Moving Bed Biofilm Process in Activated Sludge Model 1 for Reject Water Treatment

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Abstract

A moving bed biofilm (MBB) process was modelled in AQUASIM using the standard activated sludge model 1 (ASM1) as a baseline. The model was controlled against experimental data from a pilot Hybrid Vertical Anaerobic Biofilm (HyVAB) reactor installed at Knarrdalstrand wastewater treatment plant, Porsgrunn, Norway. High ammonium concentration removal from reject water was studied by applying different aeration schemes at the plant and the modelling tool. Results show that the standard ASM1 model was poor to fit experimental data. Simulation results evidenced missing biochemical mechanisms related to anaerobic ammonium oxidation (Anammox) and short cut nitrogen removal processes. However, the essential simulation outputs are biofilm thickness, substrates concentration variation, and biomass distribution, partially validated with experimental results. The model, therefore, helped to realise the nature of the bioprocess observed at the pilot reactor.

Keywords: Moving bed biofilm reactor, Reject water, Activated sludge model, Intermittent aeration, AQUASIM

1 Introduction

Reject water originated from digested sludge dewatering is usually rich in ammonium (Guo et al., 2010). The untreated discharge causes many environmental and health hazards (i.e., eutrophication and blue baby syndrome) that strictly requires proper treatment. Mixing reject water into the mainstream wastewater line is a common practice (Sivalingam et al., 2019). However, the higher nutrient load of reject water causes process instabilities. Reject water requires, therefore, an additional treatment before mixing with the mainstream treatment process.

A pilot Hybrid Vertical Anaerobic Biofilm (HyVAB) reactor was installed in the reject water line (Figure 1). Intermittent aeration was implemented into the aerobic chamber to achieve simultaneous nitrification and denitrification. The intermittent aeration strategy has several advantages compared to the conventional activated sludge process; thus, less aeration energy requirement and a single rector setup are sufficient to achieve aerobic and anoxic treatments (Di Bella and Mannina, 2020).

Authors have earlier investigated different intermittent aeration patterns to remove higher ammonium concentrations from Knarrdalstrand wastewater treatment plant (KWWTP) reject water (Sivalingam et al., 2020). However, experimentally examining various aeration schemes is tedious and resource-intensive. Therefore, a theoretical study was carried out by modelling and simulation.

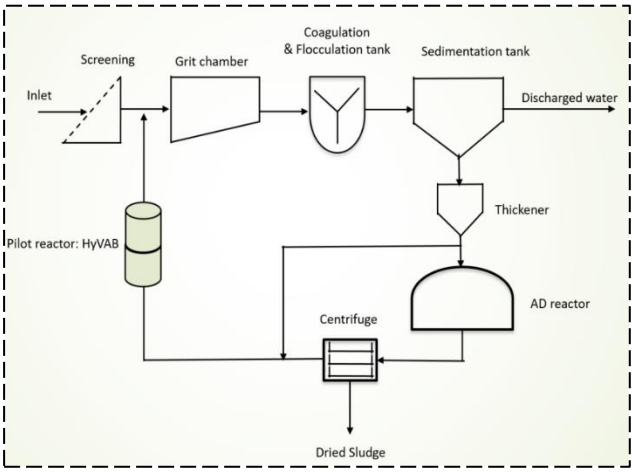

Figure 1. HyVAB pilot reactor integration at KWWTP.

This research develops a moving bed biofilm (MBB) model to study the impact of intermittent aeration on the HyVAB pilot reactor, treating reject water. The standard activated sludge model 1 (ASM1) is applied to the MBB compartment in the HyVAB reactor modelled by AQUASIM software. We present the preliminary simulation results of the 1D multi-substrate and multispecies biofilm model to give an overview of the possible process parameters examination when integrating the MBB process and ASM1 model into AQUASIM.

1.1 Activated Sludge Model 1

The ASM1 was introduced in 1983 and has been extensively studied (Nelson and Sidhu, 2009); it was developed futher to investigate the activated sludge organic and nitrogen removal process (Van Loosdrecht et al., 2015). Only a few key elements are briefly presented here to ensure the proper reading flow of this article.

In ASM1, oxygen and nitrate are the primary electron acceptors. The organic matters are classified into biodegradable chemical oxygen demand (COD), non-biodegradable COD, and active biomass. The active biomass has two subsets pertaining to heterotrophic and autotrophic organisms. The ASM1 model consists of 13 state variables. Some of the essential variables are: Active heterotrophic and autotrophic biomass, alkalinity, ammonium, nitrate, soluble and biodegradable organics, and dissolved oxygen.

The ASM1 consists nitrification and denitrification as conventional single-step reactions, converting ammonia to nitrate (nitrification) and nitrate to nitrogen gas (denitrification) (Henze et al., 2000). However the intermittent aeration facilitates conventional, short cut and anaerobic ammonium oxidative pathways to remove nitrogen from the wastewater (Miao et al., 2018)

1.2 Moving Bed Biofilm Process

Moving bed biofilm process is a Norwegian technology specially designed for nutrient removal from wastewater (Rusten et al., 1997). It is an attractive solution for high strength wastewater treatment (Sivalingam et al., 2020b) due to stable biofilm growth into a protected surface area, which is more tolerant to the process variance.

The biofilm consists of different layers of mixed culture microorganism clusters, referred to as attached growth. The diversity of microorganisms depends on nutrient and oxygen gradients along with the biofilm thickness (Wang et al., 2019). For instance, in an aerated system, the outer layer of the biofilm is rich in aerobic culture. In contrast, the inner layers favour anoxic growth, and the layers near to the substratum contain anaerobic cultures. The different cultures perform specific biochemical reactions, such as nitrification occurs at the outer layer and denitrification happens at the inner layers. This is a key benefit of using moving beds (bio carriers) in this pilot study, facilitating biofilm growth.

2 Material and methods

The HyVAB pilot reactor has two compartments, the anaerobic part is at the bottom, and the aerobic part is at the top. The purpose of the anaerobic part is to recover energy as biogas. The anaerobic effluent enters to the aerobic compartment to undergo a nutrient removal process, especially ammonium removal. The aerobic part contains BWT15® type carriers (Biowater Technology AS, Tønsberg, Norway). The sketch of the reactor is presented in Figure 2, adapted from (Sivalingam et al., 2020a).

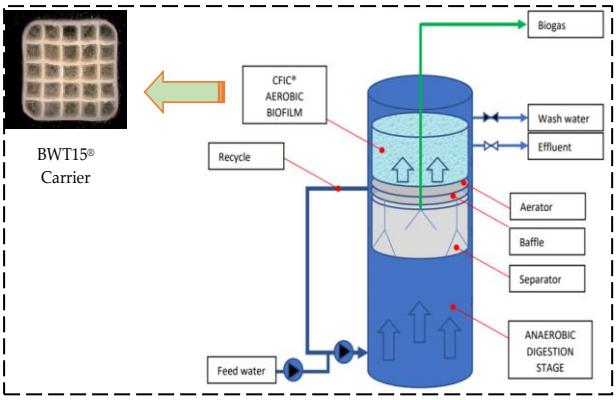

Figure 2. HyVAB reactor and matured moving bed bio carrier.

2.1 Reactor operation and experiments

Centrifuged effluent from the KWWTP anaerobic digestor was used as the reject water feed to the HyVAB reactor. The hydraulic retention time was one day, and the operational temperature was 30±2 °C. Two different intermittent aeration schemes were tested, i.e., (1) 5 min on/ 15 min off (20 min. Aeration cycle); (2) 3 min on/4 min off (7 min aeration cycle). The 2nd aeration pattern achieved 50% ammonium removal. The complete experimental study is presented in (Sivalingam et al., 2020a). The 2nd aeration scheme is used here to compare the simulation results.

2.2 Model Development

Since ammonium removal is our primary concern in reject water treatment, only the aerobic part of the pilot reactor (Biofilm compartment) and the ASM1 are modelled. The activated sludge process was incorporated into the biofilm compartment (attached growth).

The biofilm compartment in AQUASIM has been modified to comply with the biofilm part of the pilot reactor. The following assumptions are adapted from a similar study (Wanner and Morgenroth, 2004): (1) The type of reactor is confined; (2) The pore volume consists only a liquid phase and dissolved solids; (3) The biofilm matrix is in rigid form, and the volume can be changed only due to microbial activities; (4) The surface detachment velocity was assumed as a global value of 0.5*UF, where UF is the velocity by which the biofilm surface displaced due to the production and decay of microbial mass in the biofilm; (5) Biofilm surface area is constant at 10 m^2. The porosity rate was considered zero by assuming that the fraction of pore water volume of the biofilm is constant.

Nitrification, denitrification, aeration, autotrophic inactivation, heterotrophic inactivation, and aerobic heterotrophic growth are the main processes taken into account in the biofilm compartment. The complete process kinetics and stoichiometry coefficients are adapted from (Henze et al., 2000).

2.3 Intermittent Aeration implementation

Two approaches were performed to implement the intermittent aeration into this model. Firstly the aeration process activated in the biofilm compartment when aeration is 'on' and deactivated when aeration is 'off'. After activation and deactivation of the aeration process, the model was simulated with appropriate on/off time via the start/continue option from the simulation tool. It was challenging to simulate the model for a long time, like 250 days for a concise aeration cycle.

Therefore, in approach an aeration switch was introduced. First, a formula variable called 'AerSwitch' was created. The expression was defined as a sinusoidal function 207*(sin(500*t) ^2). This expression was determined by trial and error to match with experimentally calculated gas-liquid mass transfer coefficient (K_La). The desired 3 min on/off cycle was achieved by increasing the omega terms in the sine function (ω of sin ωt). Then 'AerSwitch' was assigned as the expression for K_La.

Approach 2 provides an equal time interval for both the 'on' and 'off' cycle because of the sine function. Therefore, if we indeed need more accurate cycles, the 'AerSwitch' function should be fine-tuned. However, in our experimental case, on/off cycle was 3 min on and 4 min off. Therefore 3 min on/off was considered as a reasonable number for the simulations.

The initial conditions and the input values derived from the experimental study (Sivalingam et al., 2020a) are presented in Tables 1 and 2. Other required parameters are adapted from (Rauch et al., 1999; Mannina et al., 2011; Reichert, 1998), listed in Table 3.

Table 1. Initial conditions for the model.

Variable	*Description*	*Initial values*	*Units*
L_f	Biofilm thickness	1e-005	m
X_{het}	Heterotrophs	0.1*rho	mgL^{-1}
X_{aut}	Autotrophs	0.1*rho	mgL^{-1}
C_{HCO_3}	Alkalinity	1e-005	mgL^{-1}
C_{NH_4}	Ammonium	1e-005	mgL^{-1}
C_{NO_3}	Nitrate	1e-005	mgL^{-1}
$C_{S_{Org}}$	Soluble organics	1e-005	mgL^{-1}
C_{O_2}	Dissolved oxygen	1e-005	mgL^{-1}

Table 2. Model input parameters.

Variable	*Description*	*Inputs*	*Units*
Q_{in}	In flow rate	0.065	m^3d^{-1}
X_{het}	Heterotrophs	0	mgL^{-1}
X_{aut}	Autotrophs	0	mgL^{-1}
C_{HCO_3}	Alkalinity	1952	mgL^{-1}
C_{NH_4}	Ammonium	450	mgL^{-1}
$C_{S_{Org}}$	Soluble organics	100	mgL^{-1}
C_{O_2}	Dissolved oxygen	0.5	mgL^{-1}

3 Results and Discussion

Figure 3 shows the biofilm propagation. On day 75, the biofilm thickness (L_f) reached steady-state at 1.16 mm. The biofilm contains both autotrophic (X_{Aut}) and heterotrophic (X_{het}) biomass. The distribution along the biofilm matrix is presented in Figure 4. Heterotrophic growth dominates the biomass composition. At substratum, heterotrophic biomass concentration decreases with time, the opposite happens for autotrophic biomass concentration. This could be due to the diffusion limitation of substrates.

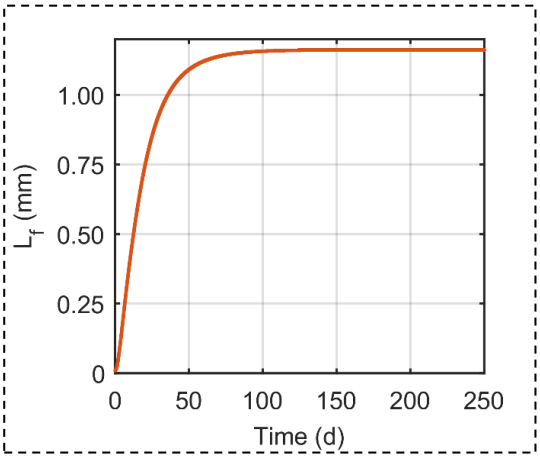

Figure 3. Biofilm thickness progression.

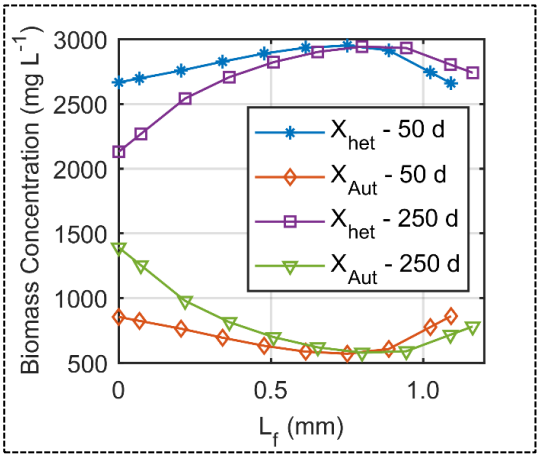

Figure 4. Autotrophic and heterotrophic bacterial distribution in the biofilm matrix on 50th and 250th days.

Table 3. Model parameters.

Symbol	*Parameter description*	*Values*	*Units*	*Reference*
DS_{O2}	Diffusion coefficient of oxygen	2.1	$cm^2 d^{-1}$	(Rauch et al., 1999)
DS_{Org}	Diffusion coefficient of organic matter	0.58	$cm^2 d^{-1}$	(Rauch et al., 1999)
DS_{NO_3}	Diffusion coefficient of nitrate nitrogen	2	$cm^2 d^{-1}$	(Rauch et al., 1999)
DS_{NH_4}	Diffusion coefficient of ammonium nitrogen	1.8	$cm^2 d^{-1}$	(Rauch et al., 1999)
DS_{HCO3}	Diffusion coefficient of alkalinity	2	$cm^2 d^{-1}$	(Reichert, 1998)
DS_{N_2}	Diffusion coefficient of nitrogen gas	1.9	$cm^2 d^{-1}$	(Reichert, 1998)
DX	Diffusion coefficient of biomass	1e-7	$cm^2 d^{-1}$	(Reichert, 1998)
μ_{Het} and μ_{Anox}	Maximum growth rate heterotrophs	2.8	d^{-1}	(Mannina et al., 2011; Rauch et al., 1999)
μ_{Aut}	Maximum growth rate autotrophs	1.0	d^{-1}	(Mannina et al., 2011)
Y_{het}	Heterotrophic yield coefficient	0.65	$\frac{mgCOD}{mgCOD}$	(Rauch et al., 1999)
Y_{Aut}	Autotrophic yield coefficient	0.22	$\frac{mgCOD}{mgNH_4}$	(Mannina et al., 2011)
b_{het}	Heterotrophic decay rate	0.1	d^{-1}	(Mannina et al., 2011)
b_{Aut}	Autotrophic decay rate	0.06	d^{-1}	(Mannina et al., 2011)
η_{het}	Coefficient for anoxic heterotrophic growth	0.80	-	(Mannina et al., 2011)
iXB_{aut}	Ammonia fraction in biomass	0.08	$\frac{mgN}{mgCOD}$	(Mannina et al., 2011)
iXP_{aut}	Ammonia fraction in particulate fraction	0.06	$\frac{mgN}{mgCOD}$	(Mannina et al., 2011)
K_{NH}	Saturation coefficient for ammonia	1	mgL^{-1}	(Mannina et al., 2011)
$K_{S_{Org}}$	Saturation coefficient for organic matter	20	mgL^{-1}	(Mannina et al., 2011)
K_{NO_3}	Saturation coefficient for nitrate	0.5	mgL^{-1}	(Mannina et al., 2011)
K_{O_2}	Saturation coefficient for oxygen	0.2	mgL^{-1}	(Mannina et al., 2011)
$K_{O_{2het}}$	Saturation coefficient for oxygen heterotrophic organism	0.2	mgL^{-1}	(Mannina et al., 2011)
$K_L a$	Oxygen transfer coefficient	207	d^{-1}	Calculated

The X_{Aut} and X_{het} biomass distribution in the biofilm bulk profiles are depicted in Figure 5. In the beginning, the X_{het} reached 30 mg L^{-1}, which is six times higher than $X_{Aut.}$ However, after 50 days of operation, it levelled at 10 mg L^{-1}, while the X_{Aut} remained stable at around 5 mg L^{-1}. The lack of soluble organics is the reason for such a remarkable reduction in X_{het}.

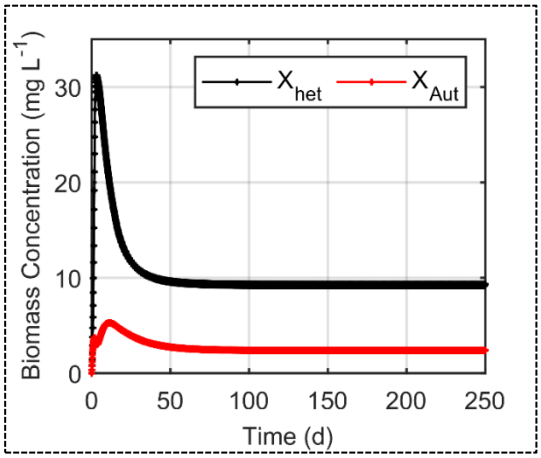

Figure 5. Autotrophic and heterotrophic biomass distribution in the biofilm bulk.

Figure 6 illustrates the dissolved oxygen (DO) concentration during the changes in aeration cycles. The on/off aeration scheme facilitates the nitrification and denitrification process, resulting in 13% ammonium removal. In addition, nitrogen gas evolution was observed. Small amounts of nitrate were also produced. All these nitrogen species concentration profiles are shown in Figure 7.

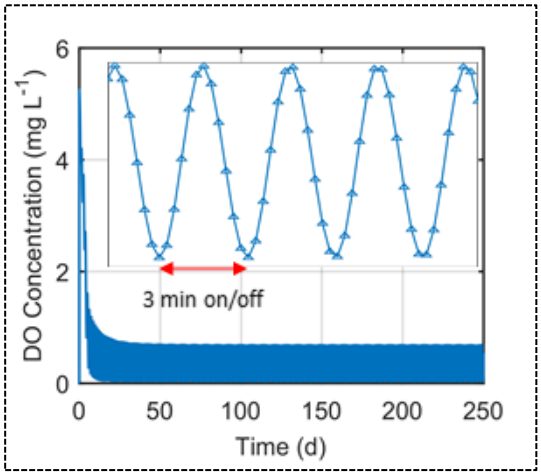

Figure 6. On/off aeration scheme enlarged version.

The DO concentration along the biofilm thickness was investigated when the aeration was switched 'on' (aerobic) and switched 'off' (anoxic). The simulation results are depicted in Figure 8. Oxygen concentration (along with biofilm thickness) is higher when aeration is "on" than where aeration is "off". The significant change in the aeration profile proves that DO concentration is the rate-limiting factor for the nitrogen removal process. However, the DO difference in those two conditions is less significant at the substratum, while a notable difference is in the outermost layer.

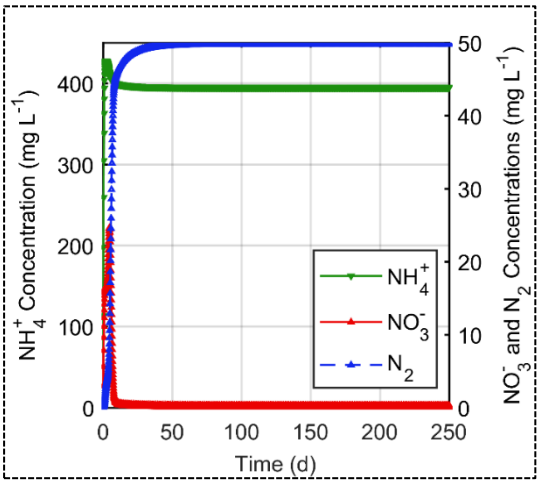

Figure 7. Nitrogen species variation in the bulk liquid.

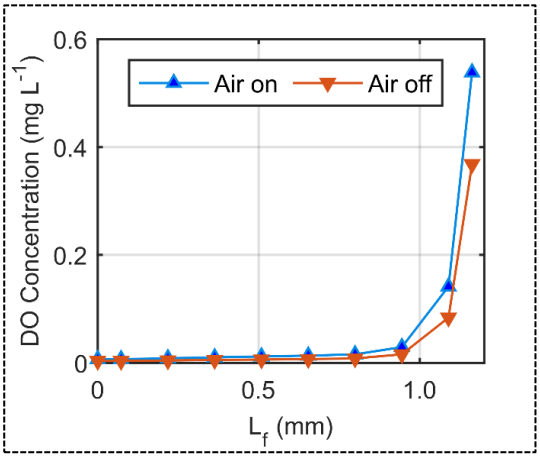

Figure 8. DO concentration profiles along with the biofilm thickness at aerobic and anoxic conditions.

Ammonium, nitrate, soluble organics, and nitrogen gas concentration changes along with the biofilm matrix at 250th day are presented in Figure 9. The ammonium, nitrate and soluble organic concentration trends have corresponded to each other; however, the gradient differs due to the different diffusion coefficients. The nitrogen gas concentration remains stable at 50 mg L^{-1} throughout the entire biofilm matrix. It is reasonable because of very sparingly soluble behaviour.

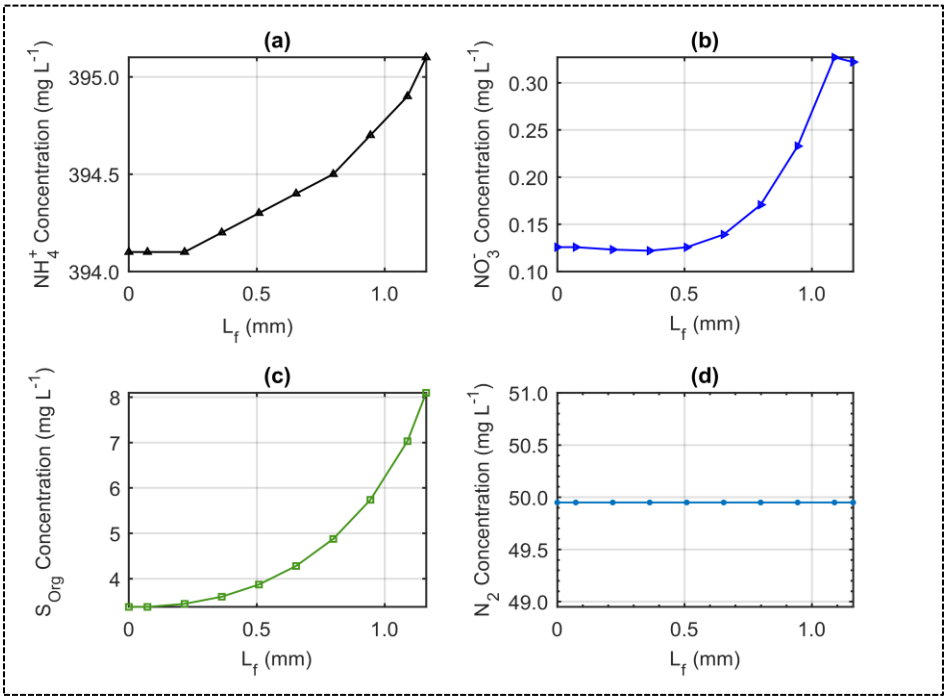

Figure 9. Substrate concentration profiles along the biofilm matrix at 250th day. (a) Ammonium, (b) Nitrate, (c) Soluble organics and (d) Nitrogen gas.

4 Conclusion and Further Development

The MBB model with activated sludge processes was successfully implemented in AQUASIM software. The simulation results illustrate that the model can study the impact of intermittent aeration on biofilm thickness, biomass and substrate distribution within the biofilm, biomass and substrates concentration in the bulk liquid.

The simulation results showed lower ammonium removal efficiency (13%) than the experimentally achieved efficiency (50%) from the pilot reactor. This is because the ASM1 does not include the possible shortcut and anaerobic ammonium oxidative pathways that occur in the experiment. Therefore, the model requires further development by integrating all possible ammonium nitrogen removal pathways to match the experimental results.

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