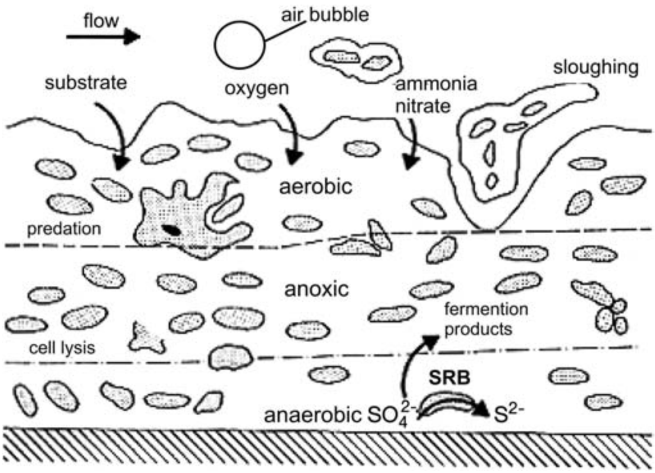

Fig. 7.1 Biofilm model (according to Marshall and Blainey 1991).

- trickling filters,
- submerged, aerated fixed bed reactors,
- rotating disc reactors.

The formation of biofilms is a requirement for their effectiveness. This chapter will describe these bioreactors and their application and will discuss some models of the processes, which are useful for understanding how they function.

7.2
Biofilm Reactors for Wastewater Treatment

7.2.1
Trickling Filters

A trickling filter consists of a layer of solid particles or bundles of synthetic material inside a cylindrical (Fig. 7.2) or prismoid container. Wastewater must be distributed uniformly at the top of the fixed bed – frequently by a rotating system of two or four horizontal tubes equipped with many nozzles.

To compensate for the fact that the area of a circular section of the reactor increases with distance from the center, the distance between nozzles must decrease the further they are away from the center in order to have an even distribution of water over the surface. Furthermore, the changes in available pressure in the rotating tubes must be considered as a function of the flow rate. Uniform distribution of the wastewater and uniform packing of the reactor with solid substances are of high importance for a high loading and removal rate. It is critical to ensure that two conditions are met:

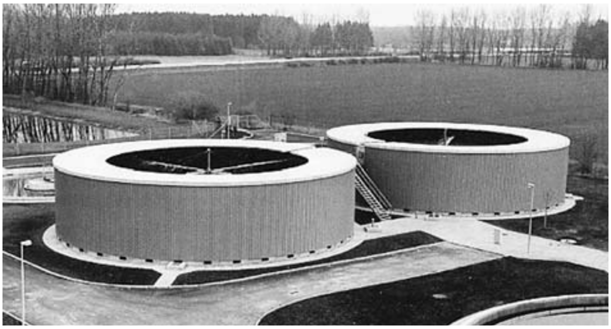

Fig. 7.2 Trickling filter, BIO-NET, Norddeutsche Seekabelwerke, Germany.

- The downward flowing liquid films must be in direct contact with the biofilm (i.e. the biofilm has to be trickled over all places and at all times) and must be in contact with the upward or downward flowing air (i.e. the trickling filter should not be flooded at any location or time).
- The wastewater must be practically free of solids. It is absolutely necessary that the wastewater passes a primary settler under controlled conditions which is never overloaded.

We distinguish between:

- *Natural aeration* as a result of density differences between the air saturated with moisture inside the trickling filter and the air outside the trickling filter, and
- F*orced aeration* by a ventilator at the top of the trickling filter. In this case, the reactor may have a height of up to 12 m and is filled with packages of synthetic supporting material.

Effective natural aeration can be expected in winter and summer. In winter, the density of cold air is greater than that of the warmer air inside the trickling filter and the air flows upwards. Accordingly, the air flows downwards in summer. In every year, there are some critical situations when water and air temperatures are nearly the same. During those times, the efficiency of trickling filters is reduced.

The composition of the biofilm of a trickling filter varies with the season. In summer, the activity of the organisms is very high. Small filter flies (Psychoda) and other insects, such as water springtails (Podura) and midges (Chironomus) as well as various protozoa lead to a thicker and more porous biofilm (Fair et al. 1986). During the autumn, this third phase of the biofilm is nearly completely sheared off and a thinner film of higher density remains. In every season of the year, smaller parts of the biofilm are rinsed away, but if the ecosystem is changed completely, the biofilm is changed in a characteristic way.

Table 7.1 presents some data for trickling filters. They can be subdivided into four types according to their hydraulic loading, their loading of substrate and their difference from low-rate to super-high-rate trickling filters.

Using these data, one can perform the initial scale concept design for the treatment of municipal wastewater (see Problem 7.1).

Table 7.1 Design and operation data for trickling filters (Nazaroff and Alvarez-Cohen 2001).

Parameter	Unit	Type of trickling filter			
		Low rate	**Intermediate rate**	**High rate**	**Super-high rate**
Support material	–	Rock, slag	Rock, slag	Rock	Plastic
Specific surface area	$m^2\ m^{-3}$	40–70	40–70	40–70	80–200
Porosity	$m^3\ m^{-3}$	0.4–0.6	0.4–0.6	0.4–0.6	0.90–0.97
Density of support material[a)]	$kg\ m^{-3}$	800–1500	800–1500	800–1500	30–100
Hydraulic loading[b)]	$m^3\ m^{-2}\ d^{-1}$	0.5–3.0	3–10	8–40	10–70
Loading per volume	$g\ m^{-3}\ d^{-1}\ BOD_5$	100–400	200–500	500–1000	500–1000
Height	m	1.0–2.5	1.0–2.5	1.0–2.5	3.0–1.02
Recirculation ratio	–	0	0–1	1–2	1–2
Removal efficiency	% BOD_5	80–90	50–70	65–85	65–80

[a)] Volume includes voids.
[b)] Includes recycled flow (Metcalf and Eddy 1991; Tschobanoglous and Schroeder 1985).

7.2.2
Submerged and Aerated Fixed Bed Reactors

In cases of high hydraulic loading, the trickling filter may be operated as a flooded bed and the pressure differential needed for the downwards flow increases. The level of wastewater necessary to overcome the flow resistance depends on the form of the substance used as support material and the thickness of the biofilm. Aerobic fixed beds must be aerated near the bottom, producing a two-phase flow in a three-phase system with an upwards air flow. As a result of friction forces, water is transported upwards in the center of the reactor and flows downwards near its walls. Biomass is attached at the surface of the support material and is also suspended as flocs. It is not easy to avoid blockages in regions of biofilms with a higher thickness and a lower local flow rate. The fixed bed must be cleaned from time to time by considerably increasing the wastewater flow rate.

Synthetic support materials such as BIOPAC (ENVICON, Germany) have been used successfully, especially where nitrifying bacteria with lower growth rates must be immobilized (Fig. 7.3).

In contrast to fixed beds with solid particles, the flow of water and air are more easily controlled and blockages can be avoided in reactors with suspended particles. In contrast to trickling filters, their air flow rates can be adjusted to match the loading of organics and ammonia. The specific surface area can be increased to up to 400 $m^2\ m^{-3}$ (Schulz and Menningmann 1999). Using membrane-type tubular aerators, fine bubbles are produced and the mass transfer rate is increased remarkably. The suspended biological sludge detaches from the surfaces as a result of the friction forces of the flow and is conveyed to the secondary settler. Obviously, blockages do not occur. Table 7.2 presents some operational data.

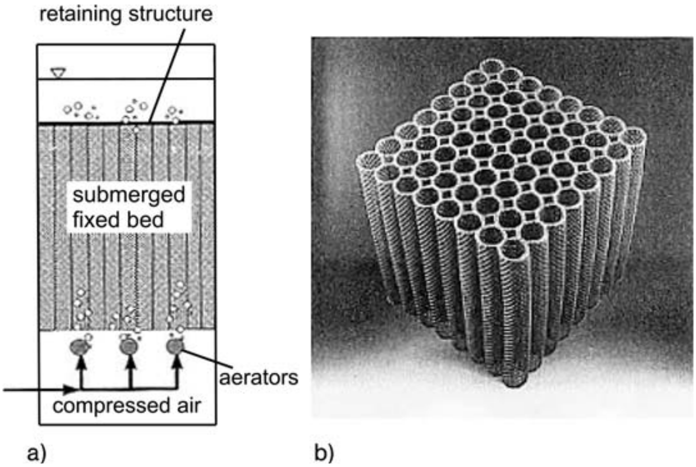

Fig. 7.3 Submerged aerated fixed bed reactor (a) and BIOPAC (b) (ENVIRON, Germany; Schulz and Menningmann 1999).

Comparing the loading per volume with that of trickling filters (Table 7.1), we can conclude that in this kind of fixed bed reactors the loading can be increased by a factor of three for intermediate and high-rate systems and by a factor of five for super-high-rate systems. This is due to the higher specific surface area of the biofilm and the technological advances which prevent clogging in the BIOPAC system, for example (Schulz and Menningmann 1999).

Table 7.2 Load, biofilm thickness and application of the BIOPAC system (Schulz and Menningmann 1999).

Parameter	**Type of trickling filter**			
	Low rate	**Intermediate rate**	**High rate**	**Super-high rate**
Loading per area ($g\ m^{-2}\ d^{-1}\ BOD_5$)	<3	3–6	6–12	12–30
Loading per volume ($g\ m^{-3}\ d^{-1}\ BOD_5$)[a]	<750	750–1500	1500–3000	3000–7500
Thickness of biofilm (mm)	1.5	1–4	4–10	10–20
Application	Complete nitrification, C elimination	Nitrification, simultaneous C elimination	C elimination, partial nitrification	C elimination

a) Specific surface area a = 100–400 m^2m^{-3}, here assumed a = 250 m^2m^{-3} (Schulz and Menningmann 1999).

7.2.3
Rotating Disc Reactors

In rotating disc reactors (RDR), the principle behind the intense transport of substrates and oxygen to the biofilm is different. In trickling filters and fixed bed reactors, water and air are moved; here, the support material with the biofilm are moved. In rotating disc reactors, circular plates with diameters of 1–2 m are fitted to a horizontal shaft with a spacing of a few centimeters. The system of parallel plates is submerged nearly halfway in a cylindrical tank through which wastewater flows. The packet of plates rotates at a speed of 0.5–5.0 rpm. Bacteria grow on both surfaces of the circular discs. During the portion of the rotation where the biofilm travels through the air, wastewater drips down and oxygen is taken up by convection and diffusion. Parts of the biofilm rinse off from the discs from time to time. Larger pieces settle in the tank and must be removed as surplus sludge, while smaller parts are suspended and involved in aerobic substrate degradation and further growth (carbon removal and nitrification). Figure 7.4 presents a rotating disc reactor.

The development of this kind of biofilm reactor was described in detail by Breithaupt (1997). Its practical application started in the 1960s. The company Stengelin used plates made of low-density synthetic material to decrease the weight which must be born by both bearings. This made it possible to increase the length of the shaft between the bearings to up to 7 m (Breithaupt 1997). Different materials with low density have been utilized in the past 35 years in laboratory- and pilot-scale RDRs (Table 7.3) for carbon removal and nitrification, to test new materials and to optimize the process.

In order to increase the surface area of the support material and to obtain a thicker and more stable biofilm, some authors used special synthetic media. The BIOSURF system was already used commercially in the late 1970s (Benefield and Randall 1980). Tyagi et al. (1993) utilized a polyurethane foam material for the aerobic treatment of a petroleum refinery wastewater. Breithaupt (1997) and Lindemann (2002), experimented successfully with a RDR and plates covered with a structured textile material made from polyethylene styrol.

From Table 7.3, one can see a range for loadings per reactor loading of about 500–4000 g m^{-3} d^{-1} COD for municipal wastewater. This agrees approximately

Fig. 7.4 Rotating disc reactor, Mecano SA Maschinenfabrik, Schwericon SG, Switzerland.

Table 7.3 Results for COD removal of different experiments with aerobic treatment of municipal wastewater and rotating disc reactors (Breithaupt 1997).

Author	Support material	Inlet (mg L^{-1} COD)	Removal (%)	Loading per volume (g m^{-3} d^{-1} COD)	Loading per area (g m^{-2} d^{-1} COD)	t_R (h)	Volume (m^3)
Clark et al. (1978)	No information	110	96	672	3.10	3.9	3.4
Cheng (1982)	Styropor	130	84	2136	10.27	1.5	39.7
Gönec and Harremoes (1985)	Polyethylene	86	–	480	7.75	1.7	0.13
Wanner et al. (1990)	Polypropylene	182	92	3984	11.30	1.1	1.3
Stegmaier (1993)	Textile structure media	410	87	1632	20.14	6.0	0.14

with the data from Table 7.2 for the fixed bed reactor (BIOPAC system; Schulz and Menningmann 1999; low rate up to high rate), if we equate BOD_5 with COD in this approximation.

Axial mixing is reduced in a RDR and the concentration of COD decreases continuously as in a tube reactor (Fig. 7.5).

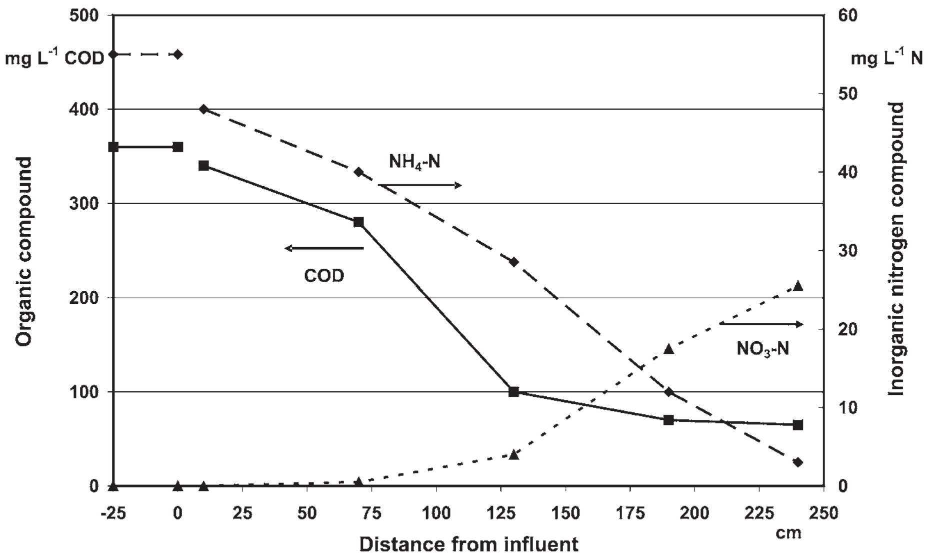

Fig. 7.5 Decrease in local COD and NH_4–N concentration as well as increase in NO_3–N concentration during aerobic treatment in a laboratory-scale rotating disc reactor (Breithaupt 1997).

In municipal wastewater containing ammonia, nitrification occurs simultaneously as a result of the immobilization of nitrifying bacteria (see Chapter 10).

7.3
Mechanisms for Oxygen Mass Transfer in Biofilm Systems

From a fundamental point of view, the three trickling filter systems discussed, aerated fixed bed reactors and rotating disc reactors can all be modelled according to a mobile air bubble phase, a mobile wastewater film and a mobile biofilm. And it is for the moment unimportant whether:

- the gas-phase does not consist of bubbles (trickling filter),
- the liquid-phase does not form a film (fixed bed reactor and rotating disc reactor),
- the biofilm is moving (rotating disc reactor).

Figure 7.6 describes five situations of rate-limiting cases for the transport of oxygen. Because of the low concentration of dissolved oxygen in tap water at an air pressure of 1 bar ($T=20\,°C$, $c^*=9.17$ mg L^{-1} O_2), the transport of oxygen is frequently the rate-limiting parameter. Before we study the rate-limiting processes in detail, we will discuss these cases shortly.

(I) Mass transfer gas/liquid (air/water) is rate-limiting. All conditions met for nearly complete oxygen consumption. Substrate concentrations (organics and NH_4) are relative high, bacterial concentration inside the biofilm is high and active, but air bubble surface area is low. The dissolved oxygen concentration decreases near the bubble surface to an even lower value. This resulting low oxygen concentration depends nearly entirely upon gas/liquid mass transfer.

(II) Mass transfer liquid/solid (water/biofilm) is rate-limiting. As a result of a high aeration rate and/or a low biofilm surface area and/or high activity, the

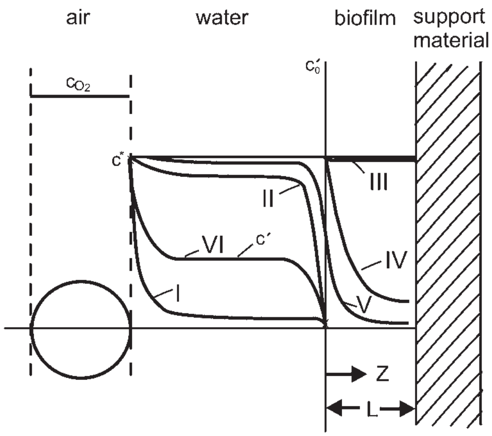

Fig. 7.6 Oxygen mass transfer in biofilm systems. (I) Mass transfer gas/liquid is rate-limiting. (II) Mass transfer liquid/solid is rate-limiting. (III) Biological reaction is rate-limiting. (IV) Diffusion and reaction inside the biofilm are rate-limiting. (V) Diffusion and reaction inside the biofilm as well as mass transfer liquid/solid are rate-limiting. (VI) Mass transfer gas/liquid and liquid/solid are rate-limiting.

dissolved oxygen concentration is only a little lower than the saturation concentration c^* and decreases near the biofilm surface to a low value. This resulting low oxygen concentration depends nearly entirely on liquid/solid mass transfer.

(III) The biological reaction is rate-limiting.

(IV) Diffusion and reaction inside the biofilm are rate-limiting. As a result of a high aeration rate, a large biofilm surface area and/or activity and a high liquid/solid mass transfer rate, the dissolved oxygen concentration is only a little lower than the saturation concentration. It decreases inside the biofilm to a low value.

(V) Mass transfer at the surface liquid/solid and the diffusion inside the biofilm are rate-limiting as a result of a high aeration rate.

(VI) Mass transfer at both surfaces is rate-limiting.

In the next section we will try to find relatively simple models for the calculation of the oxygen consumption rate for all six situations.

7.4
Models for Oxygen Mass Transfer Rates in Biofilm Systems

7.4.1
Assumptions

In this section we don't want to describe aerobic bioreactors mathematically. We will only discuss the situations mentioned in Section 7.3 by using mass balances at one point inside the reactor. Further conditions are:

- The concentration of bacteria inside the biofilm is locally constant.
- The substrate concentration should always be high enough and therefore has no influence on the removal rate.
- Endogenous respiration will be neglected.

7.4.2
Mass Transfer Gas/Liquid is Rate-limiting

The mass balance for oxygen at the outer surface of the biofilm is:

$$\underbrace{(k_L a)_G\,(c^* - c')}_{\text{rate of transport}} = \underbrace{r'_{max}\,\frac{c'}{K' + c'}}_{\text{rate of consumption}} = r' \tag{7.1}$$

Using the known yield coefficient:

$$Y^{o}_{S/O_2} = \frac{r_S}{r'} \tag{7.2}$$

we must calculate r_S to obtain r'.

In case (a), c' (at the biofilm surface) may be very low compared to c^* but large compared with K' ($c' \gg K'$). Therefore, we can write:

$$(k_L a)_G \, c^* = r'_{max} \tag{7.3}$$

The oxygen consumption rate r' and consequently the substrate removal rate r_S are limited only by mass transfer (Fig. 7.6, curve I).

In case (b), c' may be very low compared with c^* but not large compared with K'. For oxygen balance, it follows that:

$$(k_L a)_G \, c^* = r' = r'_{max} \frac{c'}{K' + c'} \tag{7.4}$$

7.4.3
Mass Transfer Liquid/Solid is Rate-limiting

For this case, a similar solution as in Section 7.4.2 can be obtained. Instead of $(k_L a)_G$, we only have to use $(k_L a)_L$ and to consider that the area a in $(k_L a)_L$ is now the specific surface of the biofilm (Fig. 7.6, curve II).

7.4.4
Biological Reaction is Rate-limiting

Oxygen concentration is nearly constant in the liquid as well as insite the biofilm. This situation will occur for very thin biofilms and very low oxygen removal rates. For this case, the oxygen consumption rate requires Henry's law ($c^* = c_{O_2}/H$; see Fig. 7.6, curve III).

$$r' = r'_{max} \frac{c^*}{K' + c^*} = r'_{max} \frac{c_{O_2}}{K' H + c_{O_2}} \tag{7.5}$$

7.4.5
Diffusion and Reaction Inside the Biofilm

In contrast to the two examples discussed above, where mass balances were written for boundary areas, we now need to write the oxygen balance for a thin slice within the biofilm, which is assumed to be smooth and of equal thickness. The oxygen balance is now written as a second-order differential equation (see Problem 7.2):

$$0 = D \frac{d^2 c'}{dz^2} - r'_{max} \frac{c'}{K' + c'} \tag{7.6}$$

The first part is the local change of the rate of diffusion inside a very thin plate of thickness dz; and the second part is the rate of oxygen consumption inside this slice.

We need to integrate twice in order to calculate $c' = f(z)$, the oxygen concentration profile inside the biofilm. For each integral, one unknown constant appears and must be determined. Thus, we need two boundary conditions for the two sides of the film (Fig. 7.6, curve IV)

$$z = 0, \quad c' = c'_0 = c^* \tag{7.7a}$$

$$z = L, \quad \frac{dc'}{dz} = 0 \tag{7.7b}$$

Now, we will use dimensionless numbers:

$$Mo' \equiv \frac{c^*}{K'} \text{ as the Monod number} \tag{7.8a}$$

$$C' = \frac{c'}{K'} \tag{7.8b}$$

and:

$$Z = \frac{z}{L} \tag{7.8c}$$

as well as the Damköhler-II number (Damköhler 1937, Thiele 1939):

$$Da_{II} \equiv \frac{r'_{max} L^2}{K' D} \equiv \frac{\text{reaction rate}}{\text{diffusion rate inside the biofilm}} \tag{7.9}$$

In literature, the name Thiele modulus $\equiv \sqrt{Da_{II}}$ is more common.

Equations (7.6), (7.7a) and (7.7b) can be written using these dimensionless parameters:

$$0 = \frac{d^2 C'}{d Z^2} - Da_{II} \cdot \frac{C'}{1 + C'} \tag{7.10}$$

$$Z = 0, \quad C' = Mo' \tag{7.11a}$$

$$Z = 1, \quad \frac{d C'}{d Z} = 0 \tag{7.11b}$$

Only numerical solutions to Eqs. (7.10) and (7.11) are available. Atkinson and Daoud (1968) were two of the first who published a solution for:

$$C' = f(Z, Da_{II}, Mo') \tag{7.12}$$

However, these concentration profiles are of limited interest. More important is to know the part of the biofilm which is supplied with oxygen and which is therefore aerobically active as well as to compare this with the highest possible activity:

$$\eta = \frac{\text{oxygen uptake rate}}{\text{maximal oxygen cosumption rate}} = \frac{r'_{eff}}{r'_{max}} \tag{7.13}$$

with $\eta \equiv$ efficiency coefficient.

The oxygen uptake rate can be calculated using the oxygen concentration profile, Eq. (7.12), and its gradient at z = 0:

$$r'_{eff} = -D \left.\frac{dc'}{dz}\right|_{z=0} \frac{A}{V} = \frac{D}{L} \left.\frac{dc'}{dz}\right|_{z=0} \tag{7.14}$$

where A is the film surface area and V is the film volume = AL; as well as:

$$r' = r'_{max} \frac{Mo'}{1+Mo'} \tag{7.15}$$

After introducing Eqs. (7.14) and (7.15) into Eq. (7.13) and considering Eqs. (7.8) and (7.9), we obtain:

$$\eta = -\frac{(1+Mo')}{Da_{II} \cdot Mo'} \left.\frac{dC'}{dZ}\right|_{Z=0} \tag{7.16}$$

Double logarithmic plots are presented in Fig. 7.7, showing the influence of Da_{II} and Mo'. With increasing Da_{II} (reaction rate compared to diffusion rate) and decreasing Mo' (dissolved oxygen concentration at boundary liquid/solid), a decreasing part of the biofilm can be supplied with oxygen (Atkinson and Davies 1967; Atkinson and Daoud 1968).

For $Mo' \ll 1$, the reaction approximates a first order reaction with:

$$\eta = -\frac{1}{Da_{II} \cdot Mo'} \left.\frac{dC'}{dZ}\right|_{Z=0} \tag{7.17}$$

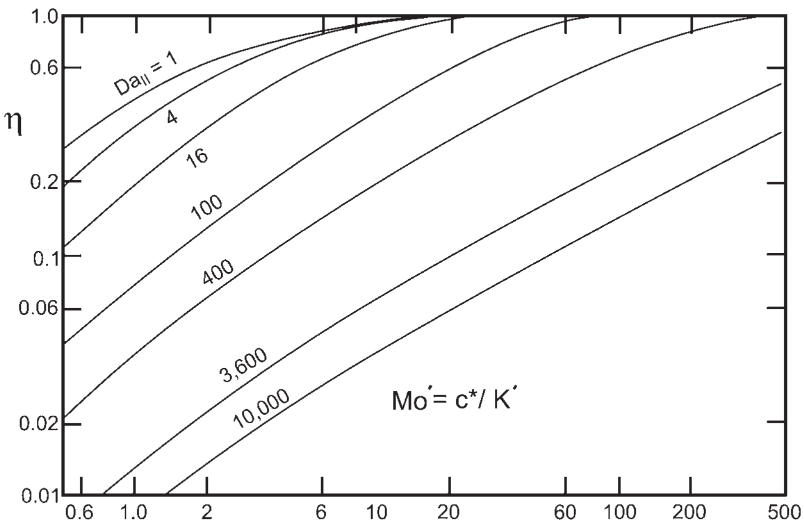

Fig. 7.7 Diffusion and reaction inside of a plane biofilm without the influence of mass transfer liquid/solid; $Da_{II} = r'_{max} L^2/K'D$, $Mo' = c^*/K'$ (Atkinson and Daoud 1967).

and an analytical solution exists (Damköhler 1937; Thiele 1939):

$$\eta = \frac{\tanh \mathrm{Da_{II}}}{\mathrm{Da_{II}}} \tag{7.18}$$

which is not influenced by the Monod number.

7.4.6
Influence of Diffusion and Reaction Inside the Biofilm and of Mass Transfer Liquid/Solid

The influence of an additional mass transfer resistance at the liquid/solid interface must be considered for the case of low $(k_L a)$ values (Fig. 7.6, curve V). The required oxygen uptake rate can only be guaranteed for sinking concentrations c_0' at $z = 0$.

The boundary condition, Eq. (7.7a), must be replaced by:

$$z = 0\,, -D \left.\frac{dc'}{dz}\right|_{z=0} \frac{A}{V} = (k_L a)_L\,(c^* - c_0') \tag{7.19}$$

After consideration of Eq. (7.7b) as well as:

$$\mathrm{Bi} \equiv \frac{(k_L a)_L\, L^2}{D} \tag{7.20}$$

which is called the Biot number as a relation of:

$$\mathrm{Bi} \equiv \frac{\text{mass transfer rate liquid/solid}}{\text{diffusion rate inside the biofilm}}$$

then Eq. (7.19) can be rewritten in dimensionless form:

$$\mathrm{Bi}\,(\mathrm{Mo}' - C_0') = -\left.\frac{dC'}{dZ}\right|_{Z=0} \tag{7.21}$$

Now, η is influenced by three numbers:

$$\eta = f(\mathrm{Da_{II}}, \mathrm{Bi}, \mathrm{Mo}') \tag{7.22}$$

and it is very difficult to present the field of results using only one figure. Therefore, we will not discuss these results in detail. Notice that, with decreasing Biot number (decreasing concentration c_0' as a result of decreasing mass transfer rate liquid/solid), the process is controlled more and more by liquid/solid mass transfer and the efficiency coefficient η decreases. Finally, the problem corresponds to that of Section 7.4.3. Also, the problem corresponds to that of Section 7.4.5 for high Bi numbers; and this follows from a high $(k_L a)_L$ and biofilm thickness L.

Results for a spherical particle filled with bacteria or enzymes were published by Fink and Schultz (1973).

7.4.7
Influence of Mass Transfer Rates at Gas Bubble and Biofilm Surfaces

A total specific mass transfer rate can be defined by Eq. (7.23):

$$K a\,(c^* - c_0') = (k_L a)_G\,(c^* - c') \tag{7.23}$$

as well as by Eq. (7.24):

$$K a\,(c^* - c_0') = (k_L a)_L\,(c' - c_0') \tag{7.24}$$

K is the overall mass transfer coefficient.

Notice that c^* is the concentration of oxygen at the bubble surface and c'_0 is the concentration of oxygen at the biofilm surface.

We write:

$$c^* - c'_0 = (c^* - c') + (c' - c'_0) \tag{7.25}$$

respectively:

$$\Delta c_\Sigma = \Delta c_1 + \Delta c_2 \tag{7.26}$$

After dividing Eq. (7.23) by Eq. (7.24) and using Eq. (7.25), we obtain:

$$\underbrace{\frac{1}{K a}}_{\text{total resistance to mass transfer}} = \underbrace{\frac{1}{(k_L a)_G}}_{\text{resistance at gas film}} + \underbrace{\frac{1}{(k_L a)_L}}_{\text{resistance at biofilm}} \tag{7.27}$$

Equation (7.27) is comparable to the addition of two electrical resistors which are coupled in series. For a high $(k_L a)_G$, only mass transfer liquid/solid at the biofilm is relevant (Section 7.4.2) and vice versa (Section 7.4.3). A possible concentration profile is presented as curve VI in Fig. 7.6.

PROBLEM 7.1

A trickling filter should be constructed for the pre-treatment of municipal wastewater. The flow rate is $Q_0 = 10^5$ m^3 d^{-1} and the influent concentration is $S_0 = 250$ mg L^{-1} BOD$_5$. Two different cases should be compared (see Table 7.1):

1. Intermediate loading, supporting material: rock
   Load per volume $B_v = 350$ g m^{-3} d^{-1} BOD$_5$
   Hydraulic load $\overline{w} = 7$ m^3 m^{-2} d^{-1}
2. Super-high-rate, supporting material: plastic
   Load per volume $B_v = 1000$ g m^{-3} d^{-1} BOD$_5$
   Hydraulic load $\overline{w} = 40$ m^3 m^{-2} d^{-1}

Calculate volume V, cross sectional area A and height H.

Solution

Loading per volume: $B_v = \frac{Q_0 S_0}{V}$

$$V = \frac{Q_0 S_0}{B_v} = \frac{10^5 \cdot 250}{350} = 7.14 \cdot 10^4 \text{ m}^3$$

Hydraulic loading: $\bar{w} = \frac{Q_0}{A}$

$$A = \frac{Q_0}{\bar{w}} = 1.4 \cdot 10^4 \text{ m}^2$$

$$H = \frac{V}{A} = \frac{7.14}{1.4} = 5.1 \text{ m}$$

Loading per volume: $B_v = \frac{Q_0 S_0}{V}$

$$V = \frac{Q_0 S_0}{B_v} = \frac{10^5 \cdot 250}{1000} = 2.5 \cdot 10^4 \text{ m}^3$$

$$A = \frac{Q_0}{\bar{w}} = \frac{10^5}{40} = 2.5 \cdot 10^3 \text{ m}^2$$

$$H = \frac{V}{A} = \frac{2.5 \cdot 10^4}{2.5 \cdot 10^3} = 10 \text{ m}$$

If this synthetic supporting material is used instead of rock, the volume of the trickling filter can be reduced by a factor of 2.9 and the cross-sectional area by a factor of 5.6.

PROBLEM 7.2

A biofilm of aerobic bacteria with a thickness of L = 0.2 mm has to be supplied with oxygen to degrade organics in wastewater. The degradation rate is limited by the oxygen concentration inside the biofilm and is not limited by the organic concentration. The concentration of dissolved oxygen is $c' = c^* = 3$ mg L^{-1} O_2 and it does not decrease remarkably near the boundary liquid/solid.

Given data:

$\mu_{max} = 10$ d^{-1}, X = 10 g L^{-1} MLSS inside the biofilm, $Y^o_{X/O_2} = 0.5$ g MLSS $(g\ O_2)^{-1}$, $K' = 0.1$ mg L^{-1} O_2, $D_{O_2} = 10^{-6}$ $cm^2\ s^{-1}$.

Calculate the efficiency coefficient η.

Solution

Damköhler II number: $Da_{II} = \dfrac{r'_{max} L^2}{D_{O_2} K'}$

Maximum oxygen uptake rate inside the biofilm:

$$r'_{max} = \frac{\mu_{max} X}{Y^o_{X/O_2}} = \frac{10 \cdot 10}{0.5} = 200\ \frac{g\ O_2}{L\ d}$$

$$Da_{II} = \frac{200 \cdot 0.04}{10^{-6}\ 0.1}\ \frac{g\ O_2\ mm^2 s\ L}{L \cdot d\ cm^2 mg\ O_2}$$

$$Da_{II} = 80 \cdot 10^6\ \frac{10^3}{24 \cdot 3600 \cdot 10^2} = 0.93 \cdot 10^4$$

$$Da_{II} = 9300$$

$$Mo' = \frac{c^*}{K'} = \frac{3}{0.1} = 30$$

From Fig. 7.7 for $Da_{II} = 9300$ and $Mo' = 30$ we find: $\eta = 0.08$.

Therefore, only 8% of the biofilm is sufficiently supplied with oxygen and is thus able to grow and to degrade the organics in the wastewater.

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