Biokube Biological Wastewater Treatment Process

Technical process documentation

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1 Biological wastewater treatment processes

1.1 Introduction

Biokube A/S develops biological wastewater treatment systems for household and industrial wastewater purification. Biokube A/S uses biofilters in the biological process step in order to remove soluble substances (organic matter and nitrogen) in all treatment systems due to the advantage and the safety of this type of treatment. In biofilters, a thin biofilm is attached to an open structured plastic media material with large specific surface area, which is directly exposed to the water in the tanks. Biofilters are particular suitable for decentralized wastewater treatment because of the self-cleaning effect and firm attachment of the biomass.

This document describes the mechanisms and mathematics behind Biokube´s tools for dimensioning bioreactors for all installations.

1.2 Substrate removal in Biokube biofilters

Determination of substrate removal rates in biofilters are much different from activated sludge processes.

The amount of biomass in biofilters is often much higher than in activated sludge plants, but due to limitation in transport of soluble substrate into the biofilm a large part of the attached biomass cannot be utilized. ***The transport of substrate into the biofilm by diffusion is the key transport phenomena to understand***. Because of this, reaction rate kinetics is influenced directly by the concentration of substrates in the water since higher concentrations in the bulk water will result in deeper penetration of substrate into the biofilm.

1.2.1 Introduction to biofilm kinetics in biofilters

Dimension of biofilters takes the biofilm surface into account as the key parameter for the volume determination. Removal rate activity in biofilters is normally described by the surface specific removal rate:

$$r_{A,C}\ \left[\frac{g\ C}{m^2 \cdot d}\right] \tag{1}$$

The surface of the biofilm [m^2] can be calculated when the specific surface area [ω] of the biofilm support media is known. Biokube typically use support media in the range between 100 – 300 m^2/m^3 depending on the load and process taking place. When the volume [V] of the reactor compartment is known the total surface area [A] can be calculated as:

$$A = \omega \cdot V\ [m^2] \tag{2}$$

The surface removal rate of the substrate [$r_{A,C}$] is more complicated to calculate. The removal rate activity is depending on the bulk water substrate concentrations (the substrate is almost always removed in a redox process with another substrate, e.g. oxygen), intrinsic bioactivity in the biofilm, temperature, diffusion coefficients and the stoichiometric relation to the other redox component. In order to calculate surface reaction rates correctly, Biokube has developed a spreadsheet model which takes the most relevant factors into account and with this Biokube has the ability to dimension – safely – any reactor configuration with any kind of wastewater composition in question.

1.2.2 Diffusion limited process rate kinetics in biofilms

In order to determine the surface specific reaction rate in the water of the substrate concentration we want to know in the outlet of the biological compartment we calculate the transport kinetics of a substance into a biofilm when we assume that the transport of the substrate merely is occurring by diffusion:

The transport through a section in the biofilm can be calculated as:

$$N = \left(N + \frac{\partial N}{\partial x} \cdot dx\right) + r_f \cdot dx \tag{3}$$

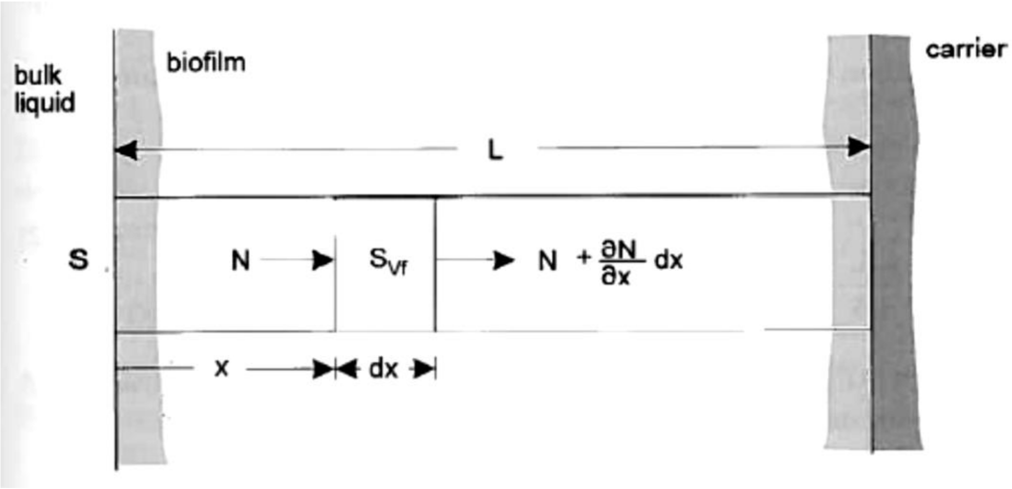


Figure 1 Illustration of an idealized biofilm where the substrate (S) is transported from the water phase into the biofilm through a cross section (N) of the biofilm.

Assuming that the transport through the cross section N takes place exclusively by diffusion, the reaction rate of a substrate in the biofilm can be described as a second order differential equation, which can be solved analytically if the bacterial kinetics (r_f) in the biofilm is either expressed as a first order reaction or a zero order reaction.

$$\frac{\delta^2 S_{Vf}}{\delta x^2} = \frac{r_f}{D} \tag{4}$$

First order reaction inside the biofilm:

$$r_f = k_{1f} \cdot S_{Vf} \tag{5}$$

Zero order reaction inside the biofilm:

$$r_f = k_{0f} \tag{6}$$

First order reactions only takes place at very low concentrations (typically less than 1 mg/l of the substrate controlling the reaction) and are normally irrelevant to evaluate with respect to wastewater treatment kinetics. The concentration at which the intrinsic reaction order changes in the biofilm (from first order to zero order) can for a given biological process be determined by the Monod kinetic saturation constant (K_S) for the single bacteria. K_S express the substrate concentration at which half the maximum growth activity is achieved. Assuming that the intrinsic reaction order changes significant from 1. order to zero order (which is an approximation – normally the transformation changes smoothly as expressed by the Monod kinetics), the zero order reaction rate will take place when:

$$S > 2 \cdot K_S \tag{7}$$

If the reaction rate in the biofilm **is in zero order**, the biofilm intrinsic reaction rate (r_f) is constant. In this case the surface removal rate in the bulk water will depend on if the controlling substrate is able to penetrate the biofilm completely or only partly.

In wastewater treatment biofilters <u>the intrinsic reaction rate order can</u> <u>almost always be assumed as a zero-order process</u> unless the biofilters should treat substrate concentrations (COD, BOD or ammonia) to very lov concentrations.

1.2.3 Full or partly penetration of biofilms (bacterial zero order process in biofilms)

When zero order intrinsic reaction rate (r_f) of substrate takes place in the biofilm the reaction rate order in the bulk liquid is either expressed as <u>a zero order reaction</u> for a fully penetrated biofilm or a <u>half order reaction</u> for a partly penetrated biofilm. Whether the biofilm is fully penetrated can be determined by calculation the ration of penetration of the substrate S:

$$\beta = \sqrt{\frac{2 \cdot D_S \cdot S}{k_{0f} \cdot L^2}} \tag{8}$$

If <u>$\beta > 1$, the biofilm is fully penetrated</u> and if <u>$\beta < 1$, the biofilm is partly penetrated</u>.

Full penetration of biofilm

If both redox components penetrate the biofilm fully, the maximum removal rate activity of the biofilm system is achieved.

The surface removal specific reaction rate of the substrate can for a fully penetrated biofilm be expressed as:

$$r_{A,S} = k_{0f,S} \cdot L \tag{9}$$

where

$r_{A,S}$ = biofilm surface specific removal rate of substance S [g S/m^2/d]

$k_{0f,S}$ = internal removal rate of substance S in the biofilm [g S/m^3 **biofilm**/d]

L = biofilm thickness [m]

This situation requires high concentrations of both substrates and is normally unrealistic to achieve since biofilms will be too thick for to penetrate, especially for oxygen. The oxygen concentration in the water phase is limited by the oxygen saturation concentration that can be achieved at a certain temperature.

Partly penetration of biofilms

If one of the redox components only penetrates the biofilm partly, the removal rate will be determined by the **extend of the penetration depth into the biofilm of this component**. We say that the biofilm removal rate is now <u>limited by the least penetrating component</u>. This situation is the most relevant to consider for design purposes of biofilm process in wastewater treatment systems. The removal rate kinetics in the water will now be a half-order reaction rate determined by the concentration of the limited component in half-order. The surface specific removal rate can be described as:

$$r_{A,S} = \left(2 \cdot D_S \cdot k_{0f,S}\right)^{½} \cdot (S)^{½} = K_{½A,S} \cdot (S)^{½} \tag{10}$$

where

$r_{A,S}$ = biofilm surface specific removal rate of substance S [g/m^2/d]

D_S = diffusion coefficient of substance S [m^2/d]

$k_{0f,S}$ = internal removal rate of substance S in the biofilm [g/m^3 **biofilm**/d]

S = concentration of substance S [g/m^3]

$K_{½A,S}$ = Half-order rate constant [gS^{½}/m$^{-½}$/d^{-1}]

In biofilters where aerobic removal of BOD is relevant to consider, it has to be determined whether oxygen or BOD will be controlling the biological process. The maximum oxygen concentration that can be achieved is limited by the saturation of oxygen in the water, which is determined by the **water temperature**. The water temperature also controls the rate at which the biological reaction occurs and the diffusion coefficient of the substances that penetrates into the biofilm.

1.2.4 Redox processes in biofilms (two component diffusion)

Biological processes are almost always redox processes which require two substrates: an oxidant and a reductant (e.g. oxygen and organic matter). In biofilm reactions it is of greatest importance to determine which of these two substances are limiting for the reaction rate – i.e. which substrate penetrate the biofilm least. If for example a biofilter compartment has plenty of soluble BOD but for some reason, the oxygen concentration is low, the reaction rate can drop dramatically because oxygen will penetrate the biofilm little.

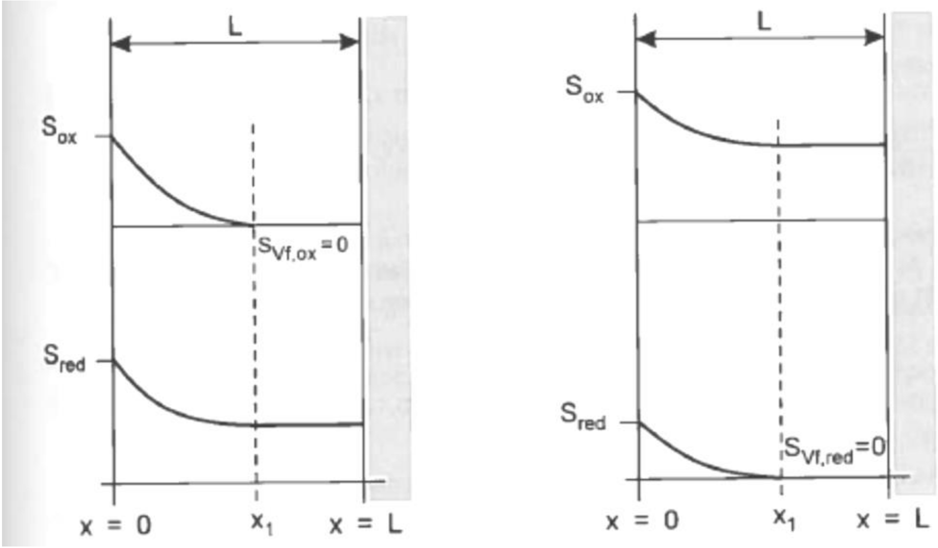


Figure 2 Substrate penetration in biofilms. The least penetrating substrate (S_{ox} or S_{red}) controls the reaction rate.

Determination of substance controlling the reaction rate in biofilters

It is quite simple to determine which substance will penetrate the biofilm least. The calculation is based on the relation between the diffusion coefficient of the substances and the stoichiometric relation between the substances during the process:

$$\frac{C_{red}}{C_{ox}} \overset{>}{\underset{<}{?}} \frac{D_{ox}}{D_{red}} \cdot \vartheta_{ox,red} \qquad (11)$$

where

C_{ox} = Electronacceptor (oxidant, e.g. oxygen concentration) (g/m^3)

C_{red} = Electrondoner (reductant, e.g. BOD concentration) (g/m^3)

D_{ox} = diffusioncoefficient, oxidant (m^2/d)

D_{red} = diffusioncoefficient, reductant (m^2/d)

$\upsilon_{ox,red}$ = stoichiometric relation between oxidant and reductant when removed in biofilm

1.3 Assumptions – Biokube biofilm kinetic calculation

In order to calculate biofilm kinetic performance of a BioKube reactor, a number of assumptions have to be made. The assumptions are important to know since they can affect the system performance if neglegtance cannot be made. In the following the most important assumptions are listed and a short explanation is made as to why the assumption has to be assumed.

Hydraulic filmdiffusion negligible

Hydraulic film diffusion is the thin layer of stagnant water layer between the biofilm surface and the bulk water. The phenomenon is also known in tubes with running water where the water flow decreases towards zero near the surface of the pipe wall. Hydraulic film diffusion is responsible for a further reduction in substrate concentration in biofilms leading to less penetration of substrate and a reduced removal rate activity in the bulk liquid of the reactor.

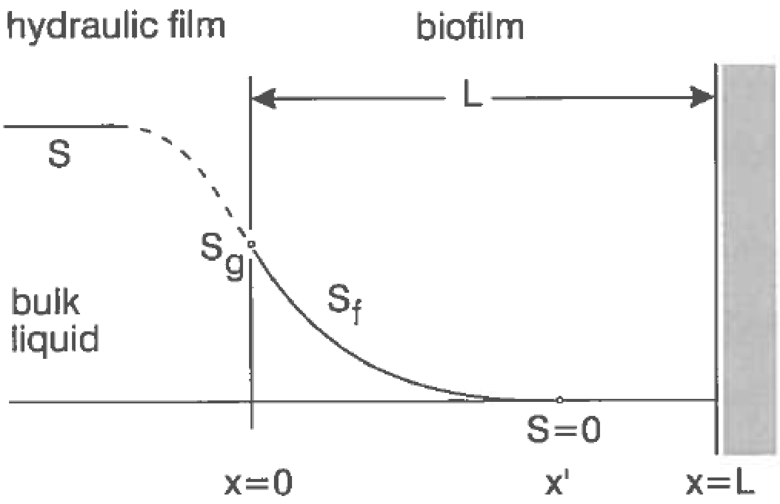


Figure 3 Hydraulic filmdiffusions effect on substrate concentration levels in the biofilm

BioKube´s biofilter system is arranged in a way that minimizes hydraulic film diffusion in two ways:

1) High efficient diffusor aeration ensure turbulent and convectional mixing around the biofilm which breaks down the hydraulic filmdiffusion at the surface of the biofilm

2) Biokube uses biofilm support media that is exposed towards the bulk liquid which makes water stagnancy impossible.

By reducing the hydraulic film diffusion we basically achieve a better removal rate activity in the water without using more energy for aeration

Biofilm homogenous in geometry and composition

Biofilm structure can be smooth or filamentous and thin or thick in its structure on the surface media. The uniform diffusor bottom aeration ensures an equal biofilm attachment at the submerged support media in the compartment and maximum control of the biofilm thickness. The bacteria in the biofilm experience same environmental conditions and will grow equally on the support media. Clogging caused by overgrowth of biofilm is virtually impossible – even in the case of treating high-strength wastewater (e.g. from industries)

Bacterial degradation of redox components in zero-order reaction inside the biofilm

The oxidant-reductant concentration regime in the bulk water is normally high enough to ensure that the substrate concentration is not limited for the bacterial degradation (Monod kinetic substrate limitation). This means that the bacteria in the outer layer of the biofilm are not inhibited by low substrate concentration and that a zero order intrinsic reaction rate can be assumed in the biofilm.

Transport of substrate into the biofilm only by diffusion

Since the kinetic transformation of substrate in biofilm systems was mathematically described it has been recognized that transportation of substrate into the biofilm is merely powered by transport by diffusion (convectional transportation only takes place in the bulk liquid). The importance of this is that the substrate transport into the biofilm is slow – and if the biofilm is dense with respect to the bacteria concentration (expressed by k_{of}) substrate is normally consumed before it can penetrate the biofilm.

Transformation of soluble substrates only

Calculation of substrate transport is only valid for soluble substrate that freely can penetrate the biofilm (by diffusion) and the bacterial cell membrane. Particulate matter is converted into soluble substrate after enzymatic hydrolysis when the particles attach to the biofilm

Biofilms considered thick (more than 500 µm) – always partly penetration of biofilms and ½. order kinetics

Biofilms in wastewater treatment systems are normally quite thick due to the rapid growth of the biofilm. For aerobic processes the oxygen concentration in the bulk liquid cannot exceed 8-10 mg O_2/l and in case that oxygen is limited for the reaction rate, the biofilm will not be penetrated by more than 50 - 100µm. Consequently, biofilms will always be partly penetrated leading to half-order kinetics in the bulk water.

Mixing conditions described as ideally mixed

Turbulent aeration in Biokube reactor compartments will lead to ideal mixing in the whole volume. This means that the concentration of substances in the bulk water is equally the same and that the effluent concentration will be equal to this concentration level. This is important to know because the bulk water concentration is controlling the reaction rate in the biofilter compartment.

1.4 Biokube biofilter reactor calculation

When a biofilter is to be dimensioned the task is always to calculate the necessary biofilm area of the biological bioreactor process. The biofilm area is the key value that enables the bioreactor to treat pollutant substances (organic matter and ammonia) below a certain level when the incoming load to the system and conditions are given.

Biokube has made a procedure for calculating the necessary biofilter area the bioreactor needs to contain. When the biofilm area is know the volume, aeration system and reactor type/configuration can be calculated so the requirement from customers can safely be met.

Step 1: Assume process parameters

Important system parameters that control the removal rate activity. Important parameters are:

1) Temperature (maximum and minimum temperature in the actual case). Important for determination of oxygen saturation concentration, biological activity and activity of diffusion.
2) Zero-order intrinsic reaction rate (k_{0f}) is determined based on the type of wastewater to be treated and expected yearly temperature ranges
3) Stoichiometric relation ($\upsilon_{red,ox}$) between oxidant and reductant
4) Discharge standards to be met for relevant concentrations

Step 2: Determine potential limiting redox component

A Biokube reactor often contains several of compartments which can have a highly different treatment performance. In the first compartment (which receive the untreated wastewater higher removal rate activity and sludge production is observed and in the last compartments, removal rate activity is reduced because the water quality has to be polished to low concentrations. In order to calculate the removal rate activity in each compartment we must calculate the potential limiting substrate in each compartment that will then control and determine the reaction rate:

$$\frac{C_{ox}}{C_{red}} \overset{>}{\underset{<}{?}} \frac{D_{red}}{D_{ox}} \cdot \vartheta_{red,ox} \qquad (12)$$

If $C_{ox} > C_{red} \cdot \frac{D_{red}}{D_{ox}} \cdot \vartheta_{red,ox}$ C_{ox} is controlling the reaction rate.

If $C_{ox} < C_{red} \cdot \frac{D_{red}}{D_{ox}} \cdot \vartheta_{red,ox}$ C_{red} is controlling the reaction rate.

Step 3: Calculate half-order reaction rate constants

The half-order rate constant can be calculated for both the oxidant and reductant once the process parameters have been determined. The reaction rate constant is given by:

$$K_{½A,ox} = \left(2 \cdot D_{ox} \cdot k_{0f,ox}\right)^{½} \qquad (13)$$

$$K_{½A,red} = \left(\frac{D_{red}}{D_{ox}} \cdot \vartheta_{ox,red}\right)^{½} \cdot K_{½A,ox} \qquad (14)$$

Once the half-order reaction rate constant has been determined the surface specific removal rate can be calculated as:

$$r_{A,ox} = K_{½A,ox}{}^{½} \cdot S_{ox}{}^{½} \text{ (if oxidant controls the reaction rate)} \qquad (15)$$

$$r_{A,red} = K_{½A,red}{}^{½} \cdot S_{red}{}^{½} \text{ (if reductant controls the reaction rate)} \qquad (16)$$

Step 4: Setup massbalance – calculate the outlet concentration with input data

A mass balance for removal of reductant (typically COD/BOD and ammonia) can now be expressed over each reactor compartment. The massbalance will be expressed for two situations: 1) oxidant is limiting for the reaction rate and 2) reductant is limiting for the reaction rate. The two mass balance equations will look like this:

1) Oxidant control reaction rate:

$$Q \cdot S_{i,red} - r_{A,ox} \cdot \vartheta_{ox,red} \cdot A = Q \cdot S_{u,red} \tag{17}$$

$$\Rightarrow S_{u,red} = S_{i,red} - \frac{K_{½A,ox}{}^{½} \cdot S_{ox}{}^{½} \cdot \vartheta_{ox,red} \cdot A}{Q} \tag{18}$$

2) Reductant control reaction rate:

$$Q \cdot S_{i,red} - r_{A,red} \cdot A = Q \cdot S_{u,red} \tag{19}$$

$$\Rightarrow \; Q \cdot S_{i,red} - K_{½A,red} \cdot S_{u,red}^{½} \cdot A = Q \cdot S_{u,red} \qquad \text{(2. order equation in } S_{u,red}\text{)} \tag{20}$$

$$\Rightarrow S_{u,red} = \frac{\sqrt{\left(K_{½A,red}^{2} A + 2Q^{2} S_{i,red}\right)^{2} - 4\left((-Q)^{2} Q^{2} S_{i,red}^{2}\right)} - \left(K_{½A,red}^{2} A^{2} + 2Q^{2} S_{u,red}\right)}{2(-Q)^{2}} \tag{21}$$

The lowest $S_{u,red}$ calculated in 1) and 2) is the correct effluent concentration.

1.5 The BioKube Generator

Biokube has developed an Excel based simulation tool based on the theoretical calculations of the biofilm kinetics in each chamber. The spreadsheet model can calculate expected effluent concentrations of reductant substrate in a biofilter compartment based on information given as input parameters. The spreadsheet model is used to calculate different scenarios with different Biokube reactor systems in order to find the optimal and most economic reactor configuration for the customers.

Input parameters:

- Specific surface area, biofilm support media
- Compartment volume (biofilm area then calculated)
- Temperature
- Flow
- Oxidant concentration in compartment (oxygen setpoint)
- Inlet reductant concentration
- Intrinsic reaction rate, biofilm ($k_{0f,ox}$)
- Temperature correction coefficient, biology
- Temperature correction coefficient, diffusion
- Stoichiometric relation between reductant and oxidant
- Diffusion coefficient, reductant
- Diffusion coefficient, oxidant

Output parameters:

- Surface specific removal rate, oxidant
- Surface specific removal rate, reductant
- Oxidant/reductant controlling the reaction rate?
- Effluent concentration, reductant

The surface specific removal rate of substrate and the concentration of substrate in the bulk liquid are closely linked together as described in the graph below. In the lower S_u concentration regimes the process will be reaction limited (half-order kinetics in the bulk liquid) whereas the reaction rate will be constant when the concentration of S_u is high (zero order kinetics in the bulk liquid).

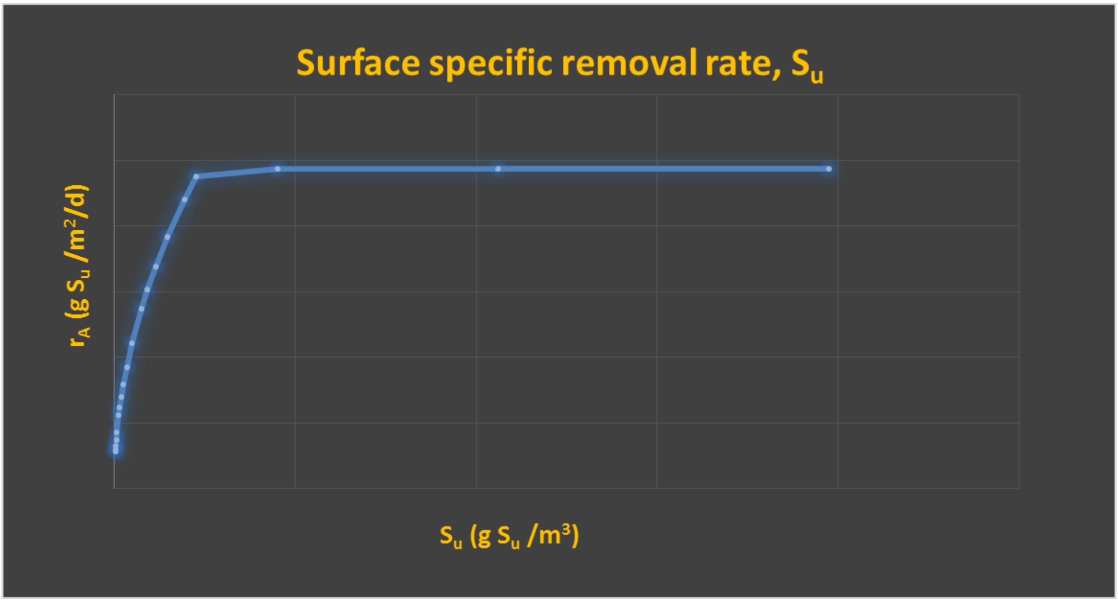


Figure 4 Relation between surface specific removal rate activity and the concentration of substrate. The graph is dynamically calculated in BioKube´s spreadsheet model based on given model input for the actual situation.

1.6 BOD/COD removal in biofilters

BOD/COD is removed in an aerobic biological process in the Biokube biofilter compartments.

The removal rate activity takes oxygen and BOD or the COD concentration into account. The substrate concentration controlling the removal rate activity is given by:

$$\frac{S_{O2}}{S_{BOD}} \overset{>}{\underset{<}{?}} \frac{D_{BOD}}{D_{O2}} \cdot \vartheta_{BOD,O2} \tag{22}$$

If

$$S_{O2} > S_{BOD} \cdot \frac{D_{BOD}}{D_{O2}} \cdot \vartheta_{BOD,O2} \tag{23}$$

BOD is controlling the reaction rate. Similar expression can be given for the COD removal:

$$S_{O2} > S_{COD} \cdot \frac{D_{COD}}{D_{O2}} \cdot \vartheta_{COD,O2} \tag{24}$$

In case of <u>oxygen control</u>, the removal rate of BOD can be determined as:

$$r_{½A,BOD} = K_{½A,O2} \cdot \vartheta_{O2,BOD} \cdot S_{O2}^{½} = \left(2 \cdot D_{O2} \cdot k_{0f,O2}\right)^{½} \cdot \vartheta_{O2,BOD} \cdot S_{O2}^{½} \tag{25}$$

In case of BOD control, the removal rate of BOD can be determined as:

$$r_{½A,BOD} = K_{½A,BOD} \cdot S_{BOD}^{½} = \left(2 \cdot D_{BOD} \cdot k_{0f,BOD}\right)^{½} \cdot S_{BOD}^{½} \qquad (26)$$

The necessary biofilter area can then be calculated by

$$Q \cdot S_{i,BOD} - r_{A,BOD} \cdot A = Q \cdot S_{u,BOD} \qquad (27)$$

$$\Rightarrow\ A = \frac{Q\left(S_{i,BOD} - S_{u,BOD}\right)}{r_{A,BOD}} \qquad (28)$$

It should always be checked if BOD or O_2 is controlling the reaction rate when determining the effluent BOD concentration of the given design. Which substance controlling the reaction can be calculated from (21).

As for COD removal the equations are identical with eq. (25) - (28) except the substrate is COD.

Temperature dependency, biological processes

Biological processes are temperature dependent. Therefore it is important to include temperature dependency when the removal rate activity is calculated. The calculation of temperature dependency is valid in the temperature range from 5 – 30 °C.

$$k_{0f,BOD,t°C} = k_{0f,BOD,20°C} \cdot e^{k \cdot (t-20)} \qquad (29)$$

Where k is the temperature constant (°C^{-1}) and t is the temperature.

The removal rate activity will be constant in the interval from 30-37 °C. Above 37 °C the removal rate activity will rapidly decrease towards zero at 40 °C.

Temperature dependency, diffusion

The diffusion coefficient is also dependent on the temperature in the water. Higher temperature result in an increase in transportation by diffusion which means the substrate will be transported quicker into the biofilm. The calculation of temperature dependency is valid in the temperature range from 2 – 40 °C.

The temperature depends of the diffusion coefficient can be calculated by:

$$D_{BOD,t°C} = D_{,BOD,20°C} \cdot e^{(d \cdot (t-20))} \qquad (30)$$

Where d is the temperature constant (°C^{-1}) and t is the temperature.

Nutrient (N, P) removal caused by BOD removal

Removal of organic matter is a heterotrophic process which requires nutrients in the bacterial growth process. The sludge produced contains nitrogen (6%), phosphor (1,5%) and other micronutrienst that is essential for the bacterial growth process. So on one hand, these nutrients have to be present in sufficient amounts and on the other hand, the nutrients will be consumed/incorporated in the sludge and thereby removed from the water. The sludge production hence the organic N and P removal is calculated based on the removal of COD.

The removal of nitrogen and phosphor can be calculated as:

$$r_{½A,N} = r_{½A,COD} \cdot Y_{obs} \cdot f_N \qquad (31)$$

$$r_{½A,P} = r_{½A,COD} \cdot Y_{obs} \cdot f_P \qquad (32)$$

where Y_{obs} is the sludge production g COD_B/g COD_S.

1.6.1 Summary, BOD removal in biofilters

The overall reaction rate situation in BOD removing biofilters can be summarized as follows:

Situation	**Removal rate activity (g BOD/m^2/d)**	**Condition bulk water**
-Oxygen control -Temperature dependency (biology and diffusion)	$r_{A,BOD} = K_{½A,O2-BOD} \cdot \vartheta_{O2,BOD} \cdot \sqrt{S_{O2}}$ $K_{½A,O2-BOD} = \sqrt{2 \cdot k_{0f,O2-BOD} \cdot e^{kh \cdot (t-20)} \cdot D_{O2} \cdot e^{d \cdot (t-20)}}$	$\frac{S_{O2}}{S_{BOD}} < \frac{D_{BOD}}{D_{O2}} \cdot \vartheta_{BOD,O2}$
-BOD control -Temperature dependency (biology and diffusion)	$r_{½A,BOD} = K_{½A,BOD} \cdot \sqrt{S_{BOD}}$ $K_{½A,BOD} = \sqrt{2 \cdot k_{0f,BOD} \cdot e^{kh \cdot (t-20)} \cdot D_{BOD} \cdot e^{d \cdot (t-20)}}$ $\frac{k_{0f,BOD}}{k_{0f,O2-BOD}} = \vartheta_{O2,BOD} \frac{gBOD}{gO_2}$	$\frac{S_{O2}}{S_{BOD}} > \frac{D_{BOD}}{D_{O2}} \cdot \vartheta_{BOD,O2}$

1.6.2 Summary, COD removal in biofilters

The overall reaction rate situation in BOD removing biofilters can be summarized as follows:

Situation	**Removal rate activity, $r_{A,COD}$ (g COD/m^2/d)**	**Condition, bulk water**
-Oxygen control -Temperature dependency (biology and diffusion)	$r_{A,COD} = K_{½A,O2-COD} \cdot \vartheta_{O2,COD} \cdot \sqrt{S_{O2}}$ $K_{½A,O2-COD} = \sqrt{2 \cdot k_{0f,O2-COD} \cdot e^{kh \cdot (t-20)} \cdot D_{O2} \cdot e^{d \cdot (t-20)}}$	$S_{O2} < S_{COD} \cdot \frac{D_{COD}}{D_{O2}} \cdot \vartheta_{COD,O2}$
-COD control -Temperature dependency (biology and diffusion)	$r_{A,COD} = K_{½A,COD} \cdot \sqrt{S_{COD}}$ $K_{½A,COD} = \sqrt{2 \cdot k_{0f,COD} \cdot e^{kh \cdot (t-20)} \cdot D_{COD} \cdot e^{d \cdot (t-20)}}$ $\frac{k_{0f,COD}}{k_{0f,O2-COD}} = \vartheta_{O2,COD} \frac{gCOD}{gO_2}$	$S_{O2} > S_{COD} \cdot \frac{D_{COD}}{D_{O2}} \cdot \vartheta_{COD,O2}$

1.7 Nitrification in biofilters

1.7.1 Nitrification without presence of organic matter (COD/BOD)

Nitrification transforms ammonia into nitrate by oxidation. The process requires ammonia oxygen and alkalinity. If the process lacks oxygen or alkalinity, the process rate will be reduced. Once the alkalinity is consumed, pH will drop and completely inhibit the nitrification.

Oxygen requirement in the nitrification process

The consumption of ammonia and oxygen can be calculated from the bacterial redox process (nitrification) that takes place in the biofilm. From this we know that the nitrification requires $\upsilon_{NH4,O2}$ = 4,6 g O_2 / g NH_4-N being oxidized. Taking diffusion limitation into account we get:

$$\frac{S_{O2}}{S_{NH4}} \underset{<}{\overset{>}{?}} \frac{D_{NH4}}{D_{O2}} \cdot \vartheta_{NH4,O2} \tag{33}$$

$$\Rightarrow \frac{S_{O2}}{S_{NH4}} \underset{<}{\overset{>}{?}}\ 3{,}4\ \frac{gO_2}{gNH_4^- - N} = 1{,}4\ \frac{mole\ O_2}{mole\ NH_4^- - N} \tag{34}$$

If the oxygen concentration in the bulk water is less than 3,4 g O_2/g NH_4-N, oxygen will be limiting for the nitrification process.

For example if the oxygen concentration in a nitrifying Biokube compartment is 7 mg O_2/l, ammonia will be limiting for the process if the ammonia concentration is lower than 2 mg NH_4-N/l.

Alkalinity requirement in the nitrification process

Reaction rate limitation can be calculated for alkalinity (expressed by HCO_3) which is being consumed by the process. We know that the nitrification consumes 2 mole alkalinity for each mole ammonia being transformed. Consequently the nitrification requires $\upsilon_{NH4,HCO3}$ = 4,3 g HCO_3 / g NH_4-N being oxidized:

$$\frac{S_{HCO3}}{S_{NH4}} \underset{<}{\overset{>}{?}} \frac{D_{NH4}}{D_{HCO3}} \cdot \vartheta_{NH4,HCO3} \tag{35}$$

$$\Rightarrow \frac{S_{HCO3}}{S_{NH4}} \underset{<}{\overset{>}{?}}\ 7{,}4\ \frac{gHCO_3^-}{gNH_4^- - N} = 3{,}4\ \frac{mole\ HCO_3^-}{mole\ NH_4^- - N} \tag{36}$$

<u>Ammonia limitation:</u>

$$\frac{mole\ HCO_3^-}{mole\ NH_4^+ - N} > 3{,}4 \wedge \frac{mole\ O_2}{mole\ NH_4^+ - N} > 1{,}4 \tag{37}$$

<u>Oxygen limitation:</u>

$$\frac{mole\ O_2}{mole\ NH_4^+ - N} < 1{,}4 \wedge \frac{mole\ HCO_3^-}{mole\ O_2} > 2{,}4 \tag{38}$$

<u>Alkalinity limitation (inhibition):</u>

$$\frac{mole\ HCO_3^-}{mole\ NH_4^+ - N} < 3{,}4 \wedge \frac{mole\ HCO_3^-}{mole\ O_2} < 2{,}4 \tag{39}$$

Alkalinity limitation is important to avoid in nitrifying biofilm systems since pH decrease inside the biofilm will inhibit the nitrifying bacteria. The production of acidity will lead to build up of CO_2 in the deeper part of the biofilm and lower pH in the biofilm compared with the bulk liquid.

If oxygen is limiting for the nitrification process (compared to ammonia) in the effluent, the alkalinity have to be higher than 0,075 times the oxygen concentration. If ammonia is limiting for the nitrification process (compared to oxygen) in the effluent, the alkalinity have to be higher than 0,24 times the ammonia concentration.

Limitation of substrate and alkalinity in the nitrification process is summarized in the figure below.

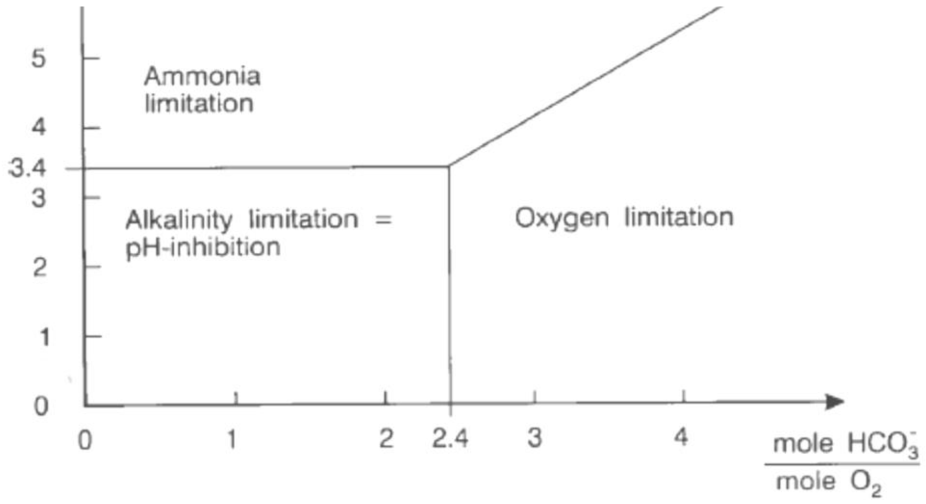


Figure 5 Borders of limitation between ammonia, oxygen and alkalinity in the nitrification process.

If wastewater contains little alkalinity only very little ammonia can be removed. If the alkalinity e.g. is 2 meqv/l (= 2 mmol HCO_3/l = 122 mg HCO_3/l), alkalinity is limiting for the process if the ammonia concentration is above 16,5 mg NH_4-N/l!

It is important to know that nitrification consumes a lot of alkalinity. If the incoming wastewater contains 4 meqv/l it can potentially remove 33 mg NH4-N/l, but the ratio between alkalinity and ammonia must never be lower than 7,4 g HCO_3/g NH_4-N in the effluent – otherwise pH might drop in the last compartment and inhibit the nitrification process.

Removal rate, nitrification

When it can be assumed that alkalinity is not limiting the nitrification process, the removal rate activity can be calculated for the redox process. Oxygen is electron acceptor (oxidant) and ammonia is the electron acceptor (reductant).

In case of <u>oxygen control</u>, the removal rate of ammonia can be determined as:

$$r_{½A,NH4-N} = K_{½A,O2} \cdot \vartheta_{O2,NH4-N} \cdot S_{O2}^{½} = \left(2 \cdot D_{O2} \cdot k_{0f,O2(nitrification)}\right)^{½} \cdot \vartheta_{O2,NH4-N} \cdot S_{O2}^{½} \qquad (40)$$

In case of <u>ammonia control</u>, the removal rate of ammonia can be determined as:

$$r_{½A,NH4-N} = K_{½A,NH4-N} \cdot S_{NH4-N}^{½} = \left(2 \cdot D_{NH4} \cdot k_{0f,NH4-N}\right)^{½} \cdot S_{NH4-N}^{½} \tag{41}$$

The stoichiometric ratio between oxygen and nitrification is $\upsilon_{O2,NH4}$ = 4,6 g O_2/g NH_4-N.

The necessary biofilter area can then be calculated by

$$Q \cdot S_{i,NH4-N} - r_{A,NH4-N} \cdot A = Q \cdot S_{u,NH4-N} \tag{42}$$

$$\Rightarrow \; A = \frac{Q\left(S_{i,NH4-N} - S_{u,NH4-N}\right)}{r_{A,NH4-N}} \tag{43}$$

It should always be checked if NH4-N or O_2 is controlling the reaction rate when determining the effluent ammonia concentration of the given design. Which substance controlling the reaction can be calculated from (21).

Temperature dependency, nitrification

Biological processes are temperature dependent which is particularly the case for nitrification. Therefore it is important to include temperature dependency when the removal rate activity is calculated. The calculation of temperature dependency is valid in the temperature range from 5 – 30 °C.

$$k_{0f,O2,t°C} = k_{0f,O2,20°C} \cdot e^{kn \cdot (t-20)} \tag{44}$$

Where k is the temperature constant (°C^{-1}) and t is the temperature.

The removal rate activity will be constant in the interval from 30-35 °C. Above 35 °C the removal rate activity will rapidly decrease towards zero at 40 °C.

Temperature dependency, diffusion

The diffusion coefficient is also dependent on the temperature in the water. Higher temperature result in an increase in transportation by diffusion which means the substrate will be transported quicker into the biofilm. The calculation of temperature dependency is valid in the temperature range from 2 – 40 °C.

The temperature depends of the ammonia diffusion coefficient can be calculated by:

$$D_{NH4,t°C} = D_{NH4,20°C} \cdot e^{d \cdot (t-20)} \tag{45}$$

Where d is the temperature constant (°C^{-1}) and t is the temperature.

1.7.2 Nitrification with presence of organic matter (BOD/COD)

In aerated biofilters high oxygen concentration and substrate (organic matter and ammonia) can be provided so that both heterotrophic and autotrophic bacteria can exist in the same biofilm. Since heterotrophic bacteria grow 10 times faster than autotrophic bacteria, they will populate the biofilm wherever there is organic matter to grow on. Autotrophic bacteria simply cannot exist in this zone of the biofilm. If the concentration of organic matter in the bulk is low enough and oxygen in the bulk is high, oxygen will penetrate deeper into the biofilm than organic matter. In this region of the biofilm, nitrification can take place. It is possible to calculate the expected extend of the nitrification if the concentrations of organic matter and oxygen are known.

From expression (22) we have:

$$S_{BOD} < S_{O2} \cdot \frac{D_{O2}}{D_{BOD}} \cdot \vartheta_{O2,BOD} \tag{46}$$

If the BOD concentration is less than $D_{O2}/D_{BOD} \cdot \upsilon_{O2,BOD}$ times the oxygen concentration, nitrification will start to take place. The extend of nitrification can be calculated from the following expression:

$$r_{A,NH4(BOD)} = r_{A,NH4(BOD=0)} \cdot f_{NH4,\mathrm{BOD}} \tag{47}$$

where the nitrification inhibition factor $f_{NH4,BOD}$ can be calculated as:

$$f_{NH4,\mathrm{BOD}} = 1 - \left(\frac{1}{\frac{D_{O2}}{D_{BOD}} \cdot \vartheta_{O2,BOD}} \cdot \frac{S_{BOD}}{S_{O2}} \right) \tag{48}$$

If $f_{NH4,BOD} < 0$, $f_{NH4,BOD}$ should be set to 0. ($f_{NH4,BOD}$ cannot be negative – this would lead to ammonia production).

If the inhibition of nitrification is described in terms of COD the same dependency can be calculated:

$$S_{COD} < S_{O2} \cdot \frac{D_{O2}}{D_{COD}} \cdot \vartheta_{O2,COD} \tag{49}$$

If the COD concentration is less than $D_{O2}/D_{COD} \cdot \upsilon_{O2,COD}$ times the oxygen concentration, nitrification will start to take place. The extend of nitrification can be calculated from the following expression:

$$r_{A,NH4(COD)} = r_{A,NH4(COD=0)} \cdot f_{NH4,\mathrm{COD}} \tag{50}$$

where the nitrification inhibition factor $f_{NH4,COD}$ can be calculated as:

$$f_{NH4,\mathrm{COD}} = 1 - \left(\frac{1}{\frac{D_{O2}}{D_{COD}} \cdot \vartheta_{O2,COD}} \cdot \frac{S_{COD}}{S_{O2}} \right) \tag{51}$$

If $f_{NH4,COD} < 0$, $f_{NH4,COD}$ should be set to 0. ($f_{NH4,COD}$ cannot be negative – this would lead to ammonia production).

1.7.3 Summary, nitrification in biofilters

The overall reaction rate situation in nitrifying biofilters can be summarized as follows:

Situation	**Removal rate activity (g NH_4-N/m^2/d)**	**Condition bulk water**
-Oxygen control -Temperature dependency (biology and diffusion) -No alkalinity limitation	$r_{A,NH4} = K_{½A,O2} \cdot \vartheta_{O2,NH4} \cdot \sqrt{S_{O2}} \cdot f_{NH4,BOD}$ $K_{½A,O2} = \sqrt{2 \cdot k_{0f,O2} \cdot e^{kn \cdot (t-20)} \cdot D_{O2} \cdot e^{d \cdot (t-20)}}$	$\frac{S_{O2}}{S_{NH4}} < 3{,}4 \frac{gO_2}{gNH_4^- - N}$ $\frac{S_{HCO3}}{S_{O2}} > 4{,}6 \frac{gHCO_3^-}{gO_2}$
-Ammonia control -Temperature dependency (biology and diffusion) -No alkalinity limitation	$r_{½A,NH4} = K_{½A,NH4-N} \cdot \sqrt{S_{NH4-N}}$ $K_{½A,NH4} = \sqrt{2 \cdot k_{0f,NH4} \cdot e^{kn \cdot (t-20)} \cdot D_{NH4} \cdot e^{d \cdot (t-20)}}$ $\frac{k_{0,O2}}{k_{0,NH4}} = \vartheta_{NH4,O2} \frac{gO_2}{gNH_4^- - N}$	$\frac{S_{O2}}{S_{NH4}} < 3{,}4 \frac{gO_2}{gNH_4^- - N}$ $\frac{S_{HCO3}}{S_{NH4}} > 7{,}4 \frac{gHCO_3^-}{gNH_4^- - N}$

1.8 Denitrification in biofilters

Complete nitrogen removal requires denitrification in the wastewater treatment process. Denitrification transform nitrate (generated from the nitrification process) into nitrogen gas that will disappear from the wastewater into the atmosphere.

COD is removed in an anoxic biological process in the Biokube biofilter compartments.

The removal rate activity takes nitrate and COD concentration into account. The substrate concentration controlling the removal rate activity is given by:

$$\frac{S_{NO3}}{S_{COD}} \overset{>}{\underset{<}{?}} \frac{D_{COD}}{D_{NO3}} \cdot \vartheta_{COD,NO3} \tag{52}$$

If

$$S_{NO3} > S_{COD} \cdot \frac{D_{COD}}{D_{O2}} \cdot \vartheta_{COD,O2} \tag{53}$$

COD is controlling the reaction rate. Similar expression can be given for the COD removal:

$$S_{O2} > S_{COD} \cdot \frac{D_{COD}}{D_{O2}} \cdot \vartheta_{COD,O2} \tag{54}$$

In case of nitrate control, the removal rate of COD can be determined as:

$$r_{½A,COD} = K_{½A,NO3} \cdot \vartheta_{O2,COD} \cdot S_{NO3}^{½} = \left(2 \cdot D_{NO3} \cdot k_{0f,NO3}\right)^{½} \cdot \vartheta_{O2,COD} \cdot S_{NO3}^{½} \tag{55}$$

In case of COD control, the removal rate of COD can be determined as:

$$r_{½A,COD} = K_{½A,COD} \cdot S_{COD}^{½} = \left(2 \cdot D_{COD} \cdot k_{0f,COD}\right)^{½} \cdot S_{COD}^{½} \tag{56}$$

The necessary biofilter area can then be calculated by

$$Q \cdot S_{i,COD} - r_{A,COD} \cdot A = Q \cdot S_{u,COD} \tag{57}$$

$$\Rightarrow \; A = \frac{Q\left(S_{i,COD} - S_{u,COD}\right)}{r_{A,COD}} \tag{58}$$

It should always be checked if COD or NO_3-N is controlling the reaction rate when determining the effluent COD concentration of the given design. Which substance controlling the reaction can be calculated from (21).

Temperature dependency, biological processes

Biological processes are temperature dependent. Therefore it is important to include temperature dependency when the removal rate activity is calculated. The calculation of temperature dependency is valid in the temperature range from 5 – 30 °C.

$$k_{0f,COD,t°C} = k_{0f,COD,20°C} \cdot e^{k \cdot (t-20)} \tag{59}$$

Where k is the temperature constant (°C^{-1}) and t is the temperature.

The removal rate activity will be constant in the interval from 30-37 °C. Above 37 °C the removal rate activity will rapidly decrease towards zero at 40 °C.

Temperature dependency, diffusion

The diffusion coefficient is also dependent on the temperature in the water. Higher temperature result in an increase in transportation by diffusion which means the substrate will be transported quicker into the biofilm. The calculation of temperature dependency is valid in the temperature range from 2 – 40 °C.

The temperature depends of the diffusion coefficient can be calculated by:

$$D_{NO3,t°C} = D_{NO3,20°C} \cdot e^{(d \cdot (t-20))} \tag{60}$$

Where d is the temperature constant (°C^{-1}) and t is the temperature.

Nutrient (N, P) removal caused by denitrification COD removal

Removal of organic matter is a heterotrophic process which requires nutrients in the bacterial growth process. The sludge produced contains nitrogen (6%), phosphor (1,5%) and other micronutrient that is essential for the bacterial growth process. So on one hand, these nutrients have to be present in sufficient amounts and on the other hand, the nutrients will be consumed/incorporated in the sludge and thereby removed from the water. The sludge production hence the organic N and P removal is calculated based on the removal of COD.

The removal of nitrogen and phosphor can be calculated as:

$$r_{½A,N} = r_{½A,COD} \cdot Y_{obs} \cdot f_N \tag{61}$$

$$r_{½A,P} = r_{½A,COD} \cdot Y_{obs} \cdot f_P \tag{62}$$

where Y_{obs} is the sludge production g COD_B/g COD_S.

1.8.1 Recirculation requirement

Denitrification requires a lot of organic matter. Nitrate consumes much more COD than oxygen (2,86 times more for respiration) so the nitrate removal will normally result in 5-6 times COD removal (e.g. removal of 50 mg NO_3-N requires 250-300 mg COD/l). The raw wastewater normally contains sufficient COD to run the denitrification process but denitrification then has to be run before the aerobic process. Since nitrate is generated after the aerobic process, recirculation has to be introduced.

The recirculation requirement depends on the nitrate generated and the discharge standard of TN. The recirculation requirement can be calculated from:

$$NO_3 - N(outlet) = \frac{1}{1+\alpha} \cdot NH_4 - N(inlet) \tag{63}$$

Where α is the recycle ratio (100% recirculation, α =1)

The recirculation rate requirement will have to be at least:

$$\alpha > \left[\frac{NH_4 - N\ (inlet)}{TN_{standard}} - 1\right] \tag{64}$$

E.g. if the inlet ammonia concentration is 50 mg NH_4-N/l and the TN standard is 10 mg N/l, the recirculation ratio should be at least 4. In this case TN outlet will be 10 mg NO_3-N/l and the ammonia concentration 0 mg NH_4-N/l. If ammonia or other nitrogen is present the outlet the TN requirement value must be reduced accordingly.

1.8.2 COD requirement

The theoretical COD requirement can be calculated from:

$$COD(inlet) > \frac{2,86}{1-Y_{obs}} \cdot NH_4 - N(transformed) \tag{65}$$

Since oxygen is being recirculated from the aerobic compartment it has to be taken into account that this oxygen will consume some of the COD from the inlet wastewater. The real amount of COD required can then be calculated from:

$$COD(inlet) > \frac{1}{1-Y_{obs}} \cdot O_2 + \frac{2,86}{1-Y_{obs}} \cdot NO_3 - N(denitrified) \tag{66}$$

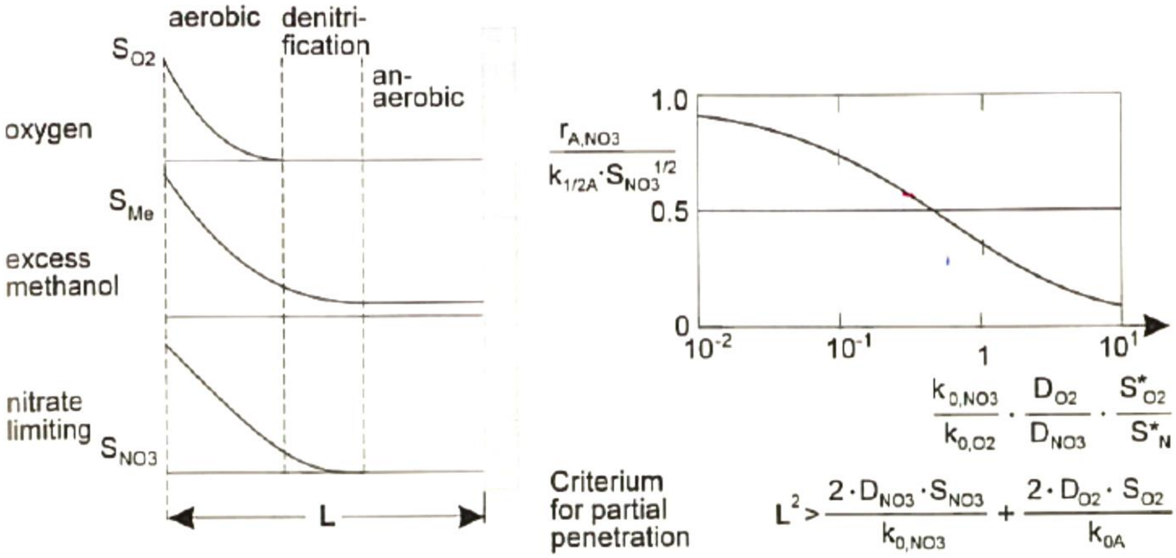
The recirculation rate should therefore be less than:

$$\alpha < \frac{COD_{in}(1-Y_{obs}) - 2,86 \cdot NH_4 - N(in)}{O_2} \tag{67}$$

It is important to note that COD in this aspect is degradable COD which in practice is equal to the BOD concentration.

1.8.3 Denitrification under influence of oxygen

If oxygen is present in the denitrification compartment it is still possible to conduct denitrification – however, the denitrification rate will be reduced. The phenomenon is often referred to as three-component diffusion because the calculations take three components into account (nitrate, oxygen and organic matter). If the oxygen concentration is not too high, and COD concentration is plenty, the nitrate can diffuse into the deeper part of the biofilm and perform denitrification:



It is necessary to calculate the relative penetration depth of nitrate compared to oxygen from the following formula:

$$\frac{k_{0f,NO3} \cdot D_{O2} \cdot S_{O2}}{k_{0f,O2} \cdot D_{NO3} \cdot S_{NO3}} \qquad (68)$$

If e.g. value (xx) is calculated to 0,3, the denitrification will be 60% efficient in the denitrification compartment with presence of oxygen and in limitation in organic matter (can be calculated).

2 Oxygen transfer and air scouring in Biokube bioreactors

Bioreactors need plenty of oxygen supplied by diffusers installed at the bottom of the reactor, below the biofilm support media. The aeration of diffusors has several of purposes:

1) Supply of oxygen to the water
2) Mixing of water in the reactor compartment
3) Cleaning of the biofilm support media (sloughing off excess biofilm)
4) Ensuring that nutrients and substrates are transported to the surface of the biofilm

2.1 Oxygen transfer

Most importantly is the calculation of the oxygen supply to the bioreactors. The oxygen supply should be sufficient to maintain a certain oxygen concentration in the bulk water – this concentration level often directly determines the reaction rate of substrate removal that can be maintained in the reactor. If the oxygen supply is insufficient, the oxygen concentration in the water will drop and the removal rate of substrate be reduced.

The aeration capacity can be determined as:

$$OC_{injection} = K_L a \cdot \left(S_{O2,m} - S_{O2}\right) \cdot V \qquad (69)$$

where

$OC_{injection}$ = oxygen injection from the installed diffusor/blower system [g O_2/d]

K_La = Aeration capacity parameter [d^{-1}]

$S_{O2,m}$ = Saturation concentration of oxygen [g O_2/m^3]

S_{O2} = Concentration of oxygen in the bulk water (to be maintained) [g O_2/m^3]

V = water volume in the bioreactor compartment

The important aeration parameter (K_La) is specifically determined in each bioreactor configuration and is depended on the diffusor type, height of the reactor and air supply.

The loss of oxygen out the reactor is caused by oxygen consumption in the biological process and by loss of oxygen in the outgoing wastewater:

$$OC_{removal} = r_{A,COD} \cdot A \cdot (1 - y_{obs}) + Q_{out} \cdot S_{O2} \qquad (70)$$

where

$OC_{removal}$ = Loss of oxygen capacity in the bioreactor [g O_2/d]

$r_{A,COD}$ = surface specific removal rate [g O_2/m^2/d]

Y_{obs} = Observed yield and COD removal [g COD_B/g COD_S]

S_{O2} = Concentration of oxygen in the bulk water (to be maintained) [g O_2/m^3]

In steady-state the added amount of oxygen equals the removed amount of oxygen:

$$OC_{injection} + OC_{inlet} = OC_{removal} \tag{71}$$

$$\Rightarrow \; K_L a \cdot \left(S_{O2,m} - S_{O2,out}\right) \cdot V + Q_{in} \cdot S_{O2,in} = r_{A,O2} \cdot A \cdot (1 - y_{obs}) + Q_{out} \cdot S_{O2,out} \tag{72}$$

Assuming that we know the surface reaction removal rate (depending on type of wastewater), the sludge yield of the process we can calculate the necessary aeration capacity in the reactor:

$$K_L a = \frac{r_{A,O2} \cdot A \cdot (1 - y_{obs}) + Q_{out} \cdot S_{O2,out} - Q_{in} \cdot S_{O2,in}}{\left(S_{O2,m} - S_{O2,out}\right) \cdot V} \tag{73}$$

Determination of $K_L a$

The aeration parameter can specifically be determined in batch experiments equipped with the installed aeration system. The experiments are performed by measuring the increase of oxygen concentration from zero to saturation concentration. The rate of change in the reaction can be determined by:

$$\frac{\partial(S_m - S)}{S_m - S_0} = -K_L a \cdot \partial t \tag{74}$$

$$\Longrightarrow \quad \frac{S_m - S}{S_m - S_0} = e^{-K_L a \cdot t} \tag{75}$$

$$\Longrightarrow \quad ln \frac{S_m - S}{S_m - S_0} = -K_L a \cdot t \tag{76}$$

A semilogaritmic plot will reveal the aeration parameter as the slope of the curve.

It is important to know how the K_La parameter of diffusors will change over time, because the efficiency of the diffusor will gradually be reduced when the diffusors starts to clog. There Biokube operates with a safety factor when designing the aeration equipment which ensures that the aeration capacity in the biofilter compartment always will be sufficient even after several of years of operation.

2.2 Airflow and scour of the biofilter media

The airflow supplied to the Biokube compartment has several of functions besides supplying air to the processes. The has a certain scouring effect that ensures turbulent mixing and the biofilm is detached from the media when it becomes thick. Powerful scouring will also minimize hydraulic filmdiffusion that can significantly reduce the removal rate activity even though concentrations in the bulk liquid are high.

It is widely recognized that the minimum air flow rate supplied to biofilters should not be less than 8 $Nm^3/m^2/h$ where the area is the cross section area of the compartment. Maximum air flow rates supplied to biofilter are normally not higher than 40 $Nm^3/m^2/h$. The air flow rate should take into account the type of process, the wastewater type and the type and specific surface area of the biofilter media.

Biokube uses an open structured biofilter media that is easy to aerate since the biofilm is directly exposed to the bulk liquid. Diffusors are placed at the bottom in a way that air bobbles will pass the biofilm structure so biofilm detachment can take place. The diffusors are each loaded with 75 litre air/min and one diffusor covers 0,75 m^2. Consequently, Biokube´s air flow rate is normally designed to ensure efficient scrubbing of the biofilter media be 26,5 $Nm^3/m^2/h$.

3 Sedimentation

Biokube normally operate all wastewater treatment system with both primary sedimentation and secondary clarification.

3.1 Primary sedimentation

The main purpose of the primary sedimentation is to remove suspended solids and COD/BOD. Primary sedimentation removes most of the organic matter as illustrated in the curve below:

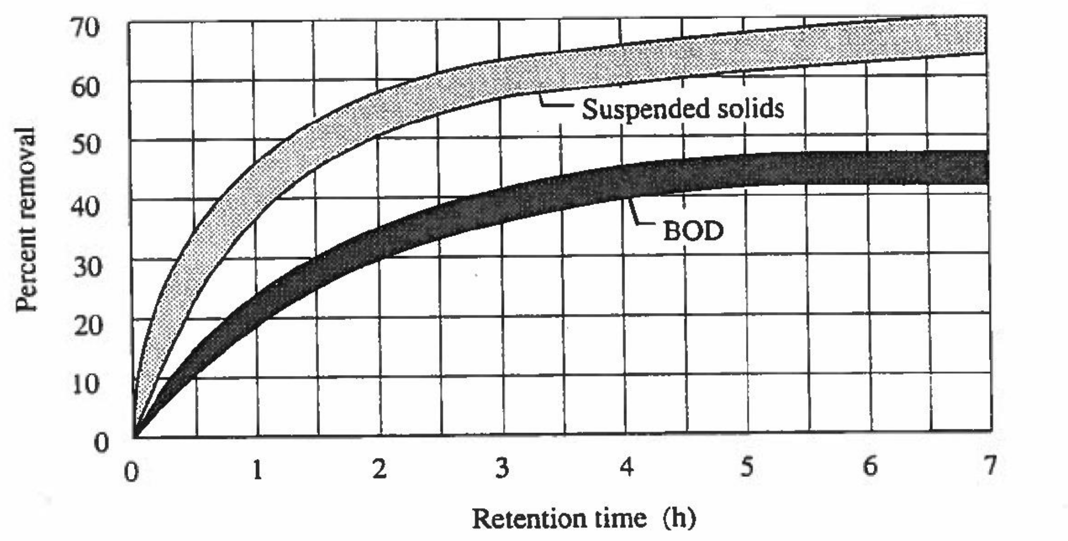


Figure 6 Removal of suspended solids and BOD in Biokube primary clarification tanks

In primary treatment 60-65% suspended solid removal can be achieved when the sludge holding tank is empty. When the sludge holding tank is at its maximum (of sludge) the suspended solid removal efficiency is 50-55%.

As for BOD removal the sludge holding tank will remove between 40-45% BOD (empty sludge holding tank) and 30-35% BOD removal when the sludge tank is full of sludge.

As for COD, 65% of the particulate COD can be removed in an empty sludge holding tank. COD particulate removal efficiency will drop to 50% when the sludge holding tank is full.

If precipitation chemical is added to enhance the primary sedimentation, 80% of particulate COD plus 20% soluble COD can be removed in the primary sedimentation.

Hydraulic loading
The hydraulic loading of the primary sedimentation should be less than

$$HOB = 1{,}8\ \frac{m^3}{m^2 \cdot h} = 40\ \frac{m^3}{m^2 \cdot d} \qquad (77)$$

3.2 Secondary clarification

Normally secondary settling requires a relative slow hydraulic loading on the tank in order to compact the sludge at the bottom. Discharge from biofilters is however much different from activated sludge plants – the sludge inlet concentration is much lower (10-20 times) but the sludge SVI can be much higher resulting in slower sludge settling.

Biokube design settling tanks very deep in order to obtain low sludge concentration in the outlet which also gives the customers a more robust and safe sedimentation process.

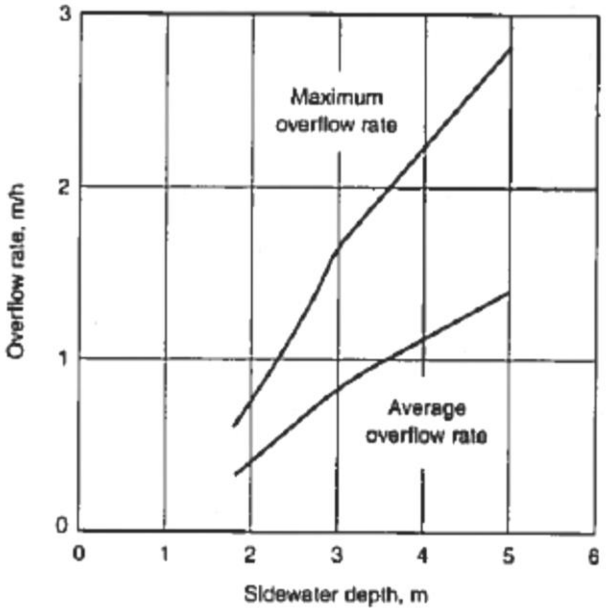


Figure 7 Average and maximum loading rate of Biokube secondary clarification tanks

The surface loading rate is in average 1,0 – 1,2 m/h whereas the maximum surface loading rate can reach 2,0 – 2,4 m/h (Biokube operates with 4 m deep clarifier tanks).

The surface area of the secondary clarifiers can be calculated as:

$$A = \frac{Qmax\left[\frac{m^3}{h}\right]}{HOB\left[\frac{m}{h}\right]} \tag{78}$$

The maximum weir loading of the secondary settling tanks must not exceed 7 m^3/m/h. The length of the weir can be calculated as:

$$Weir\ length = \frac{Qmax\left[\frac{m^3}{h}\right]}{Maximum\ weir\ loading\left[\frac{m^3}{m \cdot h}\right]} \tag{79}$$