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En analyse av dimensjoneringsgrunnlaget for HYBAS – en hybrid avløpsrenseprosess

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Master i produktutvikling og produksjon
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Norges teknisk-naturvitenskapelige universitet
Institutt for energi og prosessteknikk

Oppgavetekst

Prof. H. Ødegaard har laget et forslag til dimensjoneringsprosedyre for HYBAS. I denne oppgaven skal studenten analysere dimensjoneringsgrunnlaget for prosessen, basert dels på resultater fra pilotforsøk, dels på resultater fra anlegg i drift og dels basert på det forslag til dimensjoneringsprosedyre som er lagt fram. Kandidaten skal kritisk evaluere denne prosedyren og evt foreslå endringer samt utarbeide en regnearkmodell for dimensjonering av prosessen. Kandidaten skal også analysere et full-skala anlegg under bygging og på bakgrunn av denne analysen forutsi hvordan dette anlegget vil fungere under ulike belastningsforhold.

Mål
Målet med oppgaven er å komme fram til en forbedret dimensjoneringsprosedyre for HYBAS-prosessen, en hybrid biologisk renseprosess for avløpsvann – markedsført av selskapet AnoxKaldnes AS.

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Våren 2008

En analyse av dimensjoneringsgrunnlaget for HYBAS – en hybrid avløpsrenseprosess

An analysis of HYBAS – a hybrid wastewater treatment process

Bakgrunn

Biologisk rensing av avløpsvann foregår enten ved den såkalte aktivslamprosessen (der biomassen vokser suspendert i bioreaktorens vannvolum og separert biomasse returneres til bioreaktoren fra separasjonsreaktoren) eller ved såkalte biofilmprosesser (der biomassen vokser på en flate i bioreaktoren og separert biomasse ikke behøver å returneres til bioreaktoren).

Ved NTNU/SINTEF ble det tidlig på nitti-tallet utviklet en biofilmprosess, den såkalte MBBR (Moving Bed Biofilm Reactor) prosessen, som ble kommersialisert av Kaldnes Miljøteknologi AS (nå AnoxKaldnes AS) med hovedkontor i Tønsberg. Prosessen har fått meget stor utbredelse og er i dag den helt dominerende biologiske avløpsrenseprosess i Norge og en av de mest brukte biofilmprosesser på verdensbasis. I MBBR-prosessen vokser biomassen på små plastelementer som holdes svevende i reaktoren som et resultat av omrøring pga lufting eller mixere.

Internasjonalt er imidlertid situasjonen ofte den at man allerede har et aktivslamanlegg som imidlertid krever oppgradering (bedre renseeffekt eller større kapasitet) og i slike tilfeller er en annen prosessvariant ofte ønsket, nemlig HYBAS (Hybrid Biofilm Activated Sludge). I denne prosessen kombineres MBBR-prosessen med aktivslamprosessen ved at deler av (eller hele) aktivslamreaktoren tilsettes biofilmmediet (plastelementene). For øvrig er oppbygningen av anlegget som i et aktivslamanlegg. Den biologiske prosessen vil da dels foregå i den suspenderte biomassen (aktivslammet) og dels i den fastsittende biomassen (biofilmen). Resultatet er at kapasiteten av anlegget øker.

Det er imidlertid en utfordring å dimensjonere HYBAS-prosessen riktig på tross av at vi kjenner godt til dimensjoneringsgrunnlaget for henholdsvis aktivslam-prosesser og MBBR-prosesser. En av årsakene til dette er at aktiviteten i hhv den suspenderte og den fastsittende biomassen avhenger av den organiske belastningen på den samlede bioreaktoren. Dette studeres for tiden i pilotforsøk ved Institutt for vann- og miljøteknikk.

Prof. H. Ødegaard har laget et forslag til dimensjoneringsprosedyre for HYBAS. I denne oppgaven skal studenten analysere dimensjoneringsgrunnlaget for prosessen, basert dels på resultater fra pilotforsøk, dels på resultater fra anlegg i drift og dels basert på det forslag til dimensjoneringsprosedyre som er lagt fram. Kandidaten skal kritisk evaluere denne prosedyren og evt foreslå endringer samt utarbeide en regnearkmodell for dimensjonering av prosessen. Kandidaten skal også analysere et full-skala anlegg under bygging og på bakgrunn av denne analysen forutsi hvordan dette anlegget vil fungere under ulike belastningsforhold.

Mål
Målet med oppgaven er å komme fram til en forbedret dimensjoneringsprosedyre for HYBAS-prosessen, en hybrid biologisk renseprosess for avløpsvann – markedsført av selskapet AnoxKaldnes AS.

Oppgaven bearbeides ut fra følgende punkter:

1. Kandidaten skal beskrive aktivslamprosessen, MBBR-prosessen og HYBAS-prosessen og særlig dimensjoneringsgrunnlaget for de to førstnevnte prosessene mht ulike rensekrav for karbon (BOD)-fjerning, ammonium-fjerning (nitrifikasjon) og N-fjerning (denitrifiksajon).

2. Kandidaten skal gjennomgå og beskrive de prosessforhold som har betydning for dimensjonering av HYBAS prosessen. Kandidaten skal kritisk analysere det forslag til dimensjoneringsprosedyre som foreligger og evt komme med forslag til endringer.

3. Kandidaten skal analysere de renseresultater som kommer ut av de pilotforsøk som gjennomføres ved IVM samt resultater fra andre pilot- og full-skala anlegg med tanke på underbygging av eventuelle forslag til endringer av den eksisterende dimensjoneringsprosedyre (nevnt under pkt 2)

4. Kandidaten skal utarbeide en regnearkmodell for den dimensjoneringsprosedyre for foreslås og skal bruke denne til å gjennomføre en sensitivitetsanalyse mht inngangsparametre i modellen, herunder:
   - Belastninger (hydraulisk, organisk etc)
   - Dimensjonerende prosesshastigheter
   - Temperatur
   - Valg av biomedium

5. Kandidaten skal gjennomgå dimensjoneringen av et full-skala anlegg under bygging (forslagsvis Sharjah WWTP i Emiratene) på bakgrunn av den kunnskap som er ervervet gjennom pkt 1-4 og analysere hvordan man kan forvente at dette anlegget vil fungere under ulike belastningsforutsetninger.

Senest 14 dager etter utlevering av oppgaven skal kandidaten levere/sende instituttet en detaljert fremdrift- og evt. forsøksplan for oppgaven til evaluering og evt. diskusjon med faglig ansvarlig/ veiledere. Detaljer ved evt. utførelse av dataprogrammer skal avtales nærmere i samråd med faglig ansvarlig.

Tilretteleggning og assistanse
Under arbeidet med oppgaven vil professor Hallvard Ødegaard, Institutt for vann- og miljøteknikk (IVM) være kandidatens veileder. Råd kan også søkes hos gjesteforsker Daniele Trapani ved IVM. Professor Tor Ytrehus, Institutt for Energi og prosessteknikk (EPT) vil være kandidatens faglærer og medveileder ved EPT.

I den grad kandidaten vil utføre kjemiske analyser, utføres disse av kandidaten selv i den utstrekning dette er mulig. Forøvrig kan kandidaten søke assistanse hos instituttets laboratorie-personale.

Presentasjon og innlevering
Besvarelsen redigeres mest mulig som en forskningsrapport med et sammendrag både på norsk og engelsk, konklusjon, litteraturliste, innholdsfortegnelse etc. Ved utarbeidelsen av teksten skal

kandidaten legge vekt på å gjøre teksten oversiktlig og velskrevet. Med henblikk på lesning av besvarelsen er det viktig at de nødvendige henvisninger for korresponderende steder i tekst, tabeller og figurer anføres på begge steder. Ved bedømmelsen legges det stor vekt på at resultatene er grundig bearbeidet, at de oppstilles tabellarisk og/eller grafisk på en oversiktlig måte, og at de er diskutert utførlig.

Alle benyttede kilder, også muntlige opplysninger, skal oppgis på fullstendig måte. (For tidsskrifter og bøker oppgis forfatter, tittel, årgang, sidetall og evt. figurnummer.)

Det forutsettes at kandidaten tar initiativ til og holder nødvendig kontakt med faglærer og veileder(e). Kandidaten skal rette seg etter de reglementer og retningslinjer som gjelder ved AnoxKaldnes AS og alle andre fagmiljøer som kandidaten har kontakt med gjennom sin utførelse av oppgaven, samt etter eventuelle pålegg fra Institutt for energi- og prosessteknikk.

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Til Instituttet innleveres to - 2 komplette, kopier av besvarelsen. Ytterligere kopier til evt. medveiledere/oppgavegivere skal avtales med, og evt. leveres direkte til, de respektive.
Til instituttet innleveres også en komplett kopi (inkl. konsentrerte sammendrag) på CD-ROM i Word-format eller tilsvarende.

Innleveringsfrist : 10.06.08

Institutt for energi- og prosessteknikk
15 januar 2007

for Johan Hustad
Instituttleder

Tor Ytrehus
Faglig ansvarlig/Medveileder

Hallvard Ødegaard
Institutt for vann- og miljøteknikk
Veileder

Abstract

The Kaldnes HYBAS^{TM}(Hybrid Biofilm Activated-Sludge) wastewater treatment process consists of two fairly well understood processes: Activated-Sludge (AS) and the Moving-Bed Biofilm Reactor (MBBR^{TM}). For both of which, but especially Activated-Sludge, there is broad selection of literature describing the operation and dimensioning of these systems. In HYBAS it is important to understand the interaction between the biofilm and the suspended sludge and to have a method of dimensioning the entire system. Prof. Hallvard Ødegaard at NTNU proposed a model for the HYBAS system formulated as a 15-step calculation method, partly based on experience, but with a focus on being logical and intuitive. This model is analysed for consistency with literature. Minor modifications which improve the accuracy and generalize the model are proposed. The model is implemented into an Excel workbook to allow experimentation for further development of the model. An analysis of the model components against a real-world pilot experiment is attempted, but with significant problems. Some consistency with the model is proven, but strong disagreement with the model is also identified, with reservations.

Sammendrag

Kaldnes HYBAS^{TM}(Hybrid Biofilm Activated-Sludge) avløpsvann-renseprosess består av to prosesser som er relativt godt forstått: Aktivslam (AS) og Moving-Bed Biofilm Reactor (MBBR^{TM}), biofilm med bevegelige bærere. Det finnes en stor del litteratur, men spesielt for Aktivslam, som beskriver virkemåten og dimensjoneringsprosedyrer for de to systemene. For HYBAS er det viktig å få kunnskap om hvordan biofilm interakterer med aktivslammet og å danne en metode for dimensjonering av en fullstendig HYBAS prosess. Professor Hallvard Ødegaard ved NTNU har foreslått en modell for HYBAS, formulert som en 15-stegs utregnings-prosedyre, delvis basert på erfaringsdata, men med vekt på å være logisk og intuitiv. Denne modellen er analysert for overenstemmelse med litteraturen. Små modifikasjoner som forbedrer nøyaktigheten og generaliserer modellen er foreslått. Modellen er implementert i et Excel regneark for å muliggjøre eksperimentering og videre utvikling av modellen. En analyse av enkelte komponenter av modellen mot data fra et pilot-anlegg er forsøkt, men med betydelige problemer. Noen gode overenstemmelser med modellen blir vist, men også sterke uoverenstemmelser med modellen blir identifisert, med forbehold.

Preface

This master thesis has been completed at the Norwegian University of Science and Technology (NTNU), during the 10^{th} and final semester of my tuition in Product Development and Manufacturing. The project topic was chosen in collaboration with Professor Hallvard Ødegaard at the Department of Hydraulic and Environmental Engineering, out of my own interest for water engineering and wastewater treatment.

This work has been far from my acquired experience of precise mathematics and accurate numerical methods, delving into the world of practical engineering, with basis on experimental data. Microorganisms and wastewater treatment systems were completely new to me, and I still consider myself very "green" on the subject. Luckily this project could be carried out with little else than an open mind and critical thinking, carried by my interest for the field and the realization that it is one of the most important fields in an ever-expanding world with denser and denser urbanized living.

I would like to properly thank Professor Hallvard Ødegaard for the opportunity to engage in this topic, and for providing excellent guidance throughout the semester. He is regarded as the founder of the wastewater treatment community established at NTNU and is responsible for many innovations within the treatment sector. I also want to thank Krüger Kaldnes (former AnoxKaldnes) for the cooperation and interest in my work.

I would lastly like to thank friends and fellow students for making the semester more than just work, without them this project could not have been done.

Trondheim, Norway, 16^{th} June 2008

Simon Settem Simonsen

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Nomenclature

AS	Activated Sludge
BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
DO	Dissolved Oxygen
Q_{in}	Flowrate influent
Q_{RL}	Flowrate Return Liquor
Q_{RS}	Flowrate Return Sludge
RAS	Return Activated Sludge
RL	Return Liquor
RS	Return Sludge
SCOD	Soluble Chemical Oxygen Demand
SP	Sludge Production
SRT	Solids Retention Time
TCOD	Total Chemical Oxygen Demand
TKN	Total Kjeldal Nitrogen
TSS	Total Suspended Solids
VSS	Volatile Suspended Solids

Greek symbols

Φ_{DN}	COD consumption, denitrification
Φ_{O_2}	COD consumption, endogenous respiration
Φ_{SP}	COD consumption, cell growth

μ specific growth rate

ν_{DN} nitrogen consumption by denitrification

μ_m maximum specific growth rate

ν_{Total} total nitrogen consumption

Π Sludge Production

Θ coefficient of temperature-activity

θ hydraulic retention time

θ_c mean cell-residence time

Latin symbols

B_{BOD} BOD load

C_{BOD} BOD concentration

f_{N} fraction of nitrogen in biomass

F_T temperature correction factor

k constant, see equation (2.35)

k_d endogenous decay coefficient

K_s half-velocity constant

m_{biofilm} mass of biofilm

n reaction order constant, see equation (2.35)

Q influent flowrate

Q_e effluent flowrate

Q_w waste flowrate

r_{20} rate at temperature 20

r_d endogenous decay rate

r_{DN} rate of denitrification

r_g rate of growth

$r_g^{'}$	net growth rate
r_n	nitrification rate
r_{su}	substrate utilization rate
r_T	rate at temperature T
S	concentration of growth-limiting substrate
S_{eff}	effluent substrate concentration
S_{in}	influent substrate concentration
S_n	rate-determining constant, see equation (2.35)
T	Temperature
U_{DN}	specific denitrification rate
$U_{\text{DN}}^{'}$	actual denitrification rate
V	Volume
V_{DN}	Volume of denitrification tank
Vn	volume of nitrification tank
X	concentration of microorganisms
X_e	solids concentration in effluent
X_L	MLSS concentration
X_r	solids concentration in return line
Y	maximum yield coefficient

1. Introduction

Municipal and industrial wastewater is a cocktail of different chemicals, bacteria and viruses and as such it is necessary to treat the water before entering natural water reservoirs. Nutrients, mainly phosphorous and nitrogen, must be minimized in order to avoid algae-blooming, leading to eutrophication, pathogens and chemicals must be removed to protect plants and animals. Basically the wastewater should not affect the recipient environment in any way.

Wastewater treatment methods include mechanical, chemical and biological techniques;

Mechanical treatment removes relatively large particulate matter (down to 0.1-0.2 mm), by sedimentation or filters, for instance.

Chemical treatment involves addition of chemical agents that result in precipitation and flocculation of dissolved and colloidal matter, creating larger, readily separated, particles.

Biological treatment is the application of microorganisms that make use of dissolved and particulate matter in their metabolism and/or cell growth, resulting in simpler molecules and fresh cell mass (biological sludge).

It is the use of biological treatment that is of special focus in this report, and more specifically the treatment process known as HYBAS^{TM} [1]. There are several biological treatment processes, but they are commonly of either the Activated-Sludge (AS) or Biofilm type. The HYBAS process incorporates two common processes, namely Activated-Sludge, and the Moving Bed^{TM}biofilm plastic carriers. The two methods are applied in one tank, enabling the upgrade of Activated-Sludge plants by filling the tank with biofilm carriers, thus having biofilm carriers suspended in Activated-Sludge. The movement of the carriers is actuated by either air bubbles in the case of aerobic tanks, or by propellers in anaerobic tanks.

The HYBAS process is developed to effectively increase the nitrification rate and improve tolerance towards loading spikes. Costs of HYBAS upgrades typically includes installation of aeration tubing and sifts to contain the biocarriers within the reactor. When upgrading plants, the total volume available already needs not be expanded, but the volume might need to be partioned, depending on the what kind of treatment is needed in the HYBAS plant.

The Activated-Sludge process is a well-known and well understood process, described in detail in various literature. The Moving Bed Biofilm Reactor (MBBR) process, however,

[1] HYBAS^{TM} is patented and trademarked by AnoxKaldnes AS

is more recently developed and thus not as well documented. Still, given that biofilm processes in general have been in use for decades, it is considered a well-known process and the unique characteristics fully developed. Plant dimensioning procedures for both processes are available. The HYBAS process, though, does not have a solid foundation for dimensioning and experiments have shown that there is an interaction between the suspended biofilm and the suspended solids that is not fully mapped or understood.

Professor Hallvard Ødegaard of the Department of Hydraulic and Environmental Engineering at the Norwegian University of Science and Technology, developed a dimensioning model for HYBAS which has proven to be popular internationally because of its logic and intuitive outline. The model is in its early stages and must be further tested and developed, which is the motivation of this project.

The scope of this report is defined as

- Presentation of biological wastewater treatment
- Presentation and discussion of the HYBAS model
- Development of an Excel spreadsheet implementing the HYBAS model
- Analysis of data from a HYBAS pilot-plant with testing and evaluation of the model

2. Biological wastewater treatment

Biological wastewater treatment basically involves supplying microorganisms (primarily bacteria) with nutrients and energy for their growth, resulting in purified water and biological *sludge*. The primary function of this treatment process is to convert the organic matter and/or other constituents of the wastewater into cell growth or gaseous end-products. By promoting certain bacterial cultures, controlling oxygen and nutrients balances, the microorganisms can be targeted to specifically remove ammonium (by conversion to nitrite and nitrate, called *nitrification*) and nitrates into nitrogen gas (by *de-nitrification*). Specific combinations of anaerobic and aerobic reactors can be used to remove phosphorous as well, but this is not considered within the report. Biological treatment processes are typically divided into aerobic and anaerobic, meaning the process either has access to oxygen or not. Additionally, processes are subdivided into suspended-growth or attached-growth processes or the combination of both.

Suspended-growth processes promote the microorganisms to congregate into *flocs* which are suspended in the liquid. The flocs have a high surface area and good penetration of nutrients and oxygen. Air blowers or jets are used to supply aerobic tanks with oxygen and, importantly, provides convective flow patterns that transports and mixes the organisms with nutrients to maintain homogeneous and effective treatment. In anaerobic reactors the same effect is provides by propellers. The *Activated-Sludge* process, presented in section 2.3, is a commonly used suspended-growth process and of special focus in this report.

Attached-growth processes allow the microorganisms to grow on inert surfaces, including rocks and special ceramic or plastic materials. Bacteria attach to the surface by producing a polymer that acts like a glue and envelopes the bacteria, growing a *biofilm*. More on biofilms and attached-growth processes in the section 2.4 on the MBBR process.

One important use of these processes is the removal of organic nitrogen by a process known as *nitrification* and *denitrification* which results in organically bound nitrogen in the wastewater being converted to gaseous nitrogen which escapes into air, where it does no harm to the environment. The nitrogen transformation within a biological treatment process including nitrification and denitrification is shown in figure 2.1.

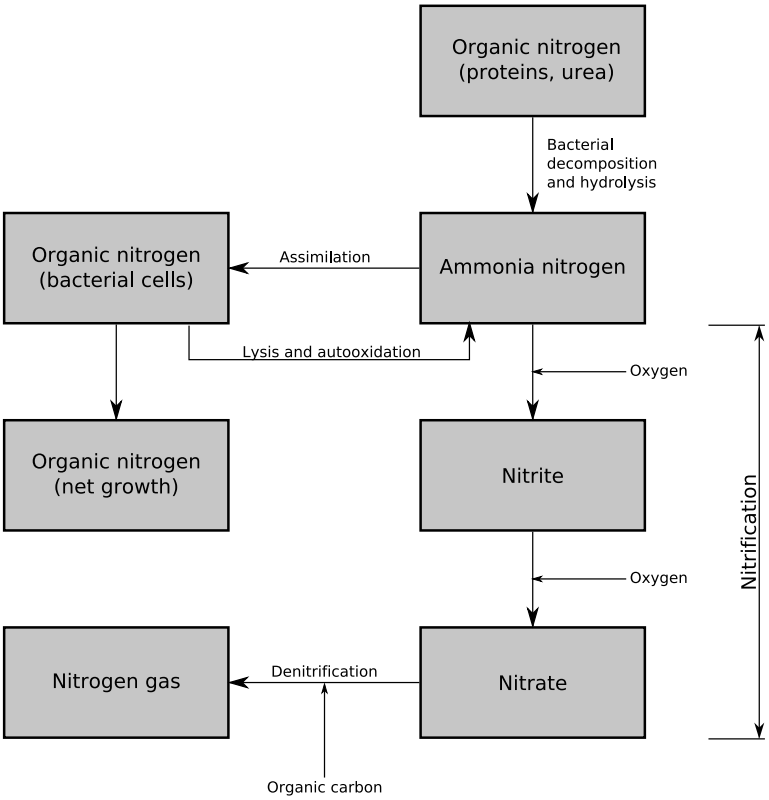

Figure 2.1.: Transformation of organic nitrogen in a biological process

2.1. Nitrification

Nitrification is the conversion of ammonia into nitrite and nitrate. Two bacteria genera are responsible for this two-step process; *Nitrosomonas* and *Nitrobacter*. *Nitrosomonas* oxidizes ammonia into nitrites, but as nitrites are consumed by neighboring *Nitrobacter* to form nitrates, nitrite is considered an intermediate product and the total reaction equation shows no nitrite build-up.

For *Nitrosomonas* we can write the (simplified) equation:

$$55\,\mathrm{NH_4^+} + 76\,\mathrm{O_2} + 109\,\mathrm{HCO_3^-} \longrightarrow \mathrm{C_5H_7O_2N} + 54\,\mathrm{NO_2^-} + 57\,\mathrm{H_2O} + 104\,\mathrm{H_2CO_3} \quad (2.1)$$

For *Nitrobacter*, we can write:

$$400\,\mathrm{NO_2^-} + \mathrm{NH_4^+} + 4\,\mathrm{H_2CO_3} + \mathrm{HCO_3^-} + 195\,\mathrm{O_2} \longrightarrow \mathrm{C_5H_7O_2N} + 3\,\mathrm{H_2O} + 400\,\mathrm{NO_3^-} \quad (2.2)$$

Note here that the the cell mass is modeled as $C_5H_7O_2N$, a simple molecule equivalent in constituents to the complex cell structure. These equations shows that approximately 4.3mg O_2 is needed per mg of ammonia-nitrogen oxidized.

Limiting factors

Nitrifying bacteria are sensitive creatures which need optimal conditions to grow healthily. The following factors influence growth considerably:

- High ammonia and nitrous acid concentrations will limit nitrification
- Optimally a pH within 7.5 to 8.6, but bacteria colonies can acclimatise to lower pH levels
- Temperature
- Dissolved Oxygen concentration must be higher than 1 $^{mg}/_{L}$.
  - The limiting DO level is higher for an attached-growth process than in suspended-growth. More on this in section 2.4.2.

2.2. Denitrification

Denitrification is the process in which microorganisms convert nitrate (NO_3^-) into molecular nitrogen (N_2). This is generally regarded as a two-step process where nitrate is reduced to nitrite (NO_2^-), and nitrite is reduced to molecular nitrogen. The bacteria involved makes use of organic compounds for energy and carbon and utilize nitrate and nitrite as electron acceptors, instead of oxygen, thus this process is a modification of the aerobic process, and is therefore called anoxic. The carbon source will in many cases need to be externally supplied, by addition of methanol, glycerol, ethanoic acid etc. 'Internal' carbon source means the use of organic compounds in the wastewater or sludge itself.

The following reactions exemplify the 2-stage denitrification process, using methanol as carbon source:

$$\begin{aligned} 3\,NO_3^- + CH_3OH &\longrightarrow 3\,NO_2^- + CO_2 + 2\,H_2O \\ 2\,NO_2^- + CH_3OH &\longrightarrow N_2 + CO_2 + H_2O + 2\,OH^- \\ &\text{total:} \\ 6\,NO_3^- + 5\,CH_3OH &\longrightarrow 3\,N_2 + 5\,CO_2 + 7\,H_2O + 6\,OH^- \end{aligned} \tag{2.3}$$

If an internal carbon source is used (simplified to $C_{18}H_{19}O_9N$), and the production of bacteria (biomass, simplified to $C_5H_7O_2N$) is included, we get the following total denitrification reaction:

$$0.65\,C_{18}H_{19}O_9N + 4.89\,NO_3^- + 4.89\,H^+ \longrightarrow C_5H_7O_2N + 2.27\,N_2 + 6.70\,CO_2 + 5.12\,H_2O \tag{2.4}$$

2.3. Activated Sludge (AS)

Activated Sludge is a suspended-growth process in which an "activated" mass of microorganisms is sustained within the reactor by recycling. There are several possible configurations of the AS process; in a single-stage system one reactor will perform both conversion of organic carbon and nitrification, typically followed by a settling tank from which "Return Activated Sludge" is transported back to the reactor. Alternatively, two separate reactors can be used, so that one reactor primarily removes large portions of the organic material before entering the nitrifying reactor. However, this requires individual settling tanks to return sludge to each reactor and makes it a costly option.

2.3.1. Kinetics

Growth rate

The net growth of microorganisms is evaluated by a few simple equations. The rate of growth of a bacterial culture can be expressed by

$$r_g = \mu X \tag{2.5}$$

where

r_g	rate of growth, mass per unit time and volume
μ	specific growth rate, time^{-1}
X	concentration of bacteria, mass per unit volume

When the growth is substrate-limited, for example by ammonia, the substrate will be depleted and growth will cease. The Monod-expression has been experimentally shown to fit well:

$$\mu = \mu_m \frac{S}{K_s + S} \tag{2.6}$$

where

μ_m	maximum specific growth rate, time^{-1}
S	concentration of growth-limiting substrate, mass per unit volume

K_s half-velocity constant; substrate constant at one half of the maximum growth rate, mass per unit volume

Thus the growth rate can be written

$$r_g = \frac{\mu_m X S}{K_s + S} \tag{2.7}$$

The amount of substrate consumed to produce a certain amount of bacterial cell mass can be defined as:

$$r_{su} = -\frac{\mu_m X S}{Y(K_s + S)} \tag{2.8}$$

where

r_{su} substrate utilization rate, mass per unit time and volume

Y maximum yield coefficient, mass cell produced per mass substrate consumed

By substituting μ_m/Y with the constant k in equation 2.8 we can write:

$$r_{su} = -\frac{kXS}{K_s + S} \tag{2.9}$$

Endogenous decay must be taken into account when evaluating the net growth of cells, as not all cells are in the state of growth at all times. An endogenous decay rate can be defined as

$$r_d = -k_d X \tag{2.10}$$

where

r_d endogenous decay rate, mass per unit time and volume

k_d endogenous decay coefficient, time^{-1}

X concentration of bacteria, mass per unit volume

We can then write the net growth rate of cells as

$$r_g^{'} = \frac{\mu_m X S}{K_S + S} - k_d X \tag{2.11}$$

$$r_g^{'} = -Y r_{su} - k_d X \tag{2.12}$$

where

$r_g^{'}$ net growth rate of bacterial cells, mass per unit time and volume

Temperature effects

Temperature has a profound influence on the growth rate of bacteria, not only by affecting the metabolism of cells, but by changing gas diffusion rates and sludge settling quality. The temperature dependence for a biological process is written:

$$r_T = r_{20}\Theta^{(T-20)} \tag{2.13}$$

where

r_T	rate at temperature T
r_{20}	rate at temperature of 20 °C
Θ	coefficient of temperature-activity

Mass balance

This section describes the mass balance of the substrate and bacteria for a complete-mix reactor with recycling, as shown in figure 2.2. This is a typical single-stage Activated-Sludge system which recycles sludge to sustain solids and wastes net growth from the recycle line.

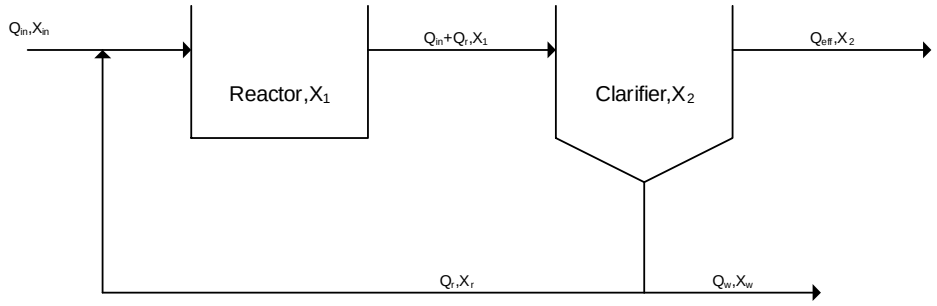

Figure 2.2.: Single-stage Activated Sludge process

There are a few assumptions about this model:

1. There are no microorganisms in the influent wastewater.
2. Negligible nitrification and oxidization occurs in the settling unit (clarifier).
3. In the calculation of the mean cell-residence time, only the volume of the reactor is included.

The mean cell-residence time, which expresses the mean time a bacteria is kept within the system, is defined as the mass of solids in the reactor, divided by the mass of solids removed from the system per day:

$$\theta_c = \frac{X \cdot V}{Q_e X_e + Q_w X_r} \tag{2.14}$$

where

θ_c	mean cell-residence time
X	solids concentration in reactor
V	volume of reactor
Q_e	effluent flowrate (influent flowrate − waste flowrate)
X_e	solids concentration in effluent
Q_w	flowrate of the wasted solids from the return line
X_r	solids concentration in return line

The mass balance of the system can be written as follows:

$$\frac{dX}{dt}V = Q_{in}X_{in} - (Q_e X_e + Q_w X_r) + V \cdot r_g^{'} \tag{2.15}$$

Now we can apply the assumption of zero microorganisms in the influent ($X_{in} = 0$), and steady-state condition ($\frac{dX}{dt} = 0$), while also substituting the growth rate $r_g^{'}$ with equation 2.12:

$$\frac{Q_w X + Q_e X_e}{V \cdot X} = -Y\frac{r_{su}}{X} - k_d \tag{2.16}$$

The left-hand side of this equation is the inverse of equation 2.14, $\frac{1}{\theta_c}$:

$$\frac{1}{\theta_c} = -Y\frac{r_{su}}{X} - k_d \tag{2.17}$$

The rate of substrate consumption, r_{su} is determined by a simple evaluation of the substrate concentration difference over the system, from influent to effluent:

$$r_{su} = -Q\frac{S_{\text{in}} - S_{\text{eff}}}{V} \tag{2.18}$$

where

S_{in},S_{eff}	substrate concentration in influent and effluent, respectively, mass per unit volume
Q	influent flowrate

With the *hydraulic retention time* for the reactor, defined as $\theta = \frac{V}{Q}$, we can express the mass concentration of the bacteria, X by substituting eq. 2.18 into eq. 2.17:

$$X = \frac{\theta_c}{\theta} \cdot \frac{Y\left(S_{\text{in}} - S_{\text{eff}}\right)}{1 + k_d\theta_c} \tag{2.19}$$

By evaluating a substrate balance as well, we can find the substrate concentration in the effluent:

$$S_{\text{eff}} = \frac{K_s(1 + k_d\theta_c)}{\theta_c(kY - k_d) - 1} \tag{2.20}$$

The observed, or actual, yield coefficient is then

$$Y_{\text{obs}} = \frac{Y}{1 + k_d\theta_c} \tag{2.21}$$

2.3.2. Dimensioning for nitrification

A common practice for determining necessary reactor volumes for an Activated-Sludge system is to set a desired sludge age, θ_c and determine the *sludge production* based on this. Sludge production is a result several mechanisms, for example:

1. Heterotrophic growth, from the conversion of organic matter
2. Autotrophic growth, from nitrification
3. Non-biodegradable suspended solids, from the influent wastewater
4. Chemical precipitation

The actual BOD and nitrification yield coefficients varies with sludge age and temperature, but as an example one can set constant coefficients for a preliminary study:

$$\Pi = 0.4 \cdot \text{SS}_{\text{in}} + 0.6 \cdot \text{BOD}_{5,\text{in}} + 0.15 \cdot \text{NH}_4\text{–N}_{\text{consumed}} + 3\,\frac{\text{g SS}}{\text{g Fe}/\text{m}^3} \tag{2.22}$$

where each factor is the yield coefficient and

Π Sludge Production

Another method of determining the sludge production rate is proposed in the German standard ATV-A 131, which is dependent on temperature, influent BOD and Suspended Solids concentrations. It also dependent on the sludge age, which means that sludge production and sludge age are implicit, but can easily be solved by iteration.

$$
\begin{aligned}
\Pi &= B_{\mathrm{BOD}} \cdot \left(0.75 + 0.6 \cdot \frac{X_{\mathrm{SS}}}{C_{\mathrm{BOD}}} - \frac{(1-0.2)\cdot 0.17 \cdot 0.75 \cdot \theta_c \cdot \mathrm{F_T}}{1 + 0.17 \cdot \theta_c \cdot \mathrm{F_T}}\right) \\
\mathrm{F}_T &= 1.072^{(T-15)} \\
&\Downarrow \\
\Pi &= B_{\mathrm{BOD}} \cdot \left(0.75 + 0.6 \cdot \frac{X_{\mathrm{SS}}}{C_{\mathrm{BOD}}} - \frac{0.102 \cdot \theta_c \cdot 1.072^{(T-15)}}{1 + 0.17 \cdot \theta_c \cdot 1.072^{(T-15)}}\right)
\end{aligned} \tag{2.23}
$$

$$
\theta_c = \frac{V_n \cdot X_L}{\Pi} \tag{2.24}
$$

Π	sludge production [kg/d]
B_{BOD}	BOD load [kg (BOD_5)/d]
X_{SS}	concentration of Suspended Solids in inlet [mg/L = g/m³]
C_{BOD}	concentration of BOD in inlet [g/m³]
$\mathrm{F_T}$	temperature correction factor
θ_c	sludge age (mean cell-residence time) [d]
V_n	volume of nitrification tank [m³]
X_L	concentration of MLSS (in reactor) [kg/m³]

A design concentration of suspended solids in the nitrifying reactor (MLSS, X_L) must be fed into the equation. Finally a recursive relationship with the reactor volume is required to solve this equation set. The volume is found from the definition of the sludge age, see eq. 2.14:

$$
V_n = \frac{\theta_c \cdot \Pi}{X_L} \tag{2.25}
$$

2.3.3. Dimensioning for denitrification

This section will briefly describe the method of determining necessary volume of a denitrifying AS reactor and will narrowly cover only single-stage combined sludge as pre-denitrification.

Combined sludge refers to the ability of an Activated-Sludge to perform several tasks simultaneously, such as bulk BOD removal, nitrification and denitrification. In this case, the AS reactor discussed will perform BOD-removal and denitrification by . *Pre-denitrification* involves the placement of the denitrifying reactor upstream of the serially connected nitrification reactor and pumping nitrified wastewater up to the denitrification reactor. By this method the DN-reactor will be supplied with organic matter from the raw wastewater and nitrates in the return liquid from the N-reactor.

Prerequisites for denitrification

To sustain denitrification, ammonium must have been converted to nitrates and an adequate amount of carbonaceous organic matter must be present for the conversion of nitrates to nitrogen gas. To check whether there is enough carbon present, the C/N ratio is defined as:

$$^{\mathrm{C}}/_{\mathrm{N}} = \frac{\text{kg COD}_{\text{soluble}}}{\text{kg NO}_{\text{x}}\text{–N}} \tag{2.26}$$

where

$\mathrm{NO_x}$–N nitrates to be consumed in denitrification reactor

Naturally it also viable to use BOD instead of $\mathrm{COD_{soluble}}$ here, as BOD more precisely reflects the readily available carbon. However, it is important to realize that the denitrification rate depends on the biodegradability of the organic material. It is reasonable to assume that when only using wastewater as the carbon source, soluble organic material is primarily consumed, before particulate material is hydrolyzed and can be used in the denitrification.

The denitrification consumes organic matter (COD) by three mechanisms:

1. Conversion of nitrates to $\mathrm{N_2}$, denitrification, Φ_{DN}
2. Sludge Production (cell growth), Φ_{SP}
3. Endogenous respiration, $\Phi_{\mathrm{O_2}}$

where Φ denotes the consumption of COD. These are defined as:

$$\begin{aligned}
\Phi_{\mathrm{DN}} &= 2.86\,{}^{\text{kg COD}}/_{\text{kg NO}_3\text{–N}_{\text{removed}}} && (2.27)\\
\Phi_{\mathrm{SP}} &= Y \cdot (\text{kg COD}_{\text{substrate}}) && (2.28)\\
\Phi_{\mathrm{O_2}} &= 1\,{}^{\text{kg COD}}/_{\text{kg O}_2} && (2.29)\\
\Phi_{\mathrm{Total}} &= \Phi_{\mathrm{DN}} + \Phi_{\mathrm{SP}} + \Phi_{\mathrm{O_2}} && (2.30)
\end{aligned}$$

where

Y yield coefficient $\frac{\text{kg COD}_{\text{biomass}}}{\text{kg COD}_{\text{substrate}}}$

The amount of nitrogen that will be removed in denitrification is the sum of the denitrification itself, and assimilation of nitrogen into the cell growth:

$$\nu_{\mathrm{Total}} = \nu_{\mathrm{DN}} + \Phi_{\mathrm{SP}} \cdot f_{\mathrm{N}} \tag{2.31}$$

where

Carbon source	U_{DN}, $\frac{\text{g } NO_3\text{-N}}{\text{g VSS d}}$	T, °C
Methanol	0.21-0.32	25
Methanol	0.12-0.90	20
Wastewater	0.03-0.11	15-27
Endogenous metabolism	0.017-0-048	12-20

Table 2.1.: Specific denitrification rates for different carbon sources

ν_{Total}	Total nitrogen consumption in denitrification process
ν_{DN}	Nitrogen consumption by conversion (denitrification)
f_{N}	Fraction of nitrogen in biomass (typically 0.07 $\frac{\text{kg N}}{\text{kg COD}_{\text{biomass}}}$)

The C/N ratio necessary for denitrification is then

$$\mathrm{C}/\mathrm{N} = \Phi_{\mathrm{Total}}/\nu_{\mathrm{Total}} \tag{2.32}$$

Denitrification rate

Metcalf & Eddy proposes the following denitrification rate[1]:

$$U'_{\mathrm{DN}} = U_{\mathrm{DN}} \cdot 1.09^{(T-20)}(1 - \mathrm{DO}) \tag{2.33}$$

where

U'_{DN}	Actual denitrification rate
U_{DN}	Specific denitrification rate
T	Temperature [°C]
DO	Dissolved Oxygen in reactor $[\frac{\text{mg}}{\text{L}}]$

The actual denitrification rate is obviously dependent on temperature and oxygen concentration. The denitrification process, as described in section 2.2, is anoxic and according to this model the denitrification rate will linearly decrease to zero with increasing DO up to 1 $\frac{\text{mg}}{\text{L}}$. Additionally, the specific denitrification rate is dependent on the source of organic content available to the bacteria, see table 2.1.

Given an incoming wastewater to a denitrification reactor at a temperature of 15 °C and using the lower end of the "wastewater rate" in table 2.1, equation 2.33 yields:

[1] Metcalf & Eddy [1], pp. 712-713

$$U'_{\mathrm{DN}} = 0.03 \cdot 1.09^{(15-20)} = 0.019 \left[\frac{\text{g } NO_3\text{–N}}{\text{g VSS d}}\right] \tag{2.34}$$

Prof. Ødegaard in [2] presents various methods of determining denitrification rate, based on experience from pilot plants in Denmark and Sweden and the German ATV-standard. According to Danish standards, a "good" wastewater, containing large amounts of easily biodegradable organic matter, a denitrification rate of $1\ \frac{\text{mg } NO_3\text{–N}}{\text{g VSS h}} = 0.024\ \frac{\text{g } NO_3\text{–N}}{\text{g VSS d}}$ is a commonly used value, assuming a C/N ratio $> 4.04.5\ \frac{\text{kg } BOD_5}{\text{kg } N_{\text{denitrified}}}$.

2.4. Moving Bed Biofilm Reactor (MBBR)

The MBBR^{TM}process is a recently developed biofilm process originally developed and patented by the company Kaldnes Miljøteknologi, now known as Krüger Kaldnes AS. The MBBR is based on small plastic carriers on which the biofilm grows. These carriers provide a very high surface area and enables complete mixing of the liquid and carriers to provide a homogeneous distribution of nutrients and biofilm alike, as their efficient density (with biofilm attached) is very similar to water. A sketch of typical biocarrier designs is seen in figure 2.3, with a Chip-type on the left and a K-type carrier on the right. The Chip design provides a higher specific surface area, but is more expensive to produce, so in many cases it is more economical to use a K-type carrier, while providing the necessary treatment.

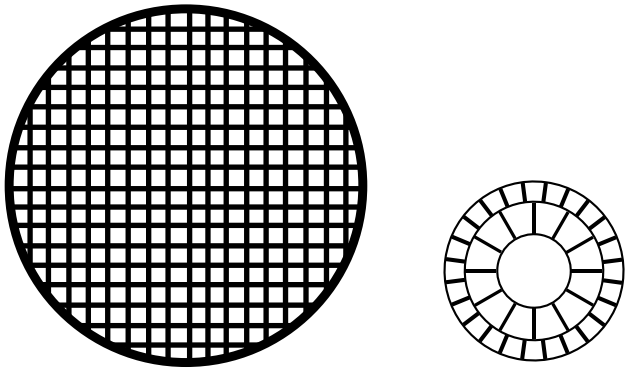

Figure 2.3.: Sketch of typical biofilm carrier design

2.4.1. Biofilm

In an attached-growth process, the bacteria grow into a "film" on a surface. When the bacteria encounter a surface, they attach and start producing an *Extracellular polymeric substance* (EPS), a polysaccharide, which envelops the bacteria, allowing them to form complex 3-dimensional structures, see figure 2.4. These "colonies" can contain many

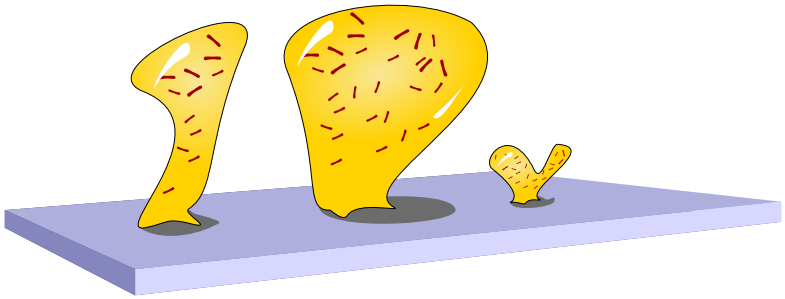

Figure 2.4.: Bacteria attaching to a surface

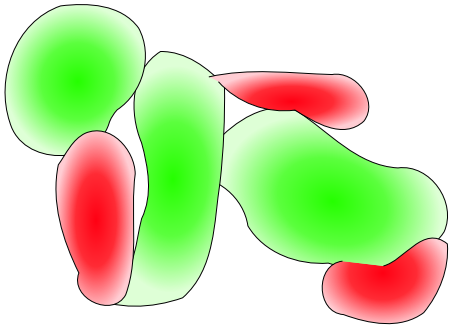

Figure 2.5.: *Nitrobacter* (red) grow onto clusters of *Nitrosomonas* (green).

different bacteria as well as fungi and other microorganisms. In the case of a nitrifying biofilm, it is shown that the *Nitrobacter*, the nitrite-oxidizing bacteria, grow in clusters around distinct clusters of *Nitrosomonas*, the ammonia-oxidizers, as roughly sketched in figure 2.5 [3, 4] [2]. This configuration leads to consumption of ammonia and oxygen at the biofilm surface, and the simultaneous production and consumption of nitrite slightly below the biofilm surface.

The rates of consumption associated with biofilm is completely dependent on the rate at which nutrients, electron carriers and products can diffuse in and out of the biofilm, or the actual EPS. Figure 2.6 shows a sketch of the ideal model used to describe the behavior of a biofilm. In the biofilm itself there is only diffusive transport, as is the case with a stagnant fluid film resting on the biofilm. Free-flowing fluid outside this film; the wastewater liquid, transports the nutrients, carbon dioxide and oxygen, electron acceptor and donor, through the fluid film and into the biofilm where the reaction takes place. Since the consumption rate of a substrate can be higher than the diffusive transfer rate, we can get limiting concentration profiles (*substrate limited*) inside the biofilm, depending on the concentration of the substrate in the fluid phase and on the thickness of the biofilm, and other factors, like the temperature influencing the metabolism of the bacteria. If all substrates are in excess all the way to the bottom of the biofilm we have

[2] Observed in [5]

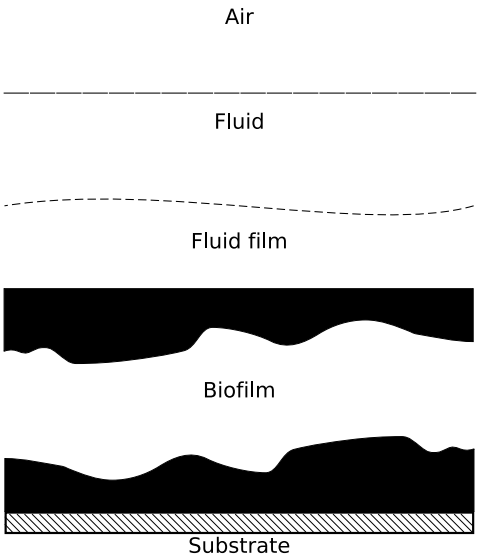

Figure 2.6.: Simplified biofilm model

a "full penetration" and a *biofilm limited* condition.

2.4.2. Dimensioning for nitrification

There are three factors influencing the nitrification rate:

1. Organic matter loading, which influences the amount of nitrifying bacteria in the biofilm
2. Oxygen concentration in the free liquid, which determines the penetration depth of oxygen in the biofilm and limits the nitrification rate
3. Ammonium concentration in the free liquid, which also determines penetration depth of ammonium and limits nitrification rate

It is problematic to estimate or define the depth of the biofilm, so it is common practice to use the surface area available to the biofilm as a dimensioning parameter and the nitrification rate for a biofilm is usually defined in the unit of $\frac{\text{g } NH_4\text{–N}}{\text{m}^2\text{d}}$.

Influence of organic load

Organic matter present in the wastewater increases the growth of heterotrophic matter and will compete with the autotrophic, nitrifying, bacteria for oxygen. Higher organic load leads to a thicker layer of heterotrophic bacteria in the biofilm and limits the nitrification. Experiments have shown that the organic surface load should not be higher than 10-15 $\frac{\text{g COD}}{\text{m}^2\text{d}}$ (or 5-10 $\frac{\text{g BOD}}{\text{m}^2\text{d}}$) in order to avoid nitrification becoming limited by organic matter, under the assumption that oxygen is not a limiting factor.

Influence of oxygen and ammonium

As mentioned in section 2.1, the influence of oxygen on the nitrification rate is more profound in an attached-growth process than suspended-growth, as a result of the diffusive resistance in the biofilm. Normally, for an ammonium-concentration higher than 3 $^{mg}/_{L}$, oxygen is the limiting factor.

The nitrification rate for a biofilm is given by the equation:

$$r_n = k \cdot (S_n)^n \tag{2.35}$$

where

r_n	nitrification rate, $\left[\frac{\text{g } NH_4\text{–N}}{m^2 d}\right]$
k	constant dependent on BOD load, i.e. the treatment process upstream the MBBR reactor
S_n	rate-determining ammonium concentration
n	reaction order constant

The rate-determining ammonium concentration, S_n, is the lower value of two possibilities:

1. Actual ammonium concentration in reactor
2. Transitional ammonium concentration, $S_{n,\text{trans}}$

The *transitional ammonium concentration* is the value at which point the nitrification is no longer limited by ammonium, but of the oxygen in the reactor, as defined by the following equation:

$$S_{n,\text{trans}} = \frac{\text{DO} - \text{DO}_{\text{depletion}}}{\left({}^{\text{DO}}/_{NH_4\text{–N}}\right)_{\text{biofilm, transition}}} \tag{2.36}$$

where

DO	Dissolved Oxygen in the bulk liquid
$\text{DO}_{\text{depletion}}$	DO depleted through the heterotrophic layer of the biofilm

The DO-to-ammonium ratio is that which occurs at the said transition from being limited by ammonium to being oxygen-limited and is set to equal 3.2 according to literature by Kaldnes. The $\text{DO}_{\text{depletion}}$ will be influenced by BOD load and other factors that determine the growth of the bacteria, but a good initial guess is to set it at 0.5 $^{mg}/_{L}$ for low soluble BOD concentrations, but can vary in the range of 0.52.0 $^{mg}/_{L}$. So equation 2.36 is simplified to:

$$S_{n,\text{trans}} = \frac{\text{DO} - 0.5\,{}^{\text{mg}}/_{\text{L}}}{3.2} \tag{2.37}$$

So if the actual ammonium concentration in the reactor is higher than $S_{n,\text{trans}}$, then $S_n = S_{n,\text{trans}}$, otherwise, $S_n =$ actual ammonium concentration.

When the nitrification rate is known, and the required efficiency of the reactor is specified, then the required surface area for the biofilm is known. The available area for the biofilm is dependent on the type of plastic carrier used and how many. The bulk volume required for the specified nitrification is then found by:

$$\text{Volume} = \frac{\left(\text{nitrification rate } \left[\frac{\text{g } NH_4\text{–N}}{\text{m}^2\text{d}}\right]\right)}{\left(\text{Specific area } \left[\frac{\text{m}^2}{\text{m}^3}\right]\right) \cdot \left(\text{Required removal rate } \left[\frac{\text{g } NH_4\text{–N}}{\text{d}}\right]\right)}$$

3. The HYBAS model

The HYBAS model is intended as an intuitive approach to estimating the treatment efficiency of a HYBAS process. When modeling the reactor containing both suspended biofilm carriers and Activated-Sludge, the Suspended Solids and Biofilm are treated separately, with best of knowledge applied to each system. One parameter connects the MLSS and Biofilm, which reduces the nitrification rate in the biofilm, according to experimental observations.

This section presents the entire HYBAS dimensioning model by detailed wording and a few modifications from the original document by Prof. Hallvard Ødegaard. Small typing errors and possible misunderstandings have been attempted to remedy. Some brief comments on selected *steps* are included.

The model is to be interpreted as an example of a dimensioning procedure for a HYBAS process, as this outline is not general in form. Figure 3.1 illustrates the process being exemplified in this model:

- Untreated wastewater enters an Activated-Sludge denitrification reactor
- A hybrid nitrification reactor follows, with plastic biofilm carriers suspended in Activated-Sludge
- *Return Liquor* is pumped from the effluent of the second reactor, back to inlet of the first reactor
- A settling tank separates sludge before the final system effluent
- Return Activated-Sludge is pumped from the settling tank, back to the inlet of the first reactor

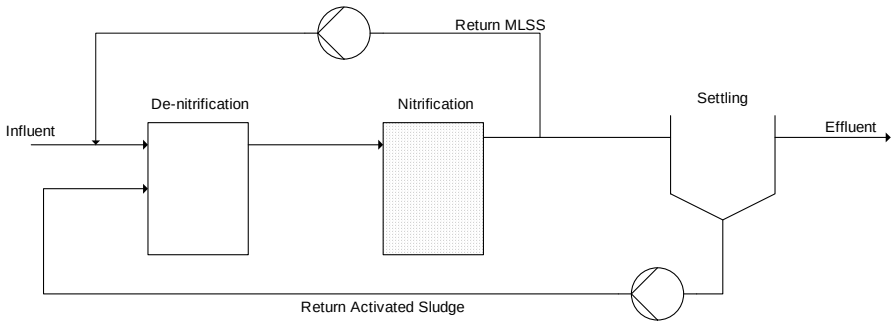

Figure 3.1.: HYBAS process with denitrification and nitrification

The entire dimensioning method, or algorithm, is divided into logical *steps* and the original model as described by Prof. Ødegaard was completely uni-directional. That is, the algorithm flowed from Step 1 to Step 15 with no back-tracking. Modifications to the model breaks this work flow from Step 7, in order to incorporate new functions and flexibility in the model. The practical implications of the directionality-break is minimal since the model is implemented in an Excel spreadsheet.

Overview

1. Calculate amount of NH_4^+-N and NO_3-N that must be nitrified and denitrifed, respectively.
2. Find necessary recycle ratios of RAS and RSS (Return Suspended Solids, from effluent of nitrification reactor) and determine amount of nitrate to be removed in the denitrification tank, taking into account oxygen supply from RSS and the effect this has on the denitrification rate.
3. Calculate organic material consumed during denitrification
4. Calculate total sludge production
5. Calculate denitrification-rate
6. Calculate volume of denitrification tank
7. Calculate volume of nitrification tank. *Design changes break work flow here as this step depends on information from* future *steps.*
8. Determine nitrification rate of MLSS
9. Determine sludge age for the aerobic MLSS
10. Determine ammonium that can be removed by MLSS
11. Determine ammonium that must be removed by *biofilm*
12. Determine maximum nitrification rate of biofilm
13. Determine *actual* nitrification rate of biofilm
14. Determine required biofilm area
15. Determine filling fraction

3.1. Step 1

First we must define the allowed nitrogen content of the effluent (or biological reactor outlet). It is assumed that the total nitrogen content of the influent will be completely converted to ammonia-nitrogen (NH_4-N). Part of the nitrogen will also be assimilated

at the amount of $0.04\,\frac{\text{kg N}}{\text{kg BOD}_{5,\text{load}}}$. A user-specified criteria of Total Kjeldal Nitrogen (TKN) in the effluent can be specified in the model, but

$$\text{NH}_4\text{-N}_{\text{nitrified}} = \text{Tot N}_{\text{in}} - 0.04 \cdot \text{BOD}_{5,\text{in}} \tag{3.1}$$

$$\text{NO}_3\text{-N}_{\text{denitrified}} = \text{NH}_4\text{-N}_{\text{nitrified}} - \text{NO}_3\text{-N}_{\text{out}} - \text{TKN}_{\text{effluent}} \tag{3.2}$$

Total Kjeldal Nitrogen (TKN) is the total amount of nitrogen in the form of ammonia or organic nitrogen, as measured by the Kjeldal method[1].

3.2. Step 2

In this step, we determine how much nitrate-nitrogen (NO_3-N) and its equivalents (from oxygen depletion) is to be consumed in the denitrification tank, depending on if we have the denitrification tank before or after the processes that remove organic material.

3.2.1. Pre-denitrification

1. Necessary treatment efficiency

$$R = \frac{\text{Tot N}_{\text{in}} - \text{Tot N}_{\text{out}}}{\text{Tot N}_{\text{in}}} \tag{3.3}$$

2. Total recirculation ratio:

$$r \approx \frac{1}{1 - R} \tag{3.4}$$

3. Return Sludge (RS) ratio:

$$r_{\text{RS}} = \frac{Q_{\text{RS}}}{Q_{\text{in}}} \tag{3.5}$$

4. Mixed-Liquor Suspended Solids, Return Liquor (RL) ratio:

$$r_{\text{RL}} = \frac{Q_{\text{RL}}}{Q_{\text{in}}} = r - r_{\text{RS}} \tag{3.6}$$

And to clarify, we also define the flow rates of the RL and RS:

- $Q_{\text{RL}} = r_{\text{RL}} \cdot Q_{\text{in}}$
- $Q_{\text{RS}} = r_{\text{RS}} \cdot Q_{\text{in}}$

[1]The Kjeldal method implies the digestion of organic nitrogen and conversion into ammonia

where Q_{in} is the flow rate into the biological process train we are designing.

It assumed that the Return Sludge contains no oxygen. Oxygen in the recirculated Mixed-Liquor will inhibit the denitrification process because the heterotrophic bacteria prefer oxygen as the electron acceptor and thus they cannot perform denitrification simultaneously. This makes it necessary to increase the volume of the denitrification tank and this model resolves this by a "virtual" increase in the amount of $NO_3{-}N$ that is to be consumed, on top of the nitrates from the nitrification tank. Oxygen concentration in the recycled MLSS can be specified in the model as a fraction of the oxygen content in the aerated tank; a typical value is 1/2.

- Oxygen depletion equivalents:

$$(NO_3\text{-}N)_{O_2} = r_{\text{RL}} \cdot Q_{\text{in}} \cdot 0.35 \cdot 1/2 \cdot \text{DO}_{\text{Aeration tank}} \tag{3.7}$$

where DO is the *Dissolved Oxygen*. The factor $(1/2 \cdot \text{DO}_{\text{Aeration tank}})$ can be recognized as the assumed oxygen concentration in the Return Activated Sludge (RAS).

The total amount of $NO_3{-}N$ and its equivalents to be consumed in the denitrification tank is the sum of the necessary treatment amount, found in Step 1, and the oxygen depletion equivalents, which effectively increases the necessary volume of the denitrification tank:

$$(NO_3{-}N)_{\text{equiv, tot}} = NO_x{-}N = (NO_3{-}N)_{NO_3} + (NO_3{-}N)_{O_2} \tag{3.8}$$

Comments

An alternative method to account for the oxygen depletion is presented in the comments in Step 5.

3.3. Step 3

In this step we will determine how much organic matter (BOD/COD) is consumed in the denitrification tank. BOD is consumed for both the denitrification process and oxygen respiration as well as for the biomass (sludge) production. Denitrification and oxygen respiration effects are combined in $NO_3{-}N_{\text{equiv,tot}}$ from Step 2.

$$\begin{aligned} C_{\text{denitrification}} &= 2.86 \cdot NO_3{-}N_{\text{equiv, degraded}} \\ C_{\text{SP,COD}} &= Y_{NO_3} \cdot NO_3{-}N_{\text{equiv, degraded}} \end{aligned}$$

where Y_{NO_3} is the *yield coefficient* correlating sludge production and *consumed organic matter* (in unit of $\frac{COD_{biomass}}{NO_3{-}N_{equiv,degraded}}$). The yield coefficient in this model is by default set to 1.4 [kg biomass produced per kg $NO_3{-}N$ consumed], which is based on an assumed yield of 0.4 (kg biomass produced per kg organic matter consumed) and the stoichiometric equation 2.4. The index *degraded* refers to the carbonaceous matter that has been biodegraded, since not all organic material is easily degradable or even soluble.

So the total consumption of biodegradable COD is:

$$\begin{aligned} C_{tot} &= 2.86 \cdot NO_3{-}N_{equiv,\ degraded} + 1.4 \cdot NO_3{-}N_{equiv,\ degraded} \\ C_{tot}\left[\frac{\text{kg } COD_{biodegradable}}{d}\right] &= 4.26 \cdot NO_3{-}N_{equiv,\ degraded} \end{aligned} \tag{3.9}$$

We can express this parameter as a consumption of BOD_5 instead, as illustrated in Appendix section A.1.1:

$$COD_{biodegradable} = 2.19 \cdot BOD_5$$

So equation 3.9 becomes:

$$\begin{aligned} C_{tot}\left[\frac{\text{kg } BOD_5}{d}\right] &= \left(\frac{4.26}{2.19}\right) \cdot NO_x{-}N_{removed} \\ &= 1.9 \cdot NO_x{-}N_{removed} \end{aligned} \tag{3.10}$$

3.3.1. C/N control

We must check that there is enough (biodegradable) organic matter in the denitrifying reactor to sustain denitrification. The necessary ratio is determined to be > 5, as represented by figure 3.2, otherwise the denitrification rate will not be optimal. The control is defined as:

$$\text{Incoming C/N: } \frac{BOD_{in}}{NO_x{-}N_{removed}} > 5 \tag{3.11}$$

3.4. Step 4

This section determines the total amount of sludge (biomass) produced. Two alternative methods are available.

Source	Value
1. Inert	40 % of incoming SS
2. BOD	$0.6\,\mathrm{g\ TSS/g\ BOD_5}$
3. NH_4-N	$0.15\,\mathrm{g\ TSS/g\ NH_4{-}N}$
4. Chemical	$3\,\mathrm{g\ TSS/g\ Fe}$ and $5\,\mathrm{g\ TSS/g\ Al}$

Table 3.1.: Typical sizes of sludge sources

3.4.1. Standard method

Sludge production has *four* sources:

1. Inert and non-biodegradable parts of the incoming suspended solids
2. BOD load
3. Ammonium ($NH_4{-}N$) load (not including assimilation)
4. Chemical sludge precipitation caused by addition of iron or aluminium

Typical quantitative values of these factors are given in table 3.1.

3.4.2. ATV-A 131 method

This method defines the sludge production rate as a function of BOD_5 load, the ratio between sludge and BOD concentrations in the inlet, sludge age and temperature. Sludge age is again a function of the Sludge Production, so an iterative procedure is used to solve both sludge age and production rate:

$$\begin{aligned} \Pi &= B_{\mathrm{BOD}} \cdot \left(0.75 + 0.6 \cdot \frac{X_{\mathrm{SS}}}{C_{\mathrm{BOD}}} - \frac{(1-0.2)\cdot 0.17 \cdot 0.75 \cdot \theta_c \cdot \mathrm{F_T}}{1 + 0.17 \cdot \theta_c \cdot \mathrm{F_T}}\right) \\ \mathrm{F}_T &= 1.072^{(T-15)} \\ &\Downarrow \\ \Pi &= B_{\mathrm{BOD}} \cdot \left(0.75 + 0.6 \cdot \frac{X_{\mathrm{SS}}}{C_{\mathrm{BOD}}} - \frac{0.102 \cdot \theta_c \cdot 1.072^{(T-15)}}{1 + 0.17 \cdot \theta_c \cdot 1.072^{(T-15)}}\right) \end{aligned} \tag{3.12}$$

$$\theta_c = \frac{V_n \cdot X_L}{\Pi} \tag{3.13}$$

Π sludge production [kg/d]

B_{BOD} BOD load [kg (BOD_5)/d]

X_{SS} concentration of Suspended Solids in inlet [mg/L = g/m³]

C_{BOD} concentration of BOD in inlet [g/m³]

F_T	temperature correction factor
θ_c	sludge age (mean cell-residence time) [d]
V_n	volume of nitrification tank $[m^3]$
X_L	concentration of MLSS (in reactor) $[kg/m^3]$

Comments

This Step is implemented as *Step 16* in the Excel spreadsheet.

3.5. Step 5

In this section we determine the rate of denitrification. This is dependent on the C/N ratio $\left[\frac{BOD_{in}}{NO_x\text{-}N_{removed}}\right]$ as found in Step 3 (3.3.1). Figure 3.2shows the design approach to nitrification rate. With plentiful carbon source, the DN-rate is set to 3 $\frac{g\ NO_x\text{-}N}{kg\ MLSS \cdot h}$:

$$\text{DN-rate} = \begin{cases} 3 & \text{for C/N} \geq 5 \\ 0.2 + \frac{14}{15}\,(\text{C/N} - 2) & \text{for } 2 < \text{C/N} < 5 \\ 0.2 & \text{for C/N} \leq 2 \end{cases} \tag{3.14}$$

The MLSS concentration must be chosen, and given as a user input in 'Design Parameters'. If upgrading an existing Active Sludge plant, the original MLSS concentration can be used. In the case of a green-field plant design, the required MLSS concentration is determined by settling tank design.

Comments

An alternative approach here would be to use Eq. 2.33 and to include the oxygen in the Return Liquor directly in the estimation of the denitrification rate, thus replacing "oxygen depletion equivalents" in Step 2, and giving the model a more intuitive outline.

3.6. Step 6

Determining the volume of the de-nitrification tank.

$$V_{DN} = \frac{(NO_x\text{-}N)_{consumed}}{X_L \cdot r_{DN}} \tag{3.15}$$

V_{DN}	Volume denitrification tank $[m^3]$
X_L	MLSS concentration $[kg\ MLSS/m^3]$
r_{DN}	rate of denitrification $[kg\ NO_x\text{-}N/kg\ MLSS \cdot h]$

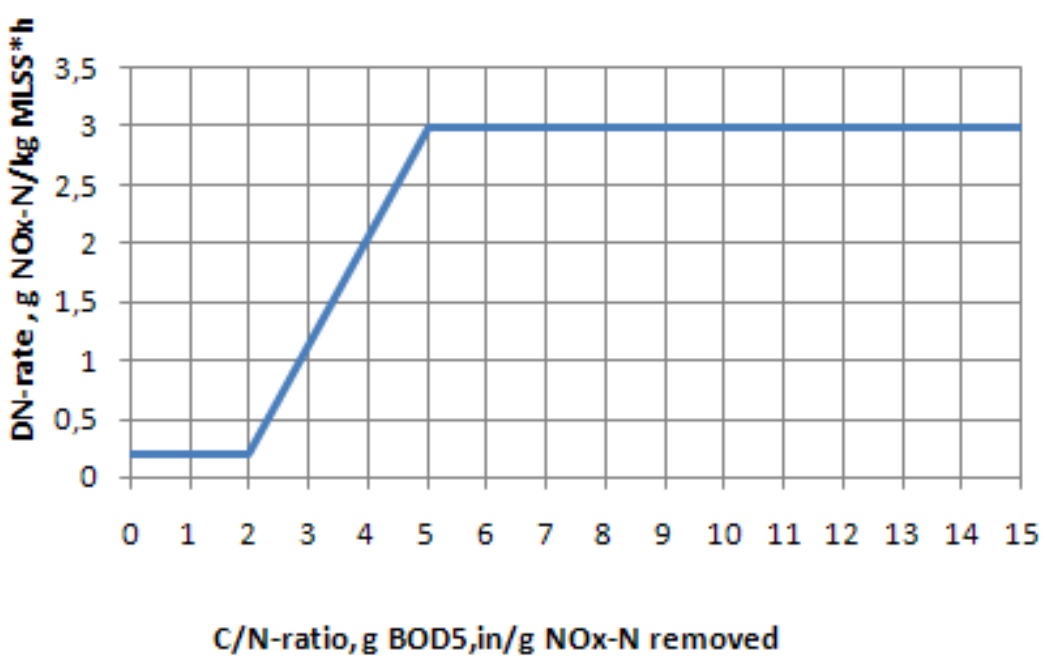

Figure 3.2.: Design denitrification rate as a function of C/N ratio

3.7. Step 7

Determining the volume of the nitrification tank. This step should be able to calculate the volume for both cases of upgrade or green-field design, so it might be moved.

3.7.1. Upgrade volume

If the plant is to be upgraded, a total available volume will be given and we can simply subtract the volume of the denitrification tank which we found in the previous step:

$$V_{nitrif} = V_{total} - V_{DN} \tag{3.16}$$

3.7.2. Green-field volume

If the model is to be used on a green-field design, we can determine the necessary nitrification volume based on a specified carrier filling fraction, or on a *design SRT*.

Design SRT

By specifying a desired Sludge Retention Time (SRT), or Sludge Age, we can simply calculate the required nitrification volume by using equation 3.20, solving for V_N:

$$V_N = \frac{SRT_{design} \cdot SP}{X_L} \tag{3.17}$$

Thus it is possible to continue solving the rest of the model as normal.

Filling fraction

Combining equations 3.21, 3.28, 3.29 and 3.30, we can express the necessary nitrification volume by:

$$V_N = \frac{M_{N,total}}{r_{NH_4,actual} \cdot (A_{K1} \cdot F) + r_{N,MLSS} \cdot X_L \cdot \left(\frac{24\,h/d}{1000}\right)} \tag{3.18}$$

$$V_N = \frac{M_{N,total}}{r_{NH_4,actual} \cdot (A_{K1} \cdot F) + r_{N,MLSS} \cdot X_L \cdot \left(\frac{24}{1000}\right)}$$

$$V_N = \begin{cases} V_{total,design} - V_{DN} & \text{for upgrade design} \\ \frac{SRT_{design} \cdot SP}{X_L} & \text{for green-field design} \end{cases}$$

3.8. Step 8

In this section we determine the nitrification rate in the MLSS. The rate will be dependent on relative amounts of autotrophic and heterotrophic biomass in the reactor, which in turn is dependent on the C/N ratio that the MLSS is exposed to. Because of recirculation and a steady-state assumption, the C/N ratio will be equal throughout the bioreactor train. Therefore we will use the known C/N ratio of the influent to find the nitrification rate. The correlation between C/N and nitrification rate used in this model, is presented in table 3.2 and illustrated in figure 3.3. In the model, Excel fits an exponential function to the given data. The function found for the data herein, is:

$$r = 5.9 \cdot 0.73^{C/N} \tag{3.19}$$

where r is the nitrification rate. This function *can* be used for determining the nitrification rate, but by default the model uses linear interpolation between the given data points. Updated correlation data can easily be implemented by replacing the data points

C/N	N-rate
0.5	6.00
1	4.75
2	3.10
3	2.10
4	1.50
5	1.10
6	0.80
7	0.70
8	0.65

Table 3.2.: C/N influence on nitrification rate

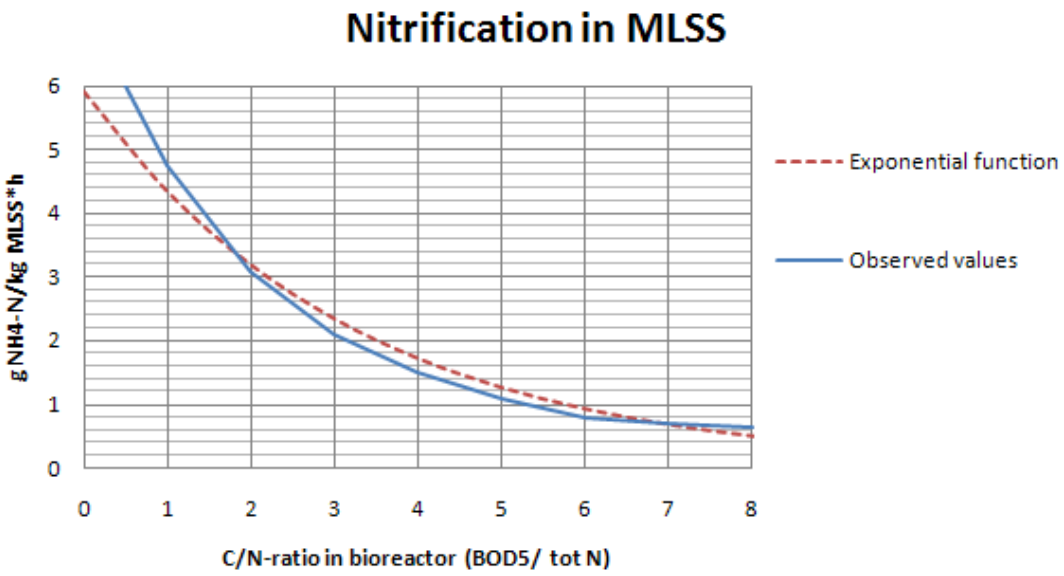

Figure 3.3.: Nitrification rate in MLSS

3.9. Step 9

This step determines the sludge age in the nitrification/aerobic tank:

$$\mathrm{SRT}_{\mathrm{MLSS}} = \frac{\mathrm{X_L} \cdot \mathrm{V_N}}{\mathrm{SP}} \tag{3.20}$$

SRT Sludge Retention Time (sludge age)

SP Sludge Production (rate)

Note that the ATV-A 131 method is applied in Step 16, which calculates a sludge based on a slightly different sludge production.

3.10. Step 10

Determining how much $NH_4{-}N$ is removed in the MLSS:

$$\mathrm{NH_4{-}N_{MLSS}}\ [\mathrm{kg\ N/d}] = \mathrm{r_{N,MLSS}} \cdot \left(24\,\frac{\mathrm{h}}{\mathrm{d}}\right) \cdot \mathrm{X_L} \cdot \mathrm{V_N} \tag{3.21}$$

3.11. Step 11

Determine how much ammonium ($NH_4{-}N$) needs to be removed by the biofilm:

$$\mathrm{M_{NH_4-N}}\ [\mathrm{kg\ N/d}] = \mathrm{M_{N,total}} - \mathrm{M_{N,MLSS}} \tag{3.22}$$

3.12. Step 12

This section determines the maximum nitrification rate in the biofilm. The following equation expresses the nitrification rate in the biofilm, which is dependent on the oxygen concentration and empirical coefficients (valid for a temperature of 10 °C):

$$\mathrm{r_{N,10}} = \mathrm{k} \cdot (\mathrm{S_n})^{\mathrm{n}}$$

where:

$$\mathrm{S_n} = \frac{\mathrm{DO} - \mathrm{DO_{depletion}}}{3.2} \tag{3.23}$$

$\mathrm{DO_{depletion}}$ "depletion dissolved oxygen" depends on organic load and MLSS concentration, and must be provided

C/N	k
0.5	0.700
1	0.650
2	0.590
3	0.550
4	0.520
5	0.490
6	0.475
7	0.460
8	0.450

Table 3.3.: Nitrification rate coefficient

k nitrification rate coefficient, dependent on C/N ratio in the aerobic reactor, correlation given by table 3.3 and figure 3.4.

The BOD load in the aerobic reactor is equal to the influent content, minus the BOD consumption in the denitrification reactor in the case of pre-denitrification;

$$\mathrm{BOD}_{\text{in, aerobic}} = \mathrm{BOD}_{\text{in}} - \mathrm{BOD}_{\text{consumed in DN}} \tag{3.24}$$

The C/N ratio is then:

$$(\mathrm{C/N})_{\text{aerobic}} = \frac{\mathrm{BOD}_{\text{in, aerobic}}}{\mathrm{NH_4{-}N}_{\text{in, aerobic}}} \tag{3.25}$$

A temperature correction from 10 to 15 °C is given by:

$$\mathrm{r}_{\mathrm{N},15} = 1.4 \cdot \mathrm{r}_{\mathrm{N},10} \tag{3.26}$$

Comments

See also section 2.4.2.

3.13. Step 13

There is empirical evidence of an interrelationship between the nitrification taking place in the biofilm and in the MLSS, which is dependent on the SRT MLSS. The higher the SRT MLSS, the lower the fraction of nitrification taking place in the biofilm. This has to be corrected for and it is proposed to use this corrected value for HYBAS design.

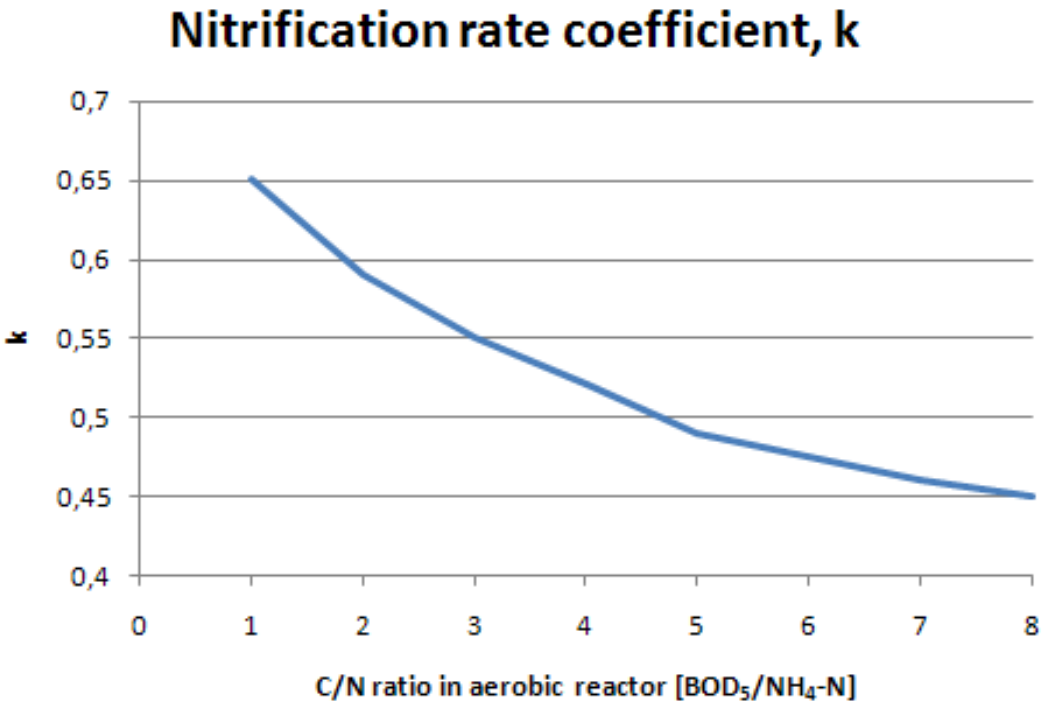

Figure 3.4.: Nitrification rate coefficient

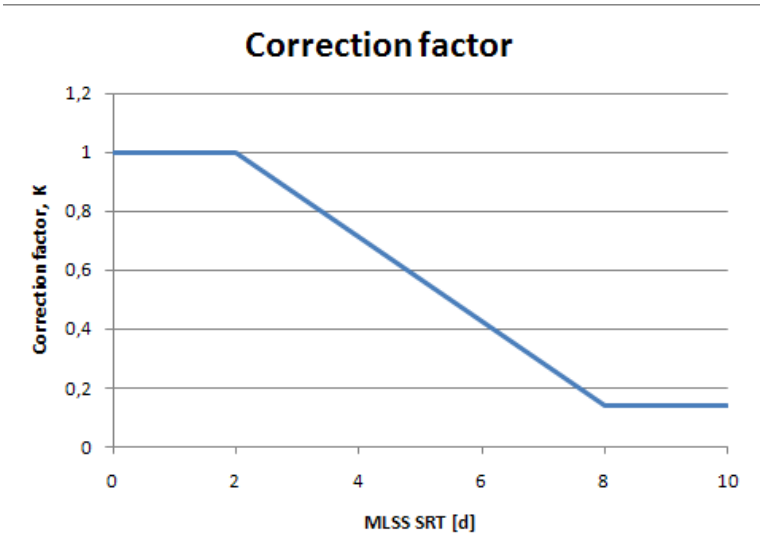

Figure 3.5.: Biofilm nitrification correction factor

The actual nitrification rate is determined by a simple correction factor, K, which depends on the C/N ratio. The relationship is presented in figure 3.5.

$$r_{NH_4-N,actual} = r_{NH_4-N,max} \cdot K \tag{3.27}$$

3.14. Step 14

Determining necessary biofilm area:

$$A_{biofilm} = \frac{M_{nitrified,\ tot}}{r_{NH_4,actual}} \tag{3.28}$$

$$A_{specific} = \frac{A_{biofilm}}{V_N} \tag{3.29}$$

3.15. Step 15

Determine filling fraction of reactor, depending on type of carrier.

Example With the K1 carrier, which has a specific area of $500\,m^{-1}$, the necessary filling fraction, F, of the nitrifying reactor would be:

$$F = \frac{A_{specific}}{500\,m^{-1}} \tag{3.30}$$

4. Excel HYBAS model

This section briefly describes the Excel HYBAS workbook which is created with basis in the work done on this project. A short "instruction manual" and some examples of the output from the model is shown. It is recommended, however, to open up the file and experiment to fully understand the workings.

4.1. Description

There are currently two versions of the HYBAS model:

1. HYBAS model-SRT
2. HYBAS model-FillingFraction

The difference between them is indicated in their names; in number 1, it is possible to choose a desired SRT when designing a "green-field" plant, while in number 2, you can use a desired filling fraction of biocarriers to determine the volume of the tanks, also when designing green-field plant. When upgrading an existing plant, only the total volume is available, both SRT and filling fraction is determined automatically.

The workbook file consists of 4 sheets with distinct functions:

1. **Design Parameters**
    a) Basic parameters about the plant to be designed is entered here; what comes in, and what should go out.
    b) Design intent is to move from *Design Parameters* directly to *Results*
2. **Calc**
    a) The calculation sheet, where the actual model resides, with a layout corresponding to the original presentation of the HYBAS model. It should be possible to modify the model itself from this sheet.
3. **Results**
    a) Intended as a practical place to collect interesting output from the model and do further calculations on the results.
4. **Parameter Study**

a) This sheet enables the ability to test variation of a chosen parameter and output selected results in a matching column.

b) Clicking on a variable name pops up a dropdown-list that is used to select the desired variable.

c) Clicking on the button "Study!" runs through the HYBAS model with the chosen parameter variation and outputs the result in two columns.

d) This sheet can be further expanded to include more advanced functions.

4.1.1. Variable names

It has been attempted to consistently give spreadsheet cells names, so for example, when referring to the design parameter *Average flow*, you can refer to "Q" instead of " 'Design Parameters'!D7 ", thus making formulas easier to read, and collecting information faster and more intuitive.

4.2. Parameter study example

The plant operator can control the concentration of the suspended solids in the reactor by wasting and controlling the recycle ratios. For a design SRT of 5 days, the effect this has on the required volume is plotted in figure 4.1.

By running the same X_L variation several times, we can copy the resulting column and collect them to plot several parameters in one, as shown in figure 4.2. This time an upgrade situation has been selected, with a given total volume available. The model first calculates the volume required for denitrification, and directly assigns the rest of the volume to the nitrification tank, therefore the two curves are symmetric. This way the required filling fraction for a system with two equally sized tanks can be found easily.

At one point, the volume of the nitrification tank is so large that the need for a biofilm completely disappears, as illustrated with the filling fraction falling sharply.

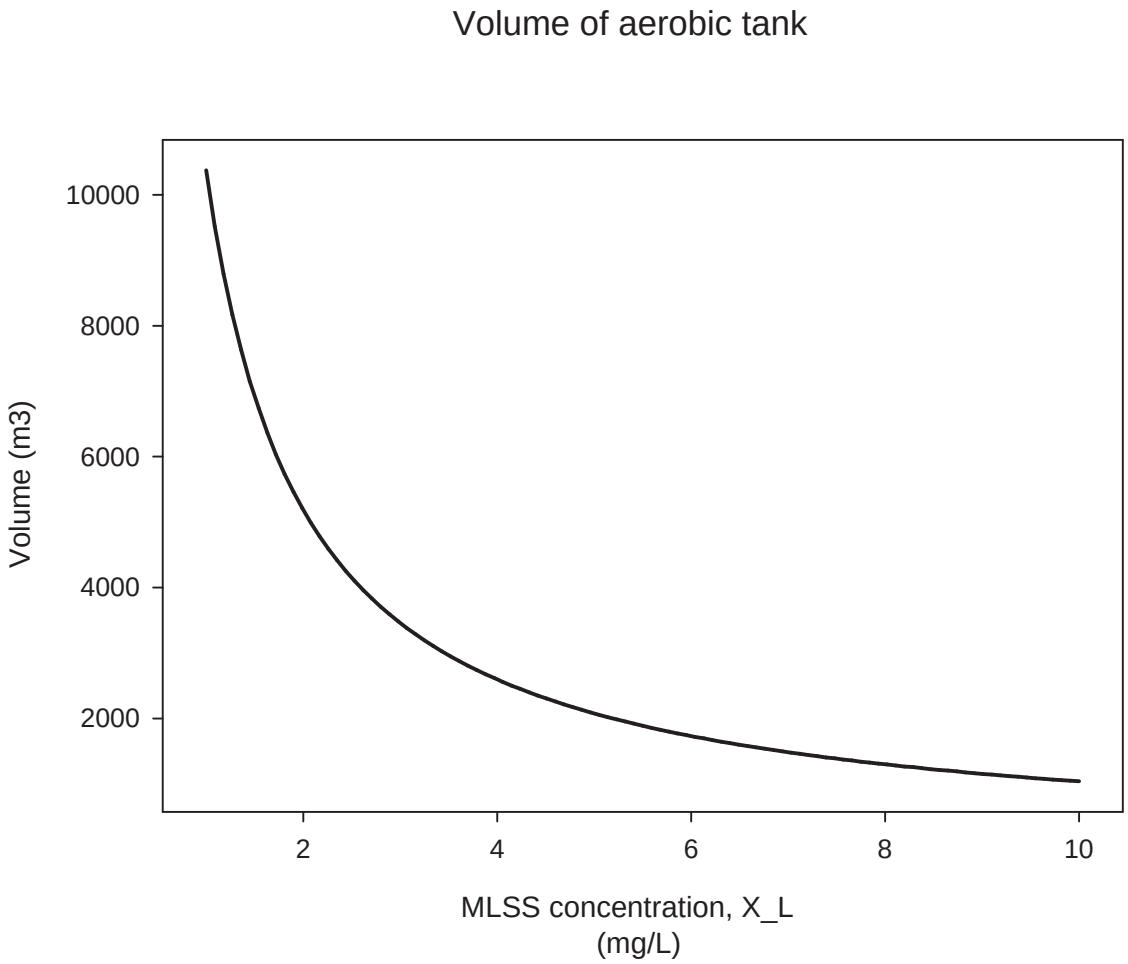

Figure 4.1.: $X_L$vs. V_N

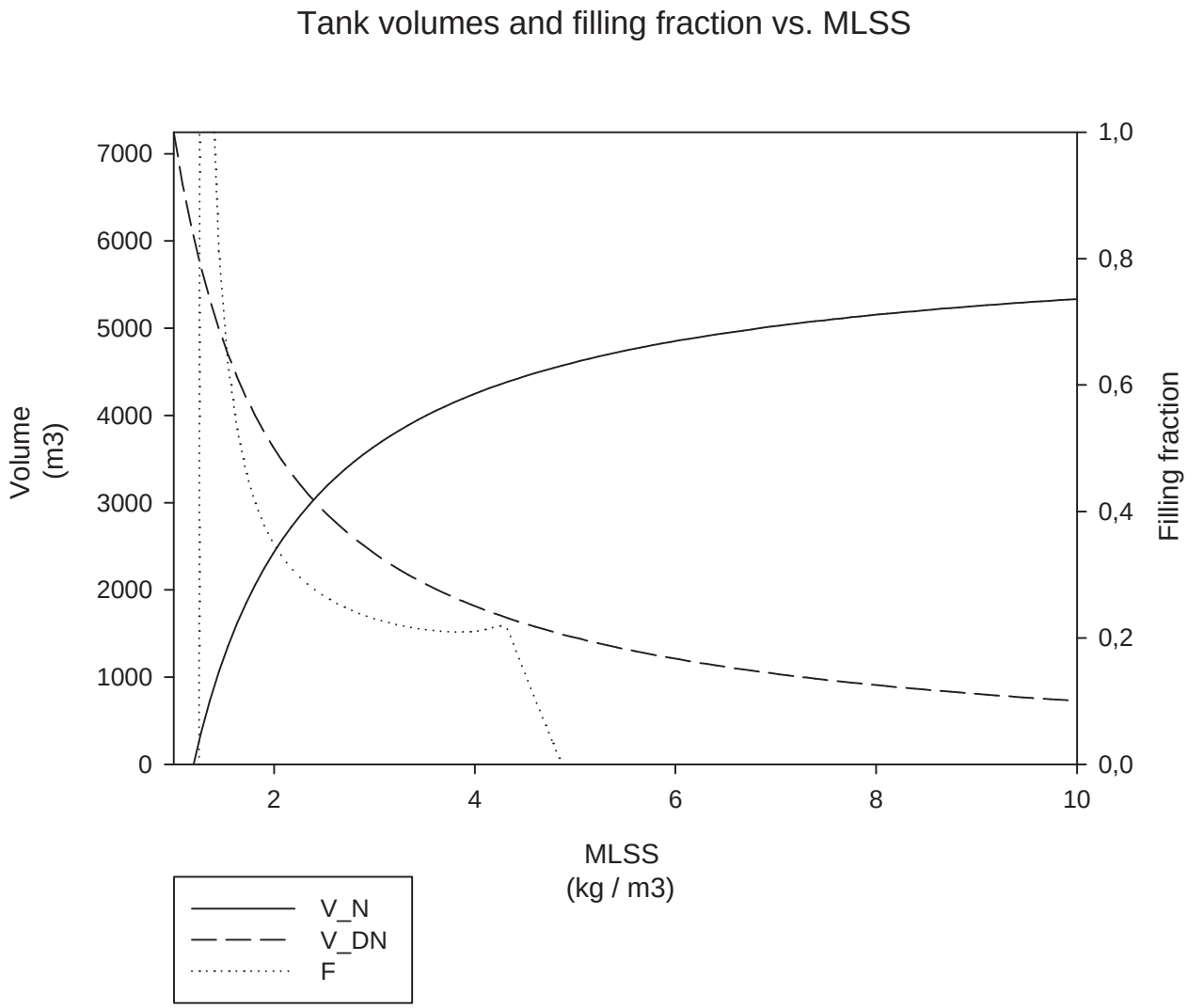

Figure 4.2.: Tank volumes and filling fraction as a function of MLSS concentration

5. Model testing

5.1. Introduction

This chapter will deal with the testing of the HYBAS model on the real-world example of a pilot project performed in Örtofta, Sweden.[6] The Örtofta pilot study consisted of three configurations and we will in this report study the first, namely configuration "a) Two aerated reactors in series at 5 days SRT".

This configuration consisted of two process trains, with two reactors in each, the first reactor is for bulk BOD oxidization, and the second for nitrification. Return Activated Sludge is pumped to reactor 1 from a clarifier after reactor 2. Wasting was also performed from reactor 2 to control the sludge age. One train, referred to as the "Hybas", had a 50% filling degree of biomedia carriers, type BiofilmChip-P^{TM}in reactor 2. The second process train, referred to as the "Reference", is identical, but has no biomedia carriers in reactor 2. The reactors are referred to as H1 & H2 for the Hybas train, and AS1 & AS2 for the Reference/Active Sludge train. Figure 5.1 shows the process layout of both systems.

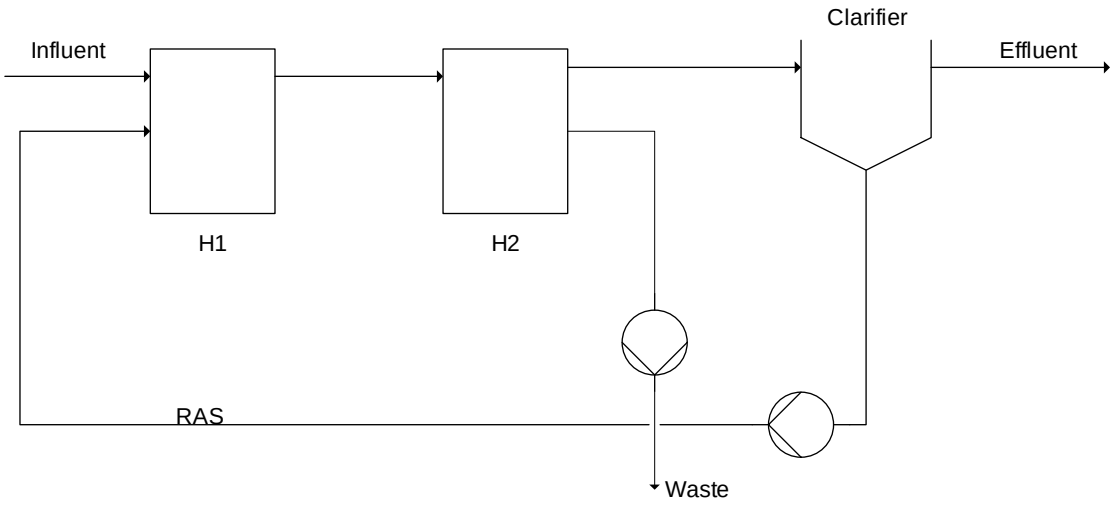

Figure 5.1.: Örtofta configuration a)

The volume of each tank was 77.3 liters, and the Hybrid reactor 2 contained 5109 Chip-P

Tank volume	$V_r = 77.3\,\text{liter}$
Number of biofilm-carriers	5109
Chip-P area	$A_{\text{chip}} = 68\,\text{cm}^2$
Total biofilm area	$A = 34.7412\,\text{m}^2$

Table 5.1.: System design

biofilm-carriers, giving a total biofilm area of

$$A = 5109 \cdot 68\,\text{cm}^2 = 34.7412\,\text{m}^2$$

The pilot plant was run in this configuration between January 23rd and November 28th 2006. A lot of data about the influent, first and second reactors, RAS and effluent, was logged and collected in an Excel spreadsheet. Collected parameters of interest to us, common to both the Reference and Hybrid systems:

- Flow rate for influent, RAS and Waste Activated Sludge
- pH, Temperature at all points
- Total COD, Total Nitrogen and BOD5 for influent and effluent
- Soluble COD, ammonium, nitrite and nitrate at all points
- Total Suspended Solids (TSS), Volatile Suspended Solids (VSS) at all points
- DO in the two reactors

Specially for the Hybrid reactor number 2, containing biofilm-carrying media:

- Biofilm solids per chip

The relevant data was collected into a separate spreadsheet, named "Örtofta analysis.xls" and derived parameters, such as the SRT and nitrification rates, are calculated within this new spreadsheet. Details about the calculation method of these parameters are presented in the following sections.

5.2. Data filtering

The goal of this pilot plant was to determine design/performance relationships for the HYBAS$^{\text{TM}}$process, determine optimal operating conditions for a hybrid system, investigate effects of ammonium loading on nitrification rate, research a model for nitrification and growth kinetics of biofilms, and to determine ratio of nitrifiers on the media and in the sludge phase.

At certain times the observed parameter values were unsuitable for this analysis, either because of nitrification-hostile environment, or unphysical values, caused by natural

variation, mechanical failures or manual modifications done in order to experiment with load responses. This instability made it necessary to filter out unwanted data points to get a set of observations that can be compared to the HYBAS^{TM}model. Table 5.4 summarizes the filtering criteria used. The following list comments on select parameters:

Temperature was controlled to maintain around 10 °C in both reactors, in both systems. The variation of this temperature is quite small, but actual temperature has been taken into account when comparing theoretical versus observed nitrification rates. No filtering applied.

	AS1	AS2	H1	H2
Mean	10.4992	10.7595	10.6334	10.9686
Std.dev.	2.0282	1.8975	2.2145	2.2390

Table 5.2.: Temperature statistics

pH was controlled to stay between 7.2 and 7.8 to not inhibit nitrification using a $NaHCO_3$ solution above 7.2 pH. A few data rows indicate a pH below 6.5 and these have been filtered out.

Flowrate,Q is the combination of influent flowrate, and RAS flowrate. The recycle ratio was ran at about 1, meaning the RAS flowrate was almost equal to the influent flowrate at all times. Due to pump failures, power outage or efforts to stabilize sludge properties, data rows that do not have a flow rate between 125 and 145 l/h have been filtered.

DO or Dissolved Oxygen in the reactors has been actively controlled to maintain around 3 mg/l in the Active Sludge tanks (AS1, AS2 and H1) and 5 mg/l in the Hybrid tank (H2). Statistics show that the mean is close to these goals and that the DO has a small variation. However, to have comparable Hybrid and Reference systems, insufficient DO has been filtered out.

	AS1	AS2	H1	H2
Mean	3.5436	3.2583	3.5527	4.9045
Std.dev.	1.3902	1.0097	1.3038	0.9675

Table 5.3.: DO statistics

This filtering reduces the number of data points from 263, to 60 and 37 for the Reference and Hybrid systems, respectively.

Start-up problems with this pilot plant can be visualized by looking at the biofilm solids, or the amount of nitrifying bacteria on the biofilm-carriers, over time, as seen in figure 5.2. Arguably, data from before 1st of May could be strictly ignored as the biofilm was not fully developed, but the filtering criteria based on parameters results in selecting

Parameter	Criteria				
pH	$pH > 6.5$				
Q	$125 < Q < 145$				
DO		AS1	AS2	H1	H2
	Minimum DO	2.0	2.5	3.5	4.5

Table 5.4.: Data filtering criteria

only 4 data rows from before 3rd of May, indicating that this dynamic filtering approach is sufficient.

5.2.1. Application in Excel

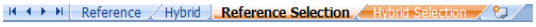

Figure 5.3.: Two sets of sheets, one set unfiltered and one filtered

The selected (unfiltered) data from the original Örtofta Excel spreadsheet is copied into two sheets; "Reference" and "Hybrid" in a new file. The filtered data, row by row, is copied by a 'macro' command into two new sheets; "Reference Selection" and "Hybrid Selection". All calculations are done on the "Reference" and "Hybrid" sheets, so that the "...Selection" sheets are only a practical way to look at the filtered data, but not manipulate them.

The filtering is done by first creating a column that checks whether all filtering criteria (Table 5.4) are upheld and prints out "OK" in that case, designating this data row as valid data for the analysis. The check is a logical IF-loop, programmatic in nature and not easily readable since it refers to column names, as seen in figure 5.4.

AE184 =IF(AND((C184+D184)>125;(C184+D184)<145;T184>2;Y184>2,5;X184>6,5;AC184>6,5);"OK";"")

X	Y	Z	AA	AB	AC	AD	AE	AF
	AS2					Effluent	Criteria check	AS1
pH	DO (mg/L)	Temp (C)	TSS (g/l)	VSS (g/l)	pH	TSS (g/l)		Load COD Tot (g COD/g TSS d)
7,48	2,8	9,2	2,48		7,34	0,024	OK	1,11
7,18	2,8	10	2,26	1,66	7,1	0,026	OK	0,96
7,44	2,96	10	2,04	1,46	7,4	0,021	OK	1,11
7,74	3	10,4	2,2	1,54	7,7	0,018	OK	1,04

Figure 5.4.: Filtering column in Excel

In this example, the IF-logic can be read as "If *Flowrate* is larger than 125 AND *Flowrate* is less than 145, AND *DO in reactor 1* is larger than 2, AND *DO in reactor 2* is larger

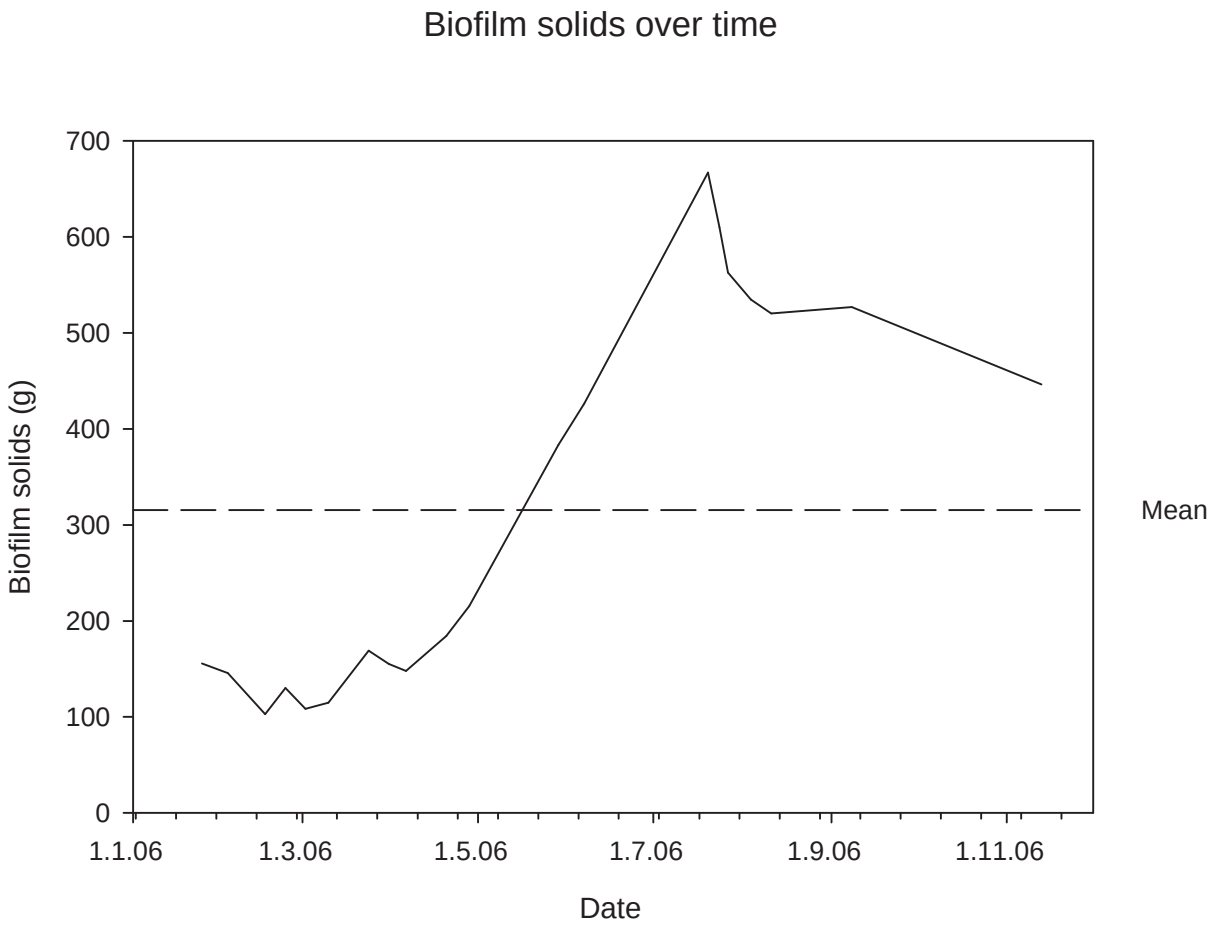

Figure 5.2.: Biofilm solids over time

than 2.5, AND *pH in both reactors* is larger than 6.5; then OK".

A 'macro' is a series of commands that can be performed by Excel automatically. In this case, a simple macro was designed to copy all rows marked "OK" into the "...Selection" sheets. This macro is called 'CopySelected' and is reachable by hitting Ctrl-O on the keyboard. The macro does not currently check if the row is marked "OK", it only copies manually defined rows, so selecting different filtering criteria can be cumbersome.

5.2.2. Noise and inconsistencies

There is a large amount of variation in the data from Örtofta, noise and inconsistencies which can be harmful for this type of analysis, in which it is a goal to find correlation between two parameters, when every parameter is heavily correlated with several other parameters.

One special concern when dealing with microorganisms is the fact that they have a long response time compared to mechanical systems. In this study, the response time is neglected, as every logged value is directly compared to each other within a very short time frame, corresponding to one row in the Excel data log. This results in invalid data when rapid load changes, for example, occur. One example is the data log at 19^{th}April 11:05, when, as commented by the responsible, a pump failure caused a spike in ammonium loading, which leads to a very low C/N ratio into the system, while the nitrification rate further downstream was not visibly affected, creating the effect of an apparently high nitrification rate at low C/N.

Figure 5.5 shows the ammonia concentration in the effluent from the Reference system; these data are unfiltered. The ellipsis envelops the time period 8. may to 22. may and shows a sudden increase in ammonia-nitrogen concentration. Assuming ammonia concentration in effluent is the same for RAS, this ammonia concentration is transported back to reactor 1. Figure **??** shows the same Effluent ammonia concentration (red), together with the ammonia Load on AS2 (green) and AS1 (blue), with individual scales. It is assumed that such sudden increases will cause an oscillation in the system, but which a direct comparison, row by row, can not pick up on, causing apparent inconsistencies. Relatively slow changes or constant values is preferred in such an analysis, but difficult to obtain in a full-scale experiment.

5.3. Analysis

5.3.1. Derived Parameters

SRT

Solids Retention Time (SRT) represent the average time (residence time) that a bacteria spends within the system, because of recycling.

$$\theta = \frac{X \cdot V}{\text{SP}} \tag{5.1}$$

where:

X	Solids concentration in system, that is, TSS (Total Suspended Solids) in reactor 1 and 2.
V	Total volume of reactors. $V = \text{constant} = 2 \cdot 77.3\,\text{liter} = 154.6\,\text{liter[l]}$
SP	Sludge Production from the system. Basically effluent TSS plus TSS in waste-flow from reactor 2, multiplied with respective flowrates [g/d]

For the hybrid system, the biofilm solids are added to the TSS, so that

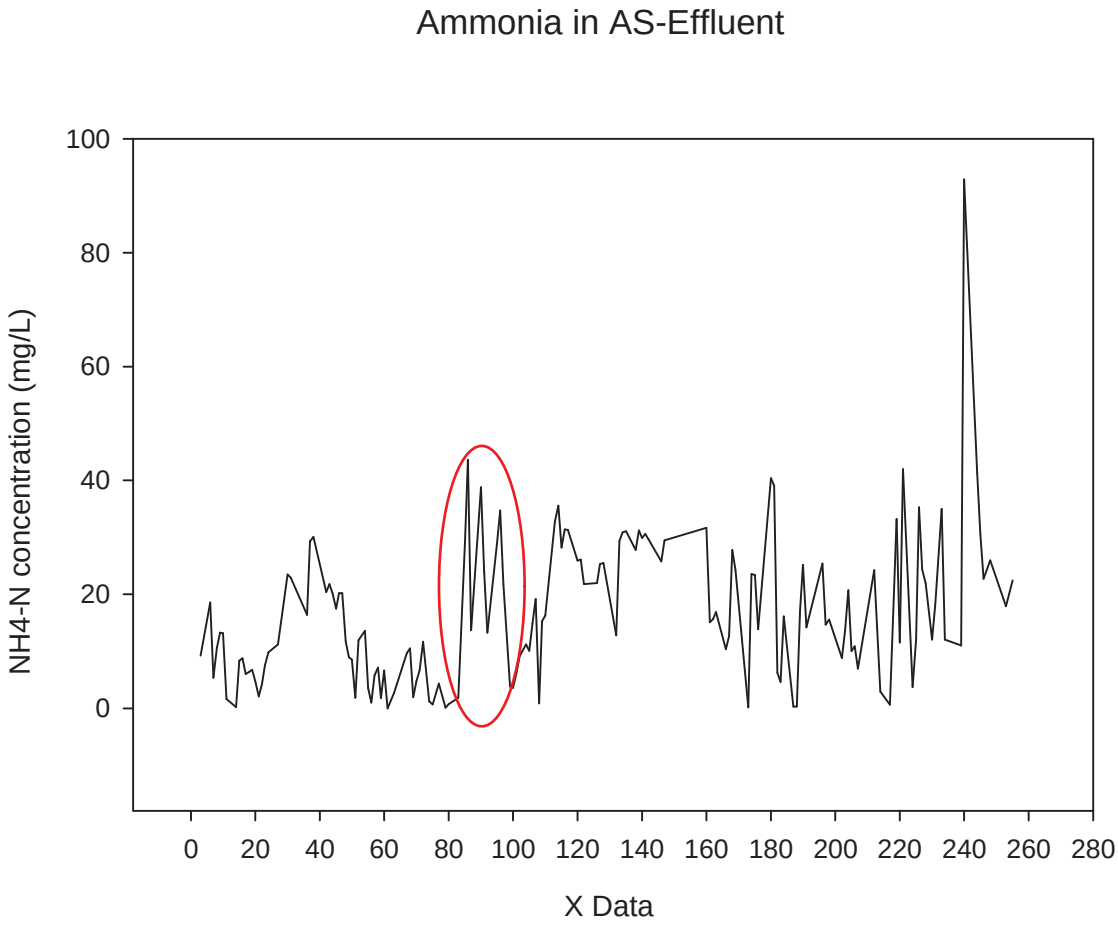

Figure 5.5.: Ammonia concentration in AS-effluent/RAS

$$\theta_{\text{hybrid}} = \frac{(\text{TSS}_{\text{H1}} + \text{TSS}_{\text{H2}}) \cdot V + m_{\text{biofilm}}}{Q_e \cdot \text{TSS}_e + Q_w \cdot \text{TSS}_{\text{H2}}} \tag{5.2}$$

where:

m_{biofilm} biofilm solids mass [g]

Q_e,Q_w Flowrate effluent and waste, respectively [l/d]

The mass of the biofilm is sparsely measured, about once a week or less, but its value has been interpolated, as figure 5.2 illustrates.

Load

Loads represent the amount of mass per time entering the system or part of the system.

$$L = Q \cdot C \tag{5.3}$$

where

L	Load [g/d]
Q	Flowrate into system [l/d]
C	Concentration of loading substance [g/l]

Rate of consumption

Rates of consumption of substances is generally the concentration difference between inlet and outlet, multiplied by the flowrate:

$$r = -\Delta C \cdot Q = (C_{in} - C_{out}) \cdot Q \tag{5.4}$$

5.3.2. MLSS nitrification

The Hybas model estimates the nitrifying capability of the MLSS (Mixed-Liquor Suspended Solids) at 10 °C by means of an empirically designed N-rate vs. C/N curve. Figure 5.6 shows a plot of the (filtered) nitrification rates in reactor AS2, vs the Carbon/Nitrogen ratio (Total Carbon / NH4-N) into the biological system. This figure also includes a plot of the Hybas model's proposed correlation curve. For sake of comparison, the horizontal axis is cut at C/N = 9, leaving out 4 points.

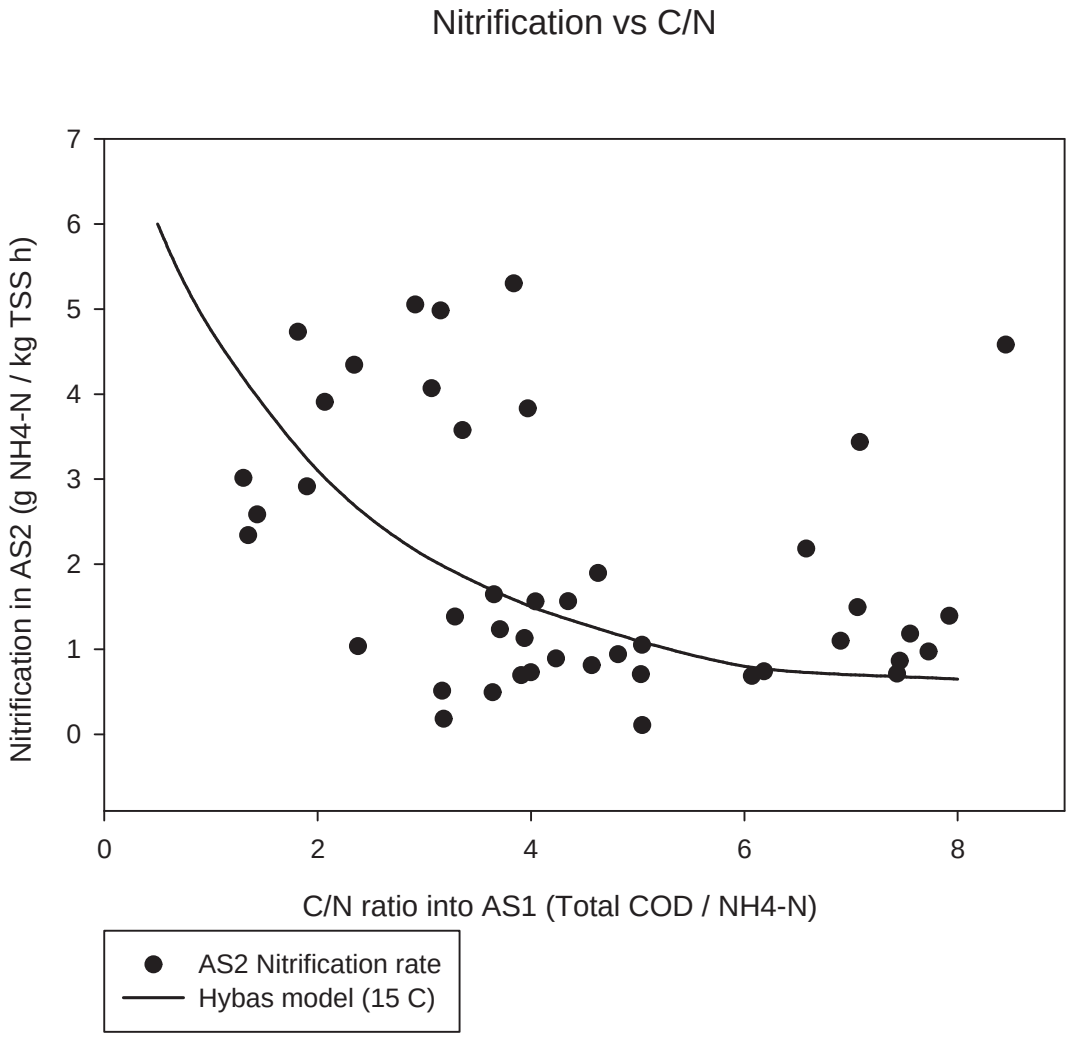

Figure 5.6.: Nitrification in AS2 vs. C/N into AS1

Figure 5.7 is a plot of the nitrification rate in unit of $\frac{\text{g NH4-N}}{\text{m}^3\cdot\text{h}}$.

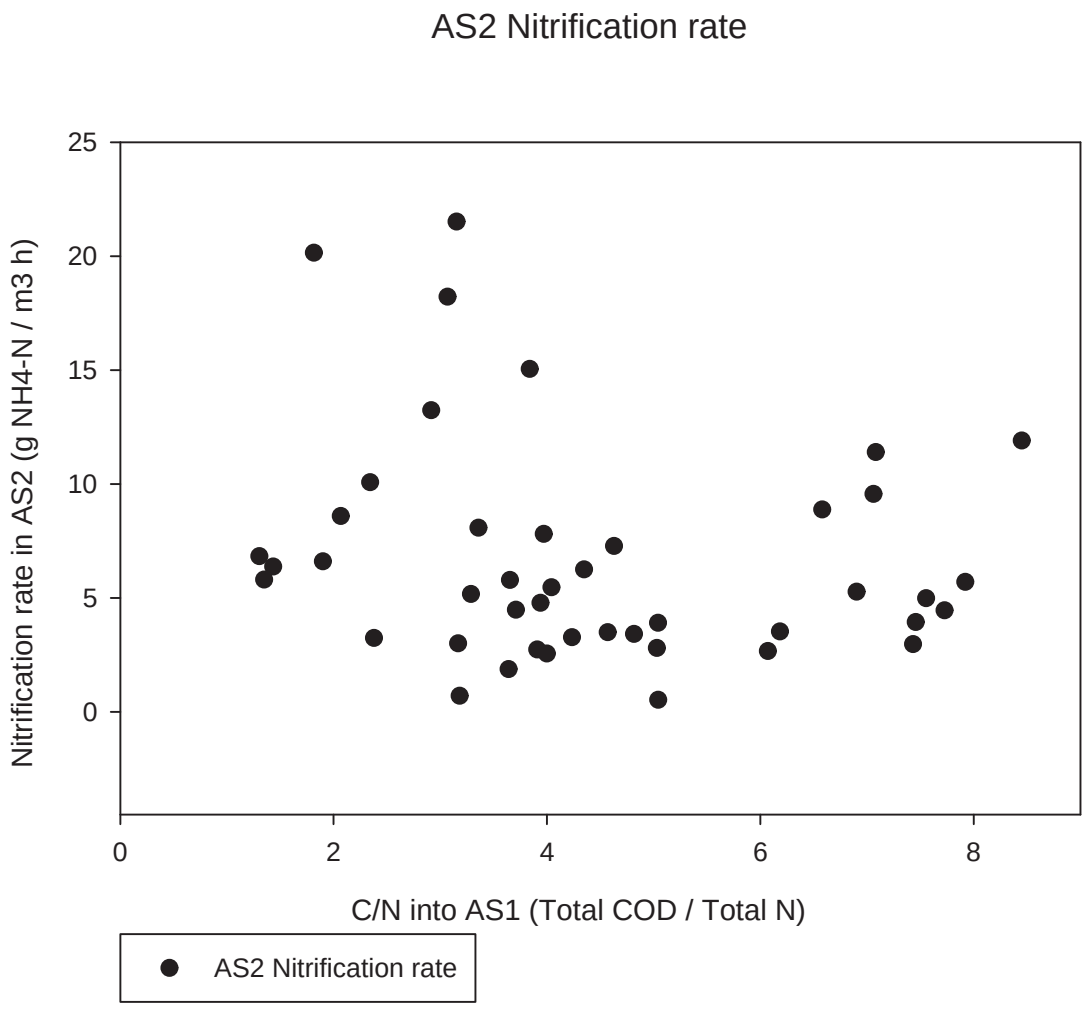

Figure 5.7.: Nitrification in AS2 vs. C/N

The plots shows that the model estimation and observed data follows a similar trend, but the data contains significant outliers. A temperature correction using equation 5.5 and the temperature in reactor 2, is plotted in figure 5.8.

$$r_{10} = r_T \cdot 1.072^{(10-T)} \tag{5.5}$$

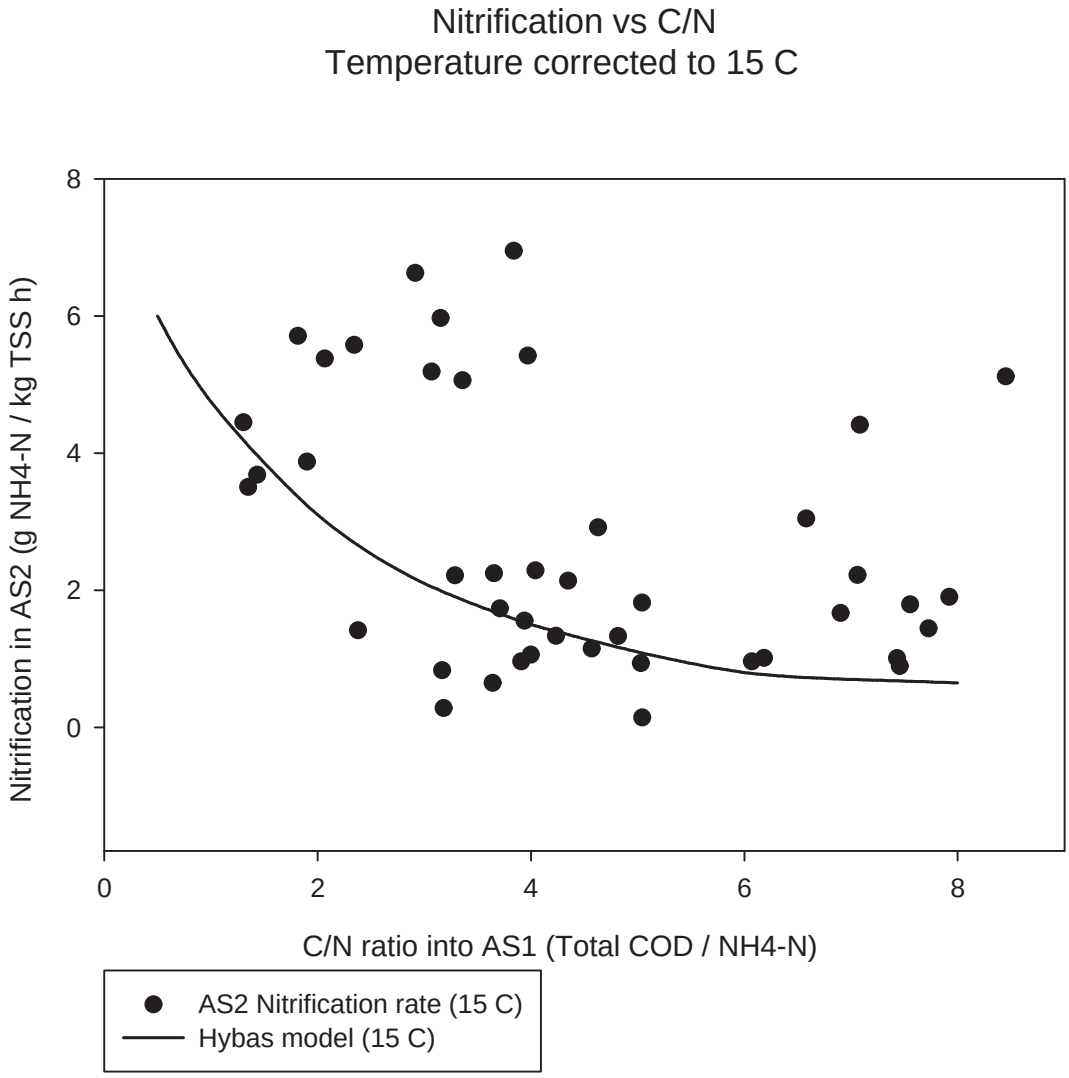

Figure 5.8.: Temperature corrected nitrification rate in AS2

5.3.3. Biofilm nitrification

Observed nitrification

Estimation of the nitrification in the biofilm is done by comparing the nitrification rate in AS2 and in H2:

- Concentration difference over H2 and concentration difference over AS2 is calcu-

lated:

$$\Delta S_{\mathrm{AS2}}$$
$$\Delta S_{\mathrm{H2}}$$

- The higher concentration difference over H2 is assumed to be caused by the biofilm:

$$\Delta S_{\mathrm{biofilm}} = \Delta S_{\mathrm{H2}} - \Delta S_{\mathrm{AS2}}$$

- The nitrification rate of the biofilm is then found by evaluating the flowrate and area of the biofilm:

$$r_{\mathrm{biofilm}} = \frac{\Delta S_{\mathrm{biofilm}} \cdot Q}{A_{\mathrm{biofilm}}}$$

Expected nitrification

The expected, or theoretical, nitrification rate is calculated as described in section 2.4.2, using values for k and K as in the HYBAS model, Step 12 and Step 13, respectively. Please note that in most cases, the rate-limiting substrate was determined to be oxygen, done automatically by the Excel spreadsheet.

Referring to figure 3.4, which shows the theoretical correlation between nitrification rate in biofilm and the incoming C/N ratio to the aerobic reactor; figure 5.9 plots a calculated value, or the *expected* nitrification rate, according to the HYBAS model, based on data provided from Örtofta. The trend is a decrease in nitrification rate with increasing C/N ratio, as expected. Severe noise is present however, possibly caused by fluctuating pH and flow rates, making it difficult to use this as a verification of the HYBAS model.

Impact of SRT

$$\theta_{\mathrm{H2}} = \frac{\mathrm{TSS}_{\mathrm{H2}} \cdot V_{\mathrm{H2}} + m_{\mathrm{biofilm}}}{\mathrm{SP}} \tag{5.6}$$

The HYBAS model predicts that the biofilm nitrification rate should decrease as the SRT of the MLSS increases, as according to figure 3.5. Figure 5.10 shows how the HYBAS model predicts the nitrification rate in the biofilm, plotted versus SRT, using the data from Örtofta. As from before, some noise is present, but the correlation is excellent. Next, the *observed* nitrification rate in the biofilm was also plotted against SRT, see figure 5.11. Apparently the theory and empirii do not match, and the observed data even indicates an increase of nitrification with increasing SRT. However, the biofilm nitrification is only an estimate, and the upwards trend might indicate that the estimate is in fact including nitrification in the MLSS.

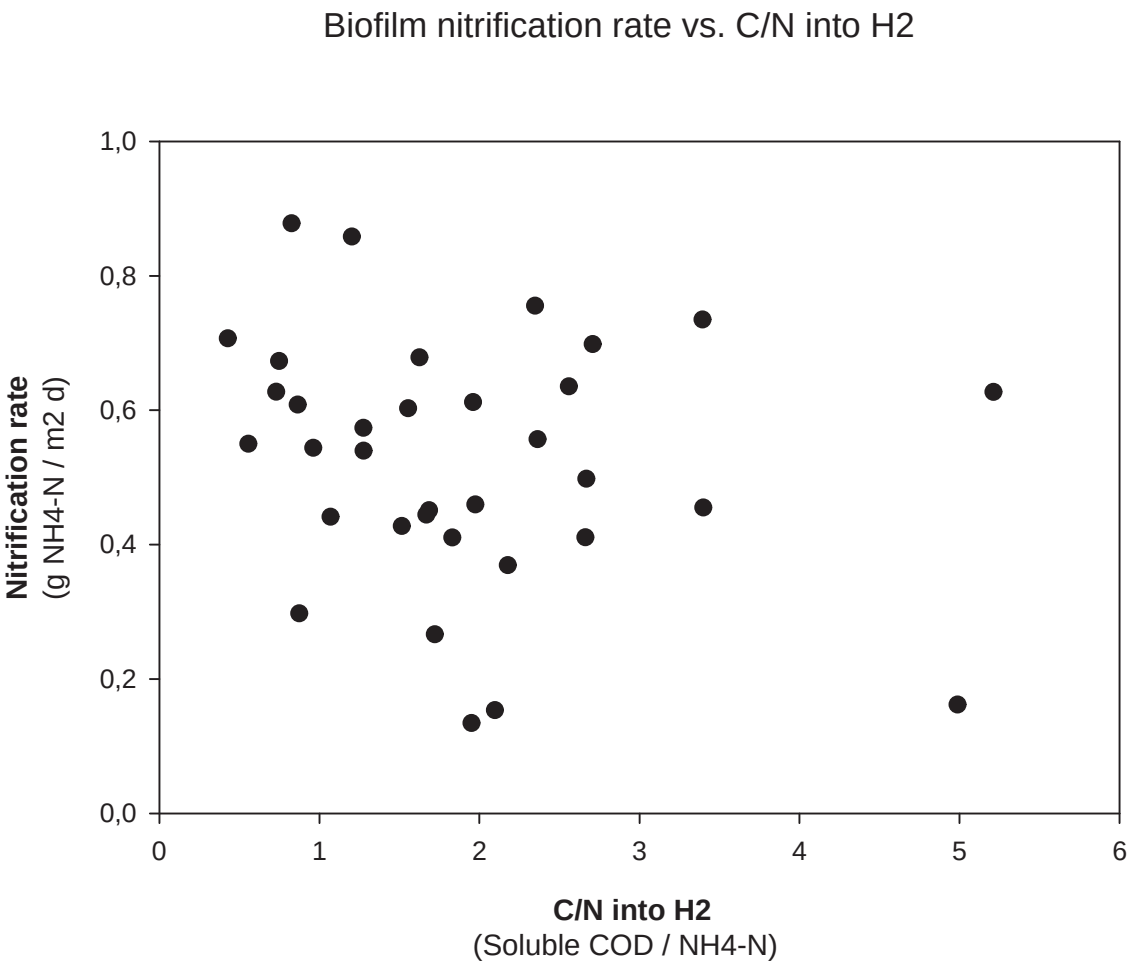

Figure 5.9.: Biofilm nitrification rate plotted against C/N into H2

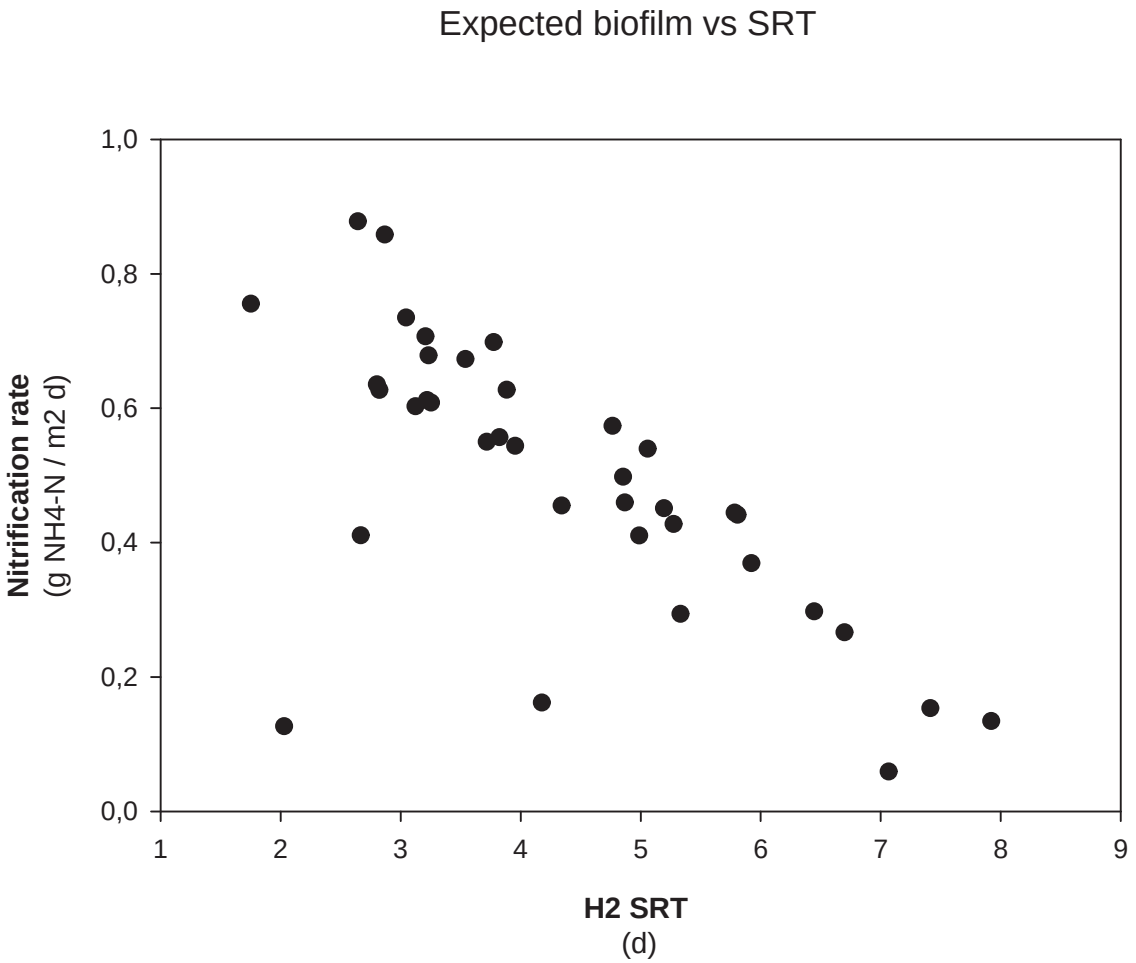

Figure 5.10.: Expected nitrification rate vs SRT

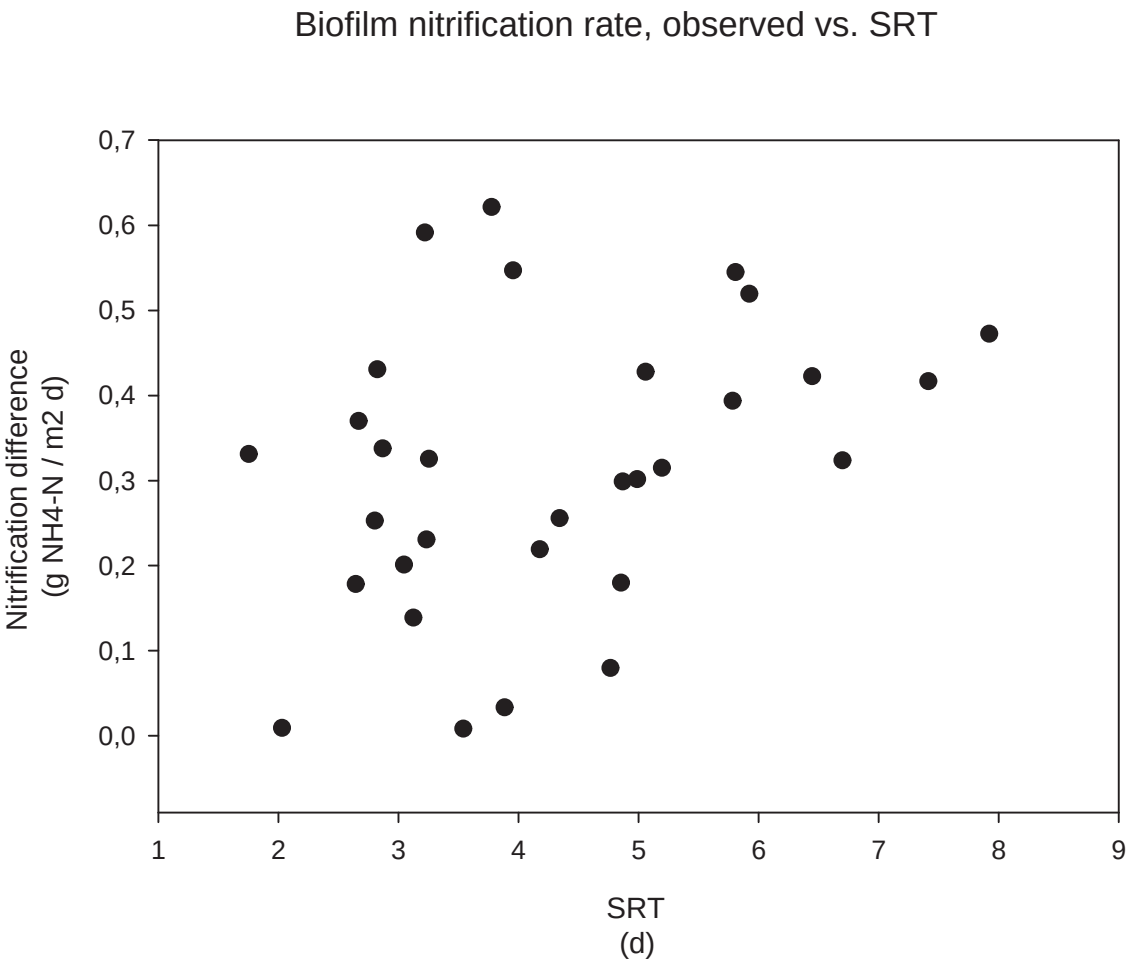

Figure 5.11.: Observed biofilm nitrification vs SRT

5.4. Summary

Some consistency between HYBAS model and observed data was found in MLSS nitrification. Numerous unknown factors and strong fluctuations makes it hard to prove or disprove the model, but the proposal of a K-factor correlating nitrification in biofilm with SRT of the MLSS was shown to be weak or erroneous, assuming the estimated biofilm nitrification was relatively correct.

6. Conclusion

The first aim of the project was to outline the existing knowledge of the Activated-Sludge and MBBR processes with regard to dimensioning of these systems for nitrification, denitrification and bulk BOD-removal. This was accomplished during the entire length of the project by literature study and guidance from Professor Hallvard Ødegaard. The work-load was reduced by focusing on configurations relevant to the HYBAS model.

The second aim was to develop a computer-model directly based on the original HYBAS dimensioning model proposed by Hallvard Ødegaard. At the very start of the project it was discussed whether this model should be created in Matlab®Simulink or as an Excel®spreadsheet. A Simulink model would be visual and have a powerful back-end, but would require the end-user to have a Matlab installation. The use of Excel was determined to be the more approachable alternative as it would also allow sharing between professor and student during the work. A working spreadsheet was successfully developed during the first part of the project. The spreadsheet serves as an illustrative example of the HYBAS model and allows the end-user to experiment with parameters and further develop the HYBAS model.

The third aim was to evaluate the HYBAS model using a real-world full-scale plant under construction, but data was not obtained for this purpose. Instead, data from a HYBAS pilot plant in Örtofta, Sweden, was used. A few HYBAS model components were tested against the results obtained from the pilot plant. MLSS nitrification proves to follow a similar trend as the model, but no quantitative results could be obtained. Biofilm nitrification was attempted to estimate by comparing the Hybrid and Reference systems, but no consistent trends could be detected. It is possible sharp fluctuations in ammonia, DO, pH and flow rates caused oscillations in the system, making a steady-state assumption too weak for a consistent analysis.

A. Calculations

A.1. Kinetics of the BOD reaction

Biochemical Oxygen Demand is the most widely used parameter of organic content in wastewater. The method to measure BOD involves measuring the dissolved oxygen used by microorganisms in the oxidation of organic matter in a test sample. This reaction is slow and theoretically takes an infinite time to finish, and is expressed as a first-order reaction rate:

$$\frac{dL_t}{dt} = -kL_t$$

where L_t is the amount of BOD remaining in the water sample at time t, and k is the reaction rate constant. Integrating this equation yields:

$$\begin{aligned} \ln L_t \Big|_0^t &= -kt \\ \frac{L_t}{L} &= e^{-kt} \end{aligned} \tag{A.1}$$

where L is the amount of BOD at time $t = 0$, i.e. the initial BOD content in the sample. The amount of BOD exerted after t days is:

$$\mathrm{BOD}_t = L - L_t = L\left(1 - e^{-kt}\right) \tag{A.2}$$

A widely used version of the BOD parameter is the 5-day BOD; the amount of BOD exerted after 5 days, which can be expressed as:

$$\mathrm{BOD}_5 = L - L_5 = L\left(1 - e^{-5k}\right)$$

The constants in this equation, L and k must be determined by a time-series measurement of the BOD and performing a regressional analysis, such as the least-squares method.

A.1.1. Biodegradable COD as a function of 5-day BOD

Chemical Oxygen Demand or COD is another test used to measure the content of organic matter in wastewater. A strong chemical oxidizing agent is used in an acidic medium, in order to measure the oxygen equivalent of the organic matter. The COD test is a much faster test than the BOD; typically 3 hours instead of 5 or 7 days in the case of BOD. However, the COD test does not distinguish between easily soluble and biodegradable organic matter and the inert organic content. In many cases it is necessary to know the carbonaceous content that is readily available to the microorganisms.

The biodegradable COD is theoretically equivalent to the BOD as measured after an infinite amount of time;

$$\mathrm{COD}_{\mathrm{biodegradable}} = \mathrm{BOD}_{\infty}$$

Using equation A.2 we can relate the biodegradable COD to the 5-day BOD as follows:

$$\frac{\mathrm{COD}_{\mathrm{biodegradable}}}{\mathrm{BOD}_5} = \frac{\mathrm{BOD}_{\infty}}{\mathrm{BOD}_5} = \frac{\lim\limits_{t\to\infty}\left(1-e^{-kt}\right)}{1-e^{-5k}} = \frac{1}{1-e^{-5k}} \tag{A.3}$$

A typical value in the case of polluted wastewater for k is $0.23\,\mathrm{d}^{-1}$ at $20\,^{\circ}\mathrm{C}$.[1] An approximate temperature correction can be made by an equation derived from the van't Hoff-Arhenius relationship;

$$k_T = k_{20}\theta^{(T-20)} \tag{A.4}$$

where k_T is the rate constant at temperature T. A value of θ valid in the temperature range between 4 and $20\,^{\circ}\mathrm{C}$ is 1.135 and for 20 to $30\,^{\circ}\mathrm{C}$ the value should be set equal to 1.056:

$$\theta = \begin{cases} 1.135 & \text{if } T\epsilon(4,20) \\ 1.056 & \text{if } T\epsilon(20,30) \end{cases}$$

So correcting to a temperature of $15\,^{\circ}\mathrm{C}$ we get:

$$k_{15} = 0.23\,\mathrm{d}^{-1}\cdot 1.135^{(15-20)} = 0.122\,\mathrm{d}^{-1} \tag{A.5}$$

And the ratio of A.3 thus becomes:

$$\begin{aligned} \frac{\mathrm{BOD}_{\infty}}{\mathrm{BOD}_5} &= \frac{1}{1-e^{-5\cdot 0.122}} \approx 2.19 \\ &\Downarrow \\ \mathrm{COD}_{\mathrm{biodegradable}} &= 2.19\cdot \mathrm{BOD}_5 \end{aligned} \tag{A.6}$$

The value of k here is given as an example to illustrate the methods used to calculate the COD and BOD relationship, as used in the HYBAS model. The reaction rate constant is strongly dependent on wastewater characteristics and is supplied as a user input to the model.

$$c = 4.3 \cdot \left(1 - e^{-5k_T}\right)$$

Bibliography

[1] "Wastewater engineering: treatment, disposal, and reuse," New York, pp. xvi, 1334 s.–, c1991.

[2] H. Ødegaard, "Fjerning av næringsstoffer ved rensing av avløpsvann," [Trondheim], pp. 327 s.–, 1992.

[3] A. Schramm, L. Larsen, N. Revsbech, N. Ramsing, R. Amann, and K. Schleifer, "Structure and function of a nitrifying biofilm as determined by in situ hybridization and the use of microelectrodes," *Applied and Environmental Microbiology*, vol. 62, no. 12, pp. 4641–4647, December 1996. [Online]. Available: http://aem.asm.org/cgi/content/abstract/62/12/4641

[4] S. Okabe, H. Satoh, and Y. Watanabe, "In situ analysis of nitrifying biofilms as determined by in situ hybridization and the use of microelectrodes," *Applied and Environmental Microbiology*, vol. 65, no. 7, pp. 3182–3191, July 1999. [Online]. Available: http://aem.asm.org/cgi/content/abstract/65/7/3182

[5] A. B. Cunningham, "Biofilms: The hypertextbook," June 2008. [Online]. Available: http://www.erc.montana.edu/biofilmbook/

[6] AnoxKaldnes, "Hybas pilot project," Tech. Rep., 2007.