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Optimal strategies of fill and aeration in a sequencing batch reactor for biological nitrogen and carbon removal

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Abstract−A modified version of the IAWQ activated sludge model No. 1 (ASM 1) is adopted for the simulation of a sequencing batch reactor (SBR) to optimize the removal of nitrogen (T-N) and organic matters (COD) from wastewater. Since the removal of nitrogen requires both aerobic nitrification and anaerobic denitrification, we seek to find the optimal strategies of substrate fill and aeration. Substrate filling strategy critically influences the removal efficiency of T-N and COD; one fast discrete fill in the beginning of a cycle leads to the best result, while a slow continuous fill results in poor nitrification. In addition, the total aeration time is more important for the removal efficiency than the aeration frequency. A short aeration is beneficial for T-N removal, while a long aeration is beneficial for COD removal as expected. As a result, there is an optimal condition of aeration for the simultaneous removal of T-N and COD.

Key words: Wastewater Treatment, Nitrogen Removal, Sequential Batch Reactor, Optimization Strategy

INTRODUCTION

The sequencing batch reactor (SBR) is a fill-and-draw activated sludge system for wastewater treatment. The SBR system usually consists of more than two reactors that are operated in a sequential mode in order to treat wastewater continuously. A reactor is filled with wastewater during a discrete period and then operated like a batch reactor. After treatment, aeration and mixing are discontinued to settle down activated sludge, and the clear supernatant is drawn or decanted from the reactor. A cycle for a typical SBR consists of the following five distinct phases: fill, react, settle, draw (or decant), and idle. During the reaction phase, the reactor can be operated in aerobic, anoxic, and anaerobic conditions to achieve a certain goal of removing organic matter, nitrogen, and phosphorus [1]. The SBR system has the same unit processes as the conventional activated sludge (CAS) system that has been the most applied method for wastewater treatment.

The major difference of two systems is that the SBR performs equalization, biological treatment, and secondary clarification in a single tank using a timed control sequence, while the CAS system accomplishes those unit processes in separate tanks. The SBR system has many advantages over the CAS system, such as operating flexibility, easy adaptation to nutrient removal, better resistance to sludge bulking, nearly ideal quiescent solid-liquid separation, ability to meet effluent limitations (organic and nutrients), and potential savings of capital cost and space by eliminating separate clarifier and equalizer. However, the SBR requires a higher level of maintenance due to timing units and controls [2,3].

Biological nitrogen removal has been adopted as the most economical method of controlling nitrogen in wastewater effluents. Nitrification is governed by autotrophs which aerobically oxidize ammonium nitrogen to nitrite mainly by *Nitrosomonas* sp., and subsequently nitrite is further oxidized to nitrate mainly by *Nitrobacter* sp. [4]. Nitrate formation is usually considered as the rate-limiting step in whole nitrification [5]. Nitrate is converted to molecular nitrogen by heterotrophic bacteria under an anoxic condition during denitrification step. Therefore, the removal of nitrogen requires both aerobic nitrification and anoxic denitrification sequentially or simultaneously.

$$NH_4^+ \rightarrow NO_2^- \rightarrow NO_3^- \rightarrow N_2(\text{gas})$$

Mathematical models provide meaningful insights for the design and prediction of complex biological processes. A general activated sludge model 1 (ASM1) was initially developed for wastewater treatment systems [6] and has been widely used. Oles and Wilderer modified the ASM1 to simulate the performance of nitrogen removal in an SBR system and suggested the most optimal strategy to be the triple repeated symmetric pulses of anoxic fill and anoxic/oxic react phases [7]. Coelho et al. also applied the ASM1 for an SBR system to find the optimal batch scheduling and filling strategy for biological nitrogen removal, and found that a discrete fill strategy of wastewater and oxygen was much efficient than other fill types [3]. However, there is no investigation for individual effects of fill and aeration on the removal efficiencies of total nitrogen (T-N) and organic matter (COD).

The purpose of this work was to optimize the performance of an SBR system for the simultaneous removal of T-N and COD by investigating the separate effects of substrate fill type and aeration type on the removal efficiencies of T-N and COD with the aid of computer simulation based on a modified ASM1.

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MATHEMATICAL MODEL AND SIMULATION

1. A Mathematical Model

The ASM1 was originally developed by the IAWPRC Task Group to simulate the uptake of organic matter, nitrification, and denitrification in a continuous flow activated sludge system [6]. The ASM1 model includes the kinetic expressions of aerobic growth of heterotrophic and autotrophic bacteria, anoxic growth of heterotrophs, decay of heterotrophs and autotrophs, organic nitrogen mineralization, hydrolysis of nitrogeneous and organic matter retained in the biofloc, and stoichiometric coefficients for each of the identified processes (Eqs. (1)-(5), Table 1). Dynamic mass balances for wastewater species in an SBR were adopted from the SBR model [3] (Eqs. (6)-(15), Table 1).

The main differences between the ASM1 model [6] and the modified model for an SBR [3] are that the rate of organic nitrogen mineralization is assumed to be governed by the anoxic growth rate in an SBR (Table 1) and that two correction factors for anoxic phase (η_g and η_h) are relatively high in an SBR (Table 2). Assumptions adopted in the original ASM 1 model were kept: constant temperature and pH, no inhibitory effects, no nutritional limitations, homogeneous biomass, complete mixing, and constant kinetic parameters.

2. Computer Simulation

For the computer simulation of an SBR system, all the kinetic and stoichiometric parameters (Table 2) were adjusted to a set of the given experimental data [7] based on the values suggested by the ASM1 model [6]. For the parameter adjustment, a heuristic method (extensive trial and error method) was used: primarily adjusting two correction factors for anoxic phase (η_g and η_h), autotrophic yield Y_A, and heterotrophic yield Y_H. A set of nonlinear ordinary differ-

Table 1. Mathematical models of an SBR. The model was originally developed for activated sludge process [6] and modified for an SBR [3]

Processes	Process rate equations
Aerobic growth of autotrophic microorganisms	$r_{A,G}=\mu_A\left(\frac{S_{NH}}{K_{NH}+S_{NH}}\right)\left(\frac{S_o}{K_{OA}+S_o}\right)X_{BA}$
Aerobic and anoxic growth of heterotrophic bacteria	$r_{H,G}^{aerobic}=\mu_H X_{BH}\left(\frac{S_s}{K_s+S_s}\right)\left(\frac{S_o}{K_{OH}+S_o}\right)$
	$r_{H,G}^{anoxic}=\mu_H X_{BH}\left(\frac{S_s}{K_s+S_s}\right)\eta_g\left(\frac{K_{OH}}{K_{OH}+S_o}\right)\left(\frac{S_{NO}}{K_{NO}+S_{NO}}\right)$
Organic nitrogen mineralization	$r_{NH}=k_a S_{ND} X_{BH}\left[\left(\frac{S_o}{K_{OH}+S_o}\right)\eta_g\left(\frac{K_{OH}}{K_{OH}+S_o}\right)\left(\frac{S_{NO}}{K_{NO}+S_{NO}}\right)\right]$
Hydrolysis of nitrogenous and organic matter	$r_h=k_h\frac{X_s/X_{BH}}{K_X+(X_s/X_{BH})}X_{BH}\left[\left(\frac{S_o}{K_{OH}+S_o}\right)\eta_h\left(\frac{K_{OH}}{K_{OH}+S_o}\right)\left(\frac{S_{NO}}{K_{NO}+S_{NO}}\right)\right]$
Mass balance for readily biodegradable substrate	$\frac{dS_s}{dt}=\frac{F}{V}(S_{s,f}-S_s)-\frac{1}{Y_H}r_{H,G}+r_h$
Mass balance for slowly biodegradable substrate	$\frac{dX_s}{dt}=\frac{F}{V}(X_{s,f}-X_s)+(1-f_p)(r_{H,d}+r_{A,d})-r_h$
Mass balance for autotrophic biomass	$\frac{dX_{BH}}{dt}=-\frac{F}{V}X_{BH}+r_{H,G}-r_{H,d}$
Mass balance for heterotrophic biomass	$\frac{dX_{BH}}{dt}=-\frac{F}{V}X_{BA}+r_{A,G}-r_{A,d}$
Mass balance for particulate material	$\frac{dX_p}{dt}=-\frac{F}{V}X_p+f_p(r_{H,d}+r_{A,d})$
Mass balance for nitrate	$\frac{dS_{NO}}{dt}=\frac{F}{V}(S_{NO,f}-S_{NO})-\frac{1}{Y_A}r_{A,G}-\left(\frac{1-Y_h}{2.86Y_h}\right)r_{H,G}^{anoxic}$
Mass balance for ammonium	$\frac{dS_{NH}}{dt}=\frac{F}{V}(S_{NH,f}-S_{NH})-\left(i_{XB}+\frac{1}{Y_A}\right)r_{A,G}+r_{NH}-i_{XB}r_{H,G}$
Mass balance for soluble organic nitrogen	$\frac{dS_{ND}}{dt}=\frac{F}{V}(S_{ND,f}-S_{ND})+r_h\left(\frac{X_{ND}}{X_S}\right)-r_{NH}$
Mass balance for particular organic nitrogen	$\frac{dX_{ND}}{dt}=\frac{F}{V}(X_{ND,f}-X_{ND})+(i_{XB}-f_p i_{XP})(r_{H,d}+r_{A,d})-r_h\left(\frac{X_{ND}}{X_s}\right)$
Mass balance for dissolved oxygen	$\frac{dS_o}{dt}=\frac{F}{V}(S_{o,f}-S_o)-\frac{1-Y_H}{Y_H}r_{H,G}^{aerobic}-\frac{4.57-Y_A}{Y_H}r_{A,G}+r_a$
Total mass balance	$\frac{dV}{dt}=F$

Table 2. Parameter values for computer simulation of an SBR. All the kinetic and stoichiometric parameters were adjusted from the ASM1 model [6] and the experimental data [7]

Parameter	Definition	Value and unit
b_a	Decay coefficient for autotrophic microorganism	0.00417/h
b_H	Decay coefficient for heterotrophic microorganisms	0.0125/h
f_p	Biomass fraction converted to particulate material	0.08
η_g	Correction factor for biomass active anoxic growth	0.85
η_h	Correction factor for anoxic hydrolysis	0.8
i_{XB}	Biomass nitrogen/COD ratio	0.086 mg N/mg COD
i_{XP}	Decay products nitrogen/COD ratio	0.06 m N/ mg COD
k_a	Ammonification rate coefficient	0.0167 L/mg/h
k_h	Maximum hydrolysis rate	0.092 mg COD/mg cell/h
K_{NH}	Ammonium saturation coefficient	1.0 mg/L
K_{NO}	Nitrate saturation coefficient	1.0 mg/L
K_{OA}	Dissolved oxygen saturation coefficient for autotrophic biomass	0.4 mg/L
K_{OH}	Dissolved oxygen saturation coefficient for heterotrophic biomass	0.2 mg/L
K_s	Readily biodegradable substrate saturation coefficient	20 mg/L
K_X	Slowly biodegradable substrate saturation coefficient	0.15 mg/L
μ_A	Maximum specific growth rate of autotrophic microorganism	0.021/h
μ_H	Maximum specific growth rate of heterotrophic microorganisms	0.417/h
t	Operation time	0-8 h
V	Reactor volume	100 L
Y_A	Autotrophic yield	0.2 mg X_{BA}/mg N
	Heterotrophic yield	0.5 mg X_{BH}/mg COD
Influent condition		
F_f	Feed flow rate	27.5 L/h
$S_{ND,f}$	Soluble organic nitrogen concentration	18.1 mg/L
$S_{NH,f}$	Ammonium concentration	40.2 mg/L
$S_{NO,f}$	Nitrate concentration	0 mg/L
$S_{o,f}$	Dissolved oxygen concentration	4 mg/L
$S_{s,f}$	Readily biodegradable substrate concentration	65 mg/L
$X_{BA,f}$	Autotrophic biomass concentration	0 mg/L
$X_{BH,f}$	Heterotrophic biomass concentration	45 mg/L
$X_{ND,f}$	Particulate organic nitrogen concentration	0 mg/L
$X_{p,f}$	Particulate material concentration	0 mg/L
$X_{s,f}$	Slowly biodegradable substrate concentration	209.3 mg/L

ential equations was solved simultaneously by using a stiff ODE solver, ODE23S of MATLAB 5.0 (The Mathworks Inc.). Initially, parameters were adjusted to validate the model and to compare to the experimental data [6]. Optimization of the SBR system was performed for a high removal efficiency of T-N and COD with respect to four types (case I, II, III, IV) of substrate filling strategy and aeration strategy (number of aeration and total aeration time).

RESULTS AND DISCUSSION

1. Model Validation

A modified ASM1 was adjusted quite well to a set of experimental data of nitrogen removal in an SBR [7] as shown in Fig. 1. During the anoxic period for 1 h in the beginning, organic nitrogen was converted to ammonium, and nitrate from ammonium was denitrified during the following oxic phases. Simulated profiles of nitrate and ammonium nitrogen slightly deviated from experimental data in the first reaction phase for initial 3 hours, particularly a rapid NO_3 increase and a rapid NH_4 drop after starting the first aeration step. However, those deviations gradually disappeared in the next reaction phases. Hence, the processes of aerobic nitrification and anoxic denitrification could be reliably predicted.

2. Effect of Substrate Fill Type

To investigate the substrate filling strategy for a high nitrogen removal efficiency, four cases of fill type (case I, one time feeding for 10 min; case II, two times feeding for 1 h fill; case III, three times feeding for 1 h fill; case IV: feeding for 8 h slowly) were applied to the SBR system under the same profile of DO (total aeration time, 3 h and aeration frequency, 4). Nitrogen profiles of two extreme cases (case I of fast fill and case IV of slow fill) are shown in Fig. 2. Clearly, a fast fill results in better removal efficiency of T-N than a slow fill, even though the fast fill produces a higher concentration of nitrate and ammonium than the slow fill. Additionally, two cases II and III with total 1 h fill resulted in the same result as case I.

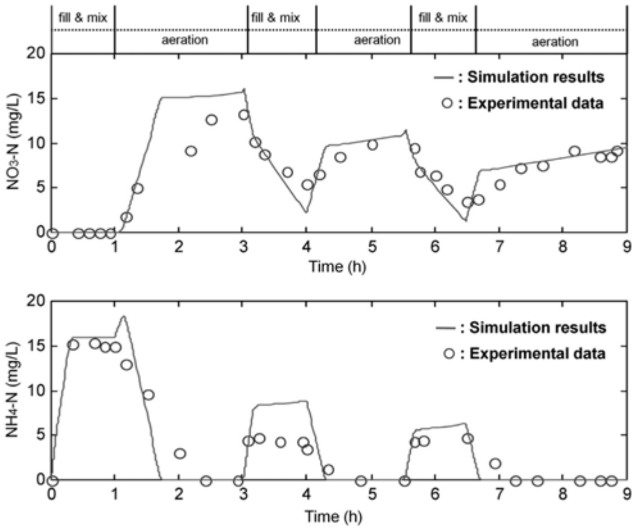

Fig. 1. Mathematical simulation of nitrogen profiles of an SBR. Substrates were filled for 10 min and mixed for 50 min under an anaerobic condition, and aeration was performed for 2 hours. Simulation results are shown as a line and experimental data are shown as a circle.

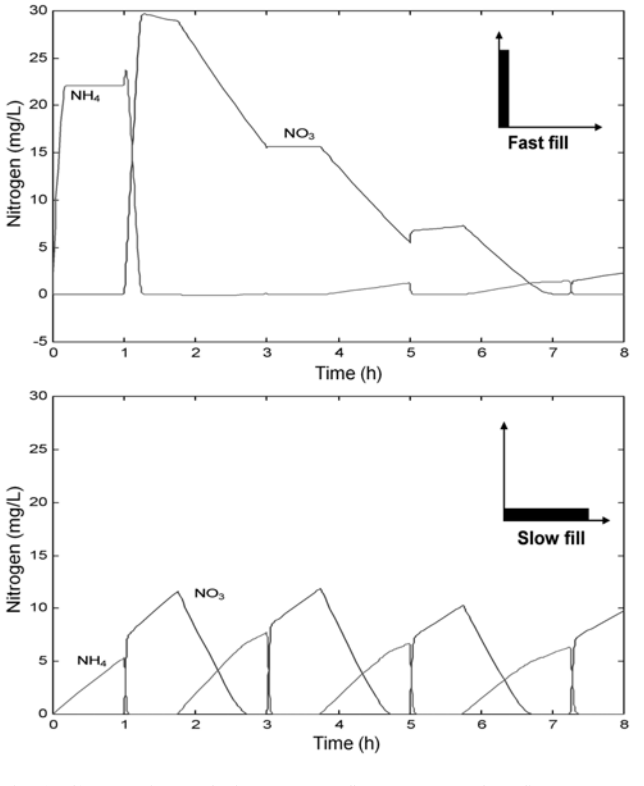

Fig. 2. Comparison of nitrogen profiles between fast fill and slow fill under the condition of 3 h total aeration time and four aeration frequency. As shown inside figures, fast fill indicates feeding substrates for only 10 min, and slow fill indicates feeding substrates for 8 h continuously.

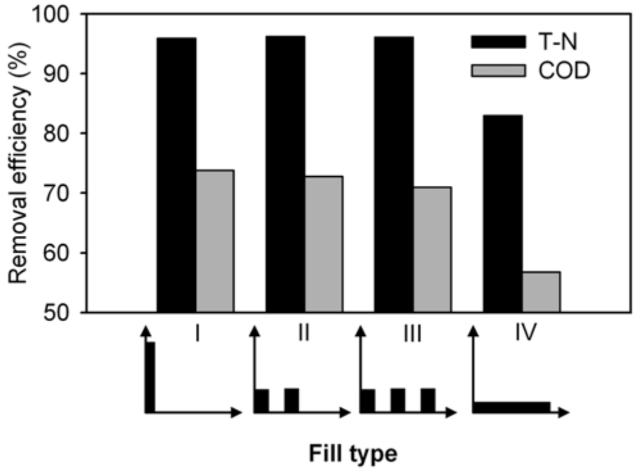

Fig. 3. Effect of fill type on removal efficiency T-N and COD for 8 h under the conditions of 3 h total aeration time and four aeration frequency. Case I, one time feeding for 10 min; case II, two times feeding for 1 h fill; case III, three times feeding for 1 h fill; case IV, feeding for 8 h slowly.

Table 3. Removal efficiency of T-N according to total aeration time and aeration frequency

		Removal efficiency of T-N (%)				
		Total aeration time (h)				
		1	2	3	4	5
Aeration frequency	1	96.3	93.5	91.1	79.7	68.1
	2	96.4	93.8	91.9	85.4	75.7
	3	96.8	94.8	92.9	84.8	71.6
	4	98.6	97.6	95.9	86.9	73.9
	5	98.9	95.8	93.5	83.3	73.7

In Fig. 3, removal efficiencies of both T-N and COD for three cases (I, II, and III) were almost same after 8 h operation, while a slow continuous fill (case IV) showed a decreased removal efficiency of T-N and COD. Due to a simpler process arrangement, one-time fast-fill (case I) is the best fill strategy to remove nitrogen and COD simultaneously in the SBR system. Recently, a similar result was reported by another group as one fast-fill led to the same result with two or three discrete fills for the nitrogen removal in an SBR [8].

3. Effect of Aeration Strategy

Nitrification of ammonium by autotrophic bacteria requires molecular oxygen dissolved in the mixed liquor by aeration (oxic react phase), while denitrification of nitrate by heterotrophic bacteria does not need oxygen (anoxic react phase) [4]. Also, sufficient oxygen (usually 2 mg/*l* DO) must be supplied into the reactor in order to biodegrade organic matter (COD) by heterotrophic bacteria. Hence, it appears there is an optimal aeration strategy to remove nitrogen and organic matter simultaneously from wastewater in a desired limit. Total aeration time and aeration frequency were changed independently to investigate the effects of these variables on removal efficiencies of T-N and COD under the same fill strategy, one-time 1 hr constant fill and mix (Tables 3 and 4). Obviously, a shorter total aeration time and long anaerobic time increased and saturated the removal efficiency of T-N, while the longer aeration time resulted in less T-N removal (Table 3). The result indirectly confirms that nitrate formation between the aerobic nitrification (from ammonium

Table 4. Removal efficiency of COD according to total aeration time and aeration frequency

		Removal efficiency of COD (%)				
		Total aeration time (h)				
		1	2	3	4	5
Aeration frequency	1	42.9	60.1	75.8	77.8	78.0
	2	45.5	61.9	73.3	77.9	78.2
	3	43.7	60.4	73.2	77.9	78.2
	4	44.6	60.8	73.8	77.9	78.2
	5	45.0	59.8	73.7	77.9	78.1

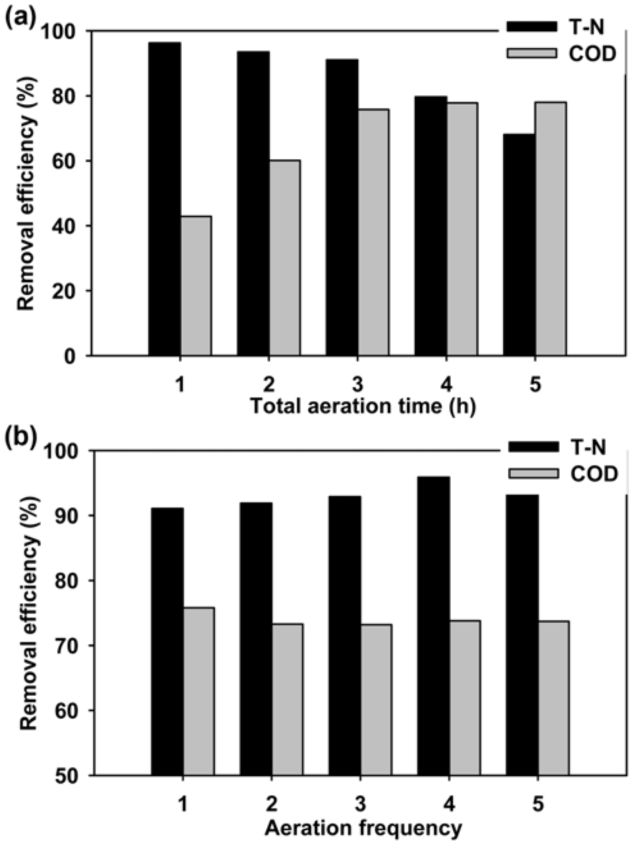

Fig. 4. Effects of total aeration time (a) and aeration frequency (b) on removal efficiency of T-N and COD. Simulation of (a) was performed under the conditions: one-time 1 h constant fill and aeration frequency 4. Simulation of (b) was performed under the conditions: one-time 1 h constant fill and 3 h total aeration time.

to nitrite) and the anaerobic denitrification process (from nitrate to nitrogen gas) is an important step for the whole nitrogen removal. For the simultaneous removal of T-N and COD in this system, the optimal aeration scheme is about 3 hour of total aeration time and aeration frequency 4 in which the efficiency of T-N removal is above 90% and the efficiency of COD removal is above 70% (Figs. 4(a) and (b)).

Tables 3 and 4 also demonstrate that the removal efficiency of T-N, but not COD, was significantly affected by the aeration frequency. For example, four times of aeration frequency was optimal with 1 h total aeration time. In contrast, the removal efficiency of COD was increased with a longer total aeration, while the aeration frequency from one to five did not much influence the removal efficiency of COD (Table 4). The results of simulation are consistent with the previous report [3], as a short aeration time is beneficial for T-N removal but a long aeration is beneficial for COD removal. From an independent study, we also experimentally observed the same result in that there is an optimal aeration time for the simultaneous removal of T-N and COD [9].

CONCLUSION

A modified ASM1 is adjusted well to simulate an SBR system for the simultaneous removal of nitrogen and COD. We found an optimal strategy of substrate fill and aeration for the SBR system. One fast discrete fill (symmetric pulse) in the beginning of a cycle under anoxic condition was best to achieve a high removal efficiency of T-N and COD. For the aeration strategy, the removal efficiencies of T-N and COD were more sensitive to total aeration time than aeration frequency, while the aeration frequency is an important factor only for only T-N removal. Also, the effects of total aeration time on the removal efficiencies of T-N and COD were a reversal each other. Hence, there was an optimal value of total aeration time for removal of nitrogen and COD in an SBR.

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