SBR SYSTEM FOR PHOSPHORUS REMOVAL: ASM2 AND SIMPLIFIED LINEAR MODEL

By Hyunook Kim,[1] Oliver J. Hao,[2] Fellow, ASCE, and Thomas J. McAvoy[3]

ABSTRACT: An SBR (sequencing batch reactor) system was evaluated for nutrient removal. The system is capable of removing 95% of influent PO_4^{3-}, or from 6.7 to 0.4 mg P/L, with the addition of acetate of 120–150 mg COD/L in the feed solution (primary effluent). Nitrification was also achieved within the preset aeration cycle time in reducing the effluent ammonia level from 16.3–19.8 mg N/L to 0.2–0.3 mg N/L. However, denitrification was incomplete due to a slower endogenous nitrate respiration rate in the idle period, resulting in an effluent nitrate level of 7–8 mg N/L. A linear version of the ASM2 (Activated Sludge Model No. 2) was developed to model the performance of an SBR system for nutrient removal. The developed model appropriately predicts the dynamic behavior of the SBR system with respect to phosphate release/uptake, nitrification, ammonification, and denitrification. Compared with the full ASM2, the calibration of model parameters and model simulation require less computational time for practical implementation of the linear model into a process control system for the SBR.

INTRODUCTION

SBR (sequencing batch reactor) activated sludge systems have been used successfully to treat a variety of pollutants, e.g., nutrients (Stephens and Stensel 1998; Furumai et al. 1999b), landfill leachates (Timur and Ozturk 1999), jet fuel (Yocum et al. 1995), phenolic compounds (Brenner et al. 1992), trichloroethylene (Segar et al. 1995), pulping black liquor (Kortekaas et al. 1998), and dyes (Krull et al. 1998). Particularly, the SBR system is very effective in nitrogen and/or phosphorus removal from wastewater. The SBR system is a temporarily alternating system, where a tank is filled, mixed, aerated, idled, settled, and decanted for predetermined time periods. These phases of sequence can be used for various microbial reactions requiring different environmental conditions. For example, during the mix period immediately after the fill stage, the system is in an anoxic/anaerobic state for anoxic denitrification and anaerobic phosphorus release. During aeration, ammonia is nitrified to nitrate by nitrifiers and phosphorus is uptaken by PAOs (phosphate accumulating organisms). Endogenous nitrate respiration takes place during the idle period after the aeration period.

The major advantage is that the phases in sequence can be rearranged, and some of them can even be omitted, depending on design purpose (Irvine and Ketchum 1988). Another advantage is that the system does not require much space and separate clarifiers, since it is operated in a temporal sequence. Also, the duration of each cycle (stage) can be varied flexibly according to the influent dynamics. A cost saving associated with aeration energy is possible, if the aeration cycle can be terminated when the desirable reactions are complete.

Various mathematical models and simulations have been proposed or used for process design, performance evaluation, or control of activated sludge systems for phosphorus removal (Wentzel et al. 1986; Ante et al. 1994; Demuynck et al. 1994; Kuba et al. 1996). The industrial standard for modeling biological phosphorus removal is the so-called ASM2 (Activated Sludge Model No. 2), formulated by a committee of the International Association of Water Quality in 1995 (Gujer et al. 1995). Various microbial reactions occurring in a biological nutrient removal system, such as organic oxidation, nitrification, denitrification, and phosphate release and uptake, can be mathematically modeled with ASM2. The model was recently upgraded to ASM2d (Henze et al. 1998). Even though the ASM2 and ASM2d are sound in providing better understanding of process dynamics, the structure of these models is too complex to be implemented in a real-time process control. For example, ASM2 has 17 rate equations, 17 state variables, and 46 stoichiometric and kinetic parameters. As a result, these models require a great deal of experimental data for calibration or evaluation; some variables of the models are not even measurable in practice (Henze 1992; Henze et al. 1995). The high complexity of the model structure and state variables has hindered the implementation of the model into the control of a real plant operation. For these reasons, only limited uses of these models have been reported in literature, e.g., simulation of the performance of SBR systems (Isaacs et al. 1995; Furumai et al. 1999a; Zhao et al. 1999) and retrofit of a biological nutrient removal process (Kurata et al. 1996).

Practically speaking, simplification of these complicated models has some benefits. The simplified models still retain process fundamentals; the model parameters can be easily calibrated with a minimum amount of experimental data and model simulations performed with less computational resources. Consequently, a simplified model can be easily implemented into a real biological system for process control. A simplified model, however, may not predict the performance of a system well as compared with the full model. The errors caused from the simplification, however, can be compensated with some error correction algorithms, such as neural networks (Zhao et al. 1997), Kalman filter (Jeppsson and Olsson 1993), or simple feedback (McAvoy et al. 1999). Furthermore, a hybrid model consisting of a simplification of ASM2 and neural networks for the error compensation appears superior to the ASM2 in terms of model predictions (Zhao et al. 1999).

The simplification approach includes order reduction (Jeppsson and Olsson 1993), elimination/combination of some processes or variables (Zhao et al. 1997), and separation of equations into subsets (Perregaard 1993). Another approach is to linearize process expressions to substitute the complicated Monod-type rate equations. In fact, a linear version of ASM1 (Activated Sludge Model No. 1) has been applied successfully to a bench scale alternating aerobic/anoxic system (Anderson et al. 2000).

In this study, a bench-scale SBR system was operated for about 8 months for phosphorus removal with three different

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[1] PhD Student, Dept. of Civ. and Envir. Engrg., Univ. of Maryland, College Park, MD 20742.

[2] Prof., Dept. of Civ. and Envir. Engrg., Univ. of Maryland, College Park, MD. E-mail: ojh1@eng.umd.edu (corresponding author).

[3] Prof., Inst. of Sys. Res., Univ. of Maryland, College Park, MD.

Note. Associate Editor: Robert Arnold. Discussion open until July 1, 2001. Separate discussions should be submitted for the individual papers in this symposium. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on February 4, 2000. This paper is part of the ***Journal of Environmental Engineering***, Vol. 127, No. 2, February, 2001. ©ASCE, ISSN 0733-9372/01/0002-0098–0104/$8.00 + $.50 per page. Paper No. 22187.

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aeration ratios (f_a: aeration cycle time/overall cycle time) to evaluate the kinetics of various microbial reactions. ORP (oxidation reduction potential) and pH were monitored to observe whether some control points cited in the literature are consistently detected for potential on-line control for terminating a particular cycle. These control points include the so-called ''ammonia valley'' on the pH profile for indicating the end of nitrification (Al-Ghusain et al. 1994) and the ''nitrate knee'' on the ORP profile for signifying the end of denitrification (Wareham et al. 1991). Additionally, a linear model of the ASM2 was used to model nutrient removal. A comparison of the model prediction with the full ASM2 and experimental data is presented, and it indicates the utility of the linear model. In an accompanying paper (Kim et al. 2001), the linear model is incorporated into an optimization scheme and applied to control an SBR system for phosphorus removal by adjusting the duration of ''aerate'' cycles.

MATERIAL AND METHODS

Sludge and Wastewater

The seeding sludge for a bench-scale SBR system was obtained from a local wastewater treatment plant. Primary effluent from the same plant was collected twice a week, stored in a refrigerator, and used as the feed to the reactor. In Phase I, sodium acetate of 60 mg COD/L was supplemented to the feed solution to enhance the anaerobic phosphorus release; later, the external carbon addition was increased to 120–150 mg COD/L in Phases II and III.

Reactor System

A bench-scale reactor (4 L) was operated in the sequence of fill, mix, aerate, idle, settle, and decant phases. Saturated air was used for aeration during the aerate period, and mixing of the reactor contents during the mix period was achieved using a magnetic stirrer. The system was equipped with solid state relays and a solenoid valve for turning the following equipment on or off: the air, the mixer, and the pumps for feeding or supernatant decant. ORP (Mettler Toledo Pt4805-DPAS-SC) and pH (Mettler Toledo 405-DPSA-SC) were monitored continuously. The influent feed (immersed in an ice water tank) was transferred to the reactor by a peristaltic pump. A MCRT (mean cell retention time) of 12 days was maintained by wasting an appropriate amount of mixed liquor directly from the reactor at the end of the aerobic cycle. During the decant period, supernatant of two liters was removed from the reactor, and the same amount of fresh feed was introduced during the subsequent fill period. The operation conditions for each phase are presented in Table 1.

Wastewater samples for dynamic studies were collected directly from the reactor. The influent samples were collected from the influent reservoir just after it was refilled. Effluent samples were taken from the effluent storage tank. Conventional parameters such as MLSS (mixed liquor suspended solids), MLVSS (mixed liquor volatile suspended solids), COD (chemical oxygen demand), TKN (total Keijdal nitrogen), NH_4^+, NO_3^-, PO_4^{3-}, and alkalinity were routinely analyzed. All the parameters in the study were analyzed according to the procedures in the APHA *Standard Methods* (1995).

TABLE 1. Operational Conditions of SBR System

Parameter (1)	Phase I (2)	Phase II (3)	Phase III (4)
Total cycle time (t_c), h	8	8	7.5
Fill, h	0.5	0.5	0.17
Mix, h	1.5	1.5	1.83
Aerate, h	4	3	3.5
Idle, h	1	2	1
Settle, h	0.5	0.5	0.5
Decant, h	0.5	0.5	0.5
Aeration ratio (f_a)	0.5	0.38	0.47
MCRT, days	12	12	12
Ratio of feed introduced to reactor content, %	50	50	50

Model Development

ASM2

Since the SBR system is operated in a cyclic mode, the full ASM2 model was coded with cyclic characteristics, e.g., the air on or off phases were implemented by toggling between DO (dissolved O_2) = 5 mg/L and DO = 0 mg/L. During settle and decant periods, it was assumed there would be no significant reactions taking place. The parameters in the ASM2 were calibrated with one set of experimental dynamic data for PO_4^{3-}, NH_4^+, and NO_3^- concentration profiles. The definition and units of the parameters in the ASM2 as well as rate expressions can be found elsewhere (Gujer et al. 1995).

Simplified Linear Model

The original ASM2 model is complex, and it requires too much time and computing resources in calibrating its parameters to be implemented into a real-time control scheme. Hence, a simplified model is more practical in that it eliminates the inert components from the model, such as S_I (inert soluble COD), S_{N2} (N_2 produced from denitrification), X_I (inert particulate COD), and X_{TSS} (total suspended solids), which are not directly involved in various reactions. Also, the effect of S_{O2} (dissolved oxygen) and S_{alk} (alkalinity) is omitted from the model, since oxygen level during the aeration cycle can be adjusted high enough so as not to limit reactions and alkalinity is partially recovered from denitrification. In fact, the half saturation coefficients for the two variables (K_{O2} and K_{alk}) in the full ASM2 are usually so small that Monod hyperbolic terms of $S_{O2}/(K_{O2} + S_{O2})$ and $S_{alk}/(K_{alk} + S_{alk})$ can be approximated to ones. The biomass concentration is assumed to be constant, since the change during one cycle is not noticeable. Overall, only eleven variables are selected from the full ASM2 model. They are S_A (COD), S_F (fermentable COD), S_{NH4} (ammonia), S_{PO4} (phosphate), S_{NO3} (nitrate), X_S (particulate COD), X_H (heterotrophs), X_{PAO} (PAOs), X_{PP} (polyphosphate granule), X_{PHA} (cell internal storage product of PAOs), and X_{AUT} (autotrophs).

Since the system operates in a temporal sequence of fill, mix (anoxic and anaerobic), aerate (aerobic), idle (endogenous nitrate respiration), settle, and decant with different reactions in each phase, each phase was modeled separately and then combined to simulate the entire cycle of operation. Just as in the case of the full ASM2 for an SBR, it is also assumed that the reactions during the settle and decant periods are neglected in the linear model. The rate expressions for each process (ρ_1–ρ_{17}; Table 2) during the anoxic, anaerobic, and aerobic cycles are adapted to linear forms from the rate expressions used in ASM2. Also, the Monod terms relating to biomass concentration are removed because of the assumption of a constant biomass concentration. Linear approximations for nonlinear hyperbolic terms in each rate equation are made and substituted with constant ''J'' terms. More information of model simplification can be found elsewhere (Anderson et al. 2000).

The matrix forms of the state variables and different processes are shown in Table 2. Linear rate expressions for each phase are presented in the last three columns of Table 2. The conversion factors in the matrix (e.g., i_{NXS}, i_{PXS}) can be found elsewhere (Gujer et al. 1995).

The first-order expressions for the major variables in each reaction are still retained in the linear phase models. For ex-

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TABLE 2. Linear Models for SBR System

Process, $j\downarrow$ (1)	State Variables, $i \rightarrow$											Process Rate Equations ρ_j, $\rho_j \geq 0$, $(M_i L^{-3} T^{-1})$		
	S_A (2)	S_F (3)	S_{NH4} (4)	S_{NO3} (5)	S_{PO4} (6)	X_S (7)	X_H (8)	X_{PAO} (9)	X_{PP} (10)	X_{PHA} (11)	X_{AUT} (12)	Aerobic (13)	Anoxic (14)	Anaerobic (15)
(a) Hydrolysis Processes														
1. Aerobic hydrolysis		1	i_{NXS}		i_{PXS}	-1						$K_h J_1 X_S$	0	0
2. Anoxic hydrolysis		1	i_{NXS}		i_{PXS}	-1						0	$K_h \cdot \eta_{NO3} \cdot J_1 \cdot X_S$	0
3. Anaerobic hydrolysis		1	i_{NXS}		i_{PXS}	-1						0	0	$K_h \cdot \eta_{fe} \cdot J_1 \cdot X_S$
(b) Heterotrophic Organisms, X_H														
4. Aerobic growth on S_F		$-1/Y_H$	$-i_{NBM}$		$-i_{PBM}$		1					$\mu_H \cdot J_2 \cdot S_F$	0	0
5. Aerobic growth on S_A	$-1/Y_H$		$-i_{NBM}$		$-i_{PBM}$		1					$\mu_H \cdot J_3 \cdot S_A$	0	0
6. Dentrification with S_F		$-1/Y_H$	$-i_{NBM}$	$-(1 - Y_H/2.86Y_H)$	$-i_{PBM}$		1					0	$\mu_H \cdot \eta_{NO3} \cdot J_4 \cdot S_F$	0
7. Dentrification with S_A	$-1/Y_H$		$-i_{NBM}$	$-(1 - Y_H/2.86Y_H)$	$-i_{PBM}$		1					0	$\mu_H \cdot \eta_{NO3} \cdot J_5 \cdot S_A$	0
8. Fermentation	1	-1										0	0	$q_{fe} \cdot J_6 \cdot S_F$
9. Lysis			i_{NBM}		i_{PBM}	1	-1					$b_H X_H$	$b_H X_H$	$b_H X_H$
(c) Phosphorus Accumulating Organisms (*PAO*), X_{PAO}														
10. Storage of X_{PHA}	-1				Y_{PO4}				$-Y_{PO4}$	1		0	0	$q_{PHA} \cdot J_7 \cdot S_A$
11. Aerobic storage of X_{PP}					-1				1	$-Y_{PHA}$		$q_{PP} \cdot J_8 \cdot S_{PO4}$	0	0
12. Aerobic growth on X_{PHA}			$-i_{NBM}$		$-i_{PBM}$			1		$-1/Y_H$		$\mu_{PAO} \cdot J_9 \cdot S_{PO4}$	0	0
13. Lysis of X_{PAO}			i_{NBM}		i_{PBM}	1		-1				$b_{PAO} X_{PAO}$	$b_{PAO} X_{PAO}$	$b_{PAO} X_{PAO}$
14. Lysis of X_{PP}									-1			$b_{PP} X_{PP}$	$b_{PP} X_{PP}$	$b_{PP} X_{PP}$
15. Lysis of X_{PHA}	1									-1		$b_{PHA} X_{PHA}$	$b_{PHA} X_{PHA}$	$b_{PHA} X_{PHA}$
(d) Nitrifying Organisms: X_{AUT}														
16. Aerobic growth of X_{AUT}			$-1/Y_A$ $-i_{NBM}$	$1/Y_A$	$-i_{PBM}$						1	$\mu_{AUT} \cdot J_{10} \cdot S_{NH4}$	0	0
17. Lysis of X_{AUT}			i_{NBM}		i_{PBM}	1					-1	$b_{AUT} X_{AUT}$	$b_{AUT} X_{AUT}$	$b_{AUT} X_{AUT}$

ample, the rate equation for phosphate release or storage of polyhydroxyalkanoates, PHA (ρ_{10} in Table 2), is determined by the concentration of acetate (S_A), which determines the PHA content. During the mix periods, the system experiences both anoxic and anaerobic conditions, and the rate equation for phosphate release is not included in the anoxic model. In fact, it is believed that anoxic phosphorus release does not take place (Henze et al. 1998). Therefore, it is required to distinguish between anoxic and anaerobic conditions during the mix periods by checking nitrate concentration (S_{NO}) in the reactor at each time step. The following rule is used:

If S_{NO} ≤ 0.1 mg/L
Use model for anaerobic state
else Use model for anoxic state

RESULTS AND DISCUSSION

Overall Performance

A bench-scale SBR system was operated for over 8 months. The overall performance of the SBR system is presented in Fig. 1 with a summary in Table 3. In Phase I (addition of acetate of 60 mg COD/L), the system did not show a significant phosphate removal (Fig. 1), with a removal efficiency of only 40%, and removal efficiencies for COD and nitrogen were 81 and 67%, respectively. The 40% reduction of phosphorus may be mainly attributed to metabolic *P* requirement of cell synthesis. In Phase II, the idle period was increased from 1 to 2 h to reduce effluent nitrate concentration. Since a low phosphorus release/uptake has been attributed to acetate limiting conditions (Stephens and Stensel 1998), a sodium acetate equivalency of 120–150 mg COD/L was added into the feed solution in Phase II (day 75) for enhancing phosphate release. About 20 days after the increased amount of acetate addition, the system started to show excellent phosphate removal capabilities [Period A in Fig. 1(a)]. The effluent phosphate concentration was reduced to 0.4 mg P/L, with a *P*-removal efficiency of 94% in Phase II. However, only 65% of TN was removed even with the enlarged idle cycle time of 2 h, and the result is certainly due to a slower endogenous nitrate respiration rate. Nonetheless, the *N*/*P* removal efficiencies are comparable with those of others (Artan et al. 1999; Furumai et al. 1999b).

The system had to be restarted due to pump malfunction at the end of Phase II, which resulted in a loss of biomass in the system. At this time, the aeration cycle time was increased from 3 to 3.5 h (Phase III), and the fill cycle time was shortened to 10 min. The idle period was again reduced to 1 h, since the enlarged cycle time did not improve the nitrate removal efficiency. Approximately two months after the restartup, performance similar to that in Phase II was obtained with a 95% removal efficiency of PO_4^{3-} [Period B in Fig. 1(a)].

Overall, the system showed good COD and ammonia removal efficiencies for the entire study period. Effluent COD and NH_4^+-N were 37–60 mg/L and 0.2–0.3 mg/L, respectively. As mentioned above, once the biological phosphate removal takes place, the system demonstrates 95% *P* removal efficiency (Table 3). Since *P* was uptaken within three hours, both Phase II (aeration time of 3 h) and Phase III (aeration time of 3.5 h) showed a similar performance for phosphorus removal. Again, the effluent nitrate levels were rather high, resulting in high effluent TN concentrations (about 9 mg N/L).

TABLE 3. Overall Performance of SBR System[a]

Parameter (1)	Phase I Influent (mg/L) (2)	Phase I Effluent (mg/L) (3)	Phase I % removal (4)	Phase II Influent (mg/L) (5)	Phase II Effluent (mg/L) (6)	Phase II % removal (7)	Phase III Influent (mg/L) (8)	Phase III Effluent (mg/L) (9)	Phase III % removal (10)
Wastewater									
COD	310	60	81	360	39	89	366	37	90
PO_4^{3-}-P	4.8	2.9	40	7.1	0.36[b]	95	6.5	0.32[b]	95
TN	33.6	11.2	67	27.9	9.8	65	27.8	9.1	67
Org·N	13.8	1.8	87	11	1.7	85	11.5	1.7	85
NH_4^+-N	19.8	0.2	99	16.9	0.3	98	16.3	0.2	99
NO_3^--N		9.2			7.8			7.2	
Alkalinity[c]	181	30.5		173	106		210	142	
Reactor									
MLVSS, mg/L		1,740			1,680			1,920	

Note: Phase I—f_a = 0.5; t_c = 8 h; mix = 1.5 h; aeration = 4 h, idle = 4 h. Phase II—f_a = 0.38; t_c = 8 h; mix = 1.5 h; aeration = 3 h, idle = 2 h. Phase III—f_a = 0.47; t_c = 7.5 h; mix = 1.8 h; aeration = 3.5 h; idle = 1 h.

[a] MCRT = 12 days; reactor was filled with 2 L of wastewater at each fill cycle; temperature = 25 ± 3°C; acetate (about 60 mg COD/L) was added to feed in Phase I, and 120–150 mg COD/L was added in Phases II and III.

[b] Effluent PO_4^{3-} data with biological *P*-removal [periods A and B in Fig. 1(a)].

[c] As mg $CaCO_3$/L.

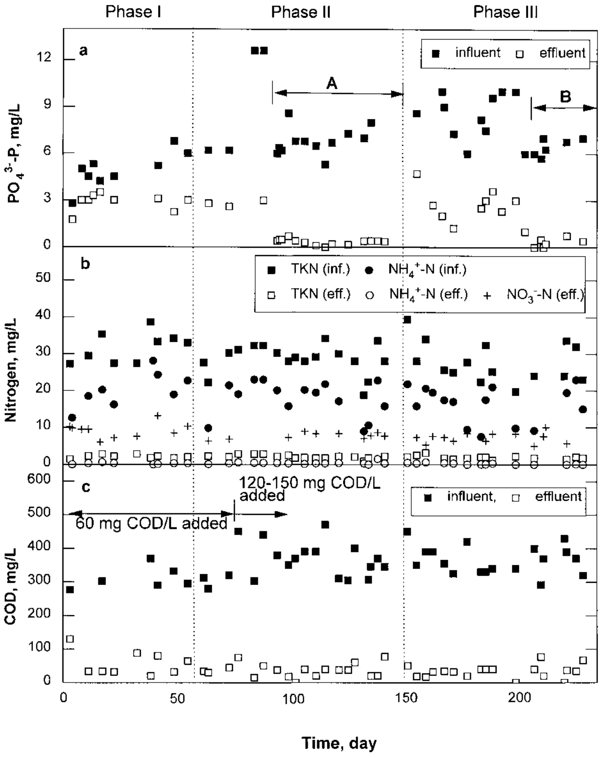

FIG. 1. Overall Performance of SBR System

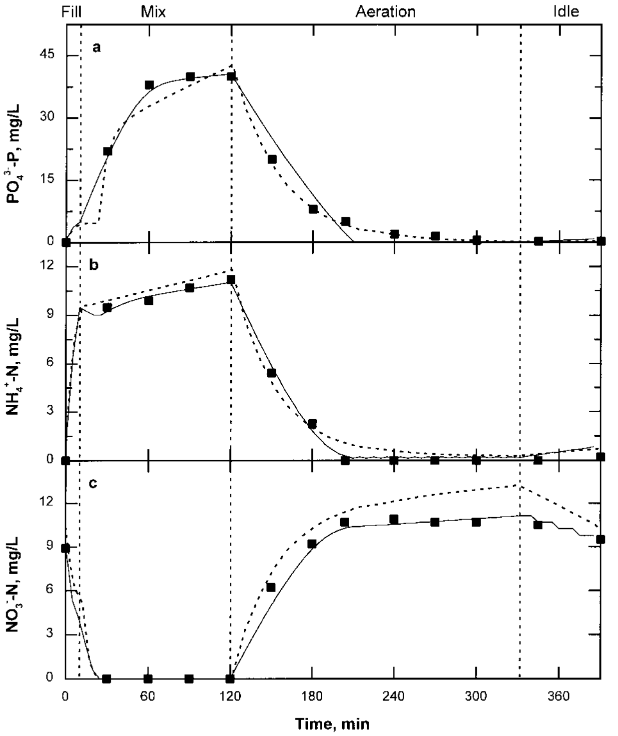

FIG. 2. PO_4^{3-}, NH_4^+, and NO_3^- Dynamics of SBR System (Phase III)

Nutrient Dynamics

Several dynamic studies were performed during the operation of the SBR system to evaluate microbial kinetics of nitrification, denitrification and phosphate release/uptake. The data were also used for calibration of model parameters and validation of the calibrated models. Fig. 2 shows a typical data set of NH_4^+, NO_3^-, and PO_4^{3-} concentration profiles from Phase III studies. Expected biological phenomena are clearly seen in these profiles: denitrification, phosphorus release, and ammonification during the mix period (anoxic and anaerobic cycle); *P* release in the absence of nitrate; nitrification and phosphorus uptake during the aerate period; and endogenous nitrate respiration during the idle period.

Based on five track studies, the specific nitrification and endogenous nitrate respiration rates during aerobic and idle periods ranged from 4.2 to 5.6 mg NH_4^+-N/g MLVSS-h and from 0.7 to 1.4 mg NO_3^--N/g MLVSS-h, respectively. These values are comparable with those reported by others, e.g., 2.0–4.9 mg NH_4^+-N/g MLVSS-h (Artan et al. 1998; Furumai et al. 1999a) and 0.4–3.7 mg NO_3^--N/g MLVSS-h (Chang and Hao 1996; Furumai et al. 1999a). The initial specific phosphate release and uptake rate constants (16.1–20.6 mg P/g MLVSS-h and 10.9–12.1 mg P/g MLVSS-h, respectively) of the system under study were also similar to those reported by others (Carucci et al. 1995; Chang and Hao, 1996; Petersen et al. 1998; Furumai et al. 1999a), e.g., *P* uptake of 4.0–18.9 mg P/g MLVSS-h and *P* release of 6.1–37 mg P/g MLVSS-h. The average ammonification rate under anaerobic conditions is about 0.4 mg NH_4^+-N/g MLVSS-h.

The averaged ratios between the consumed alkalinity and nitrification and between the alkalinity recovered and denitrification are 7.4 mg $CaCO_3$/mg NH_4^+-N and 4.2 mg $CaCO_3$/mg NO_3^--N, which are reasonably close to the theoretical values

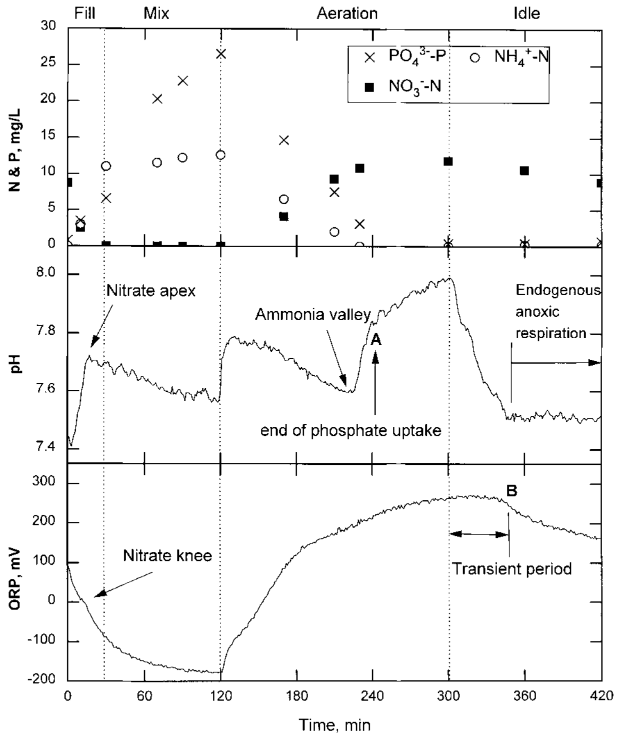

FIG. 3. PO_4^{3-}, NH_4^+, and NO_3^- Dynamics along with pH and ORP Profiles (Phase II)

(7.14 mg $CaCO_3$/mg NH_4^+-N and 3.6 mg $CaCO_3$/mg NO_3^--N).

ORP and pH Profiles

pH and ORP profiles often provide useful information about the state of temporal systems for nitrogen removal with several significant points, e.g., the ‘‘nitrate knee’’ inflection point for signifying the end of denitrification in the ORP profiles and the ‘‘ammonia valley’’ on the pH profile, which indicates the end of nitrification. Fig. 3 shows typical pH and ORP profiles along with NH_4^+, NO_3^-, and PO_4^{3-} concentration profiles. During the fill period, pH initially increases [Fig. 3(b)] due to a higher pH content in the feed and, to some extent, denitrification [Fig. 3(a)]. Once denitrification is complete, pH decreases due to anaerobic fermentation result in a local peak, called a ‘‘nitrate apex’’ (Al-Ghusain et al. 1994). The corresponding ‘‘nitrate knee’’ in the ORP profile, however, could not be easily distinguished due to the fast drop in the ORP value [Fig. 3(c)]. The continued pH drop in the mix stage is due to fermented byproducts and phosphorus release, since PHA formation generates reducing power, which would lower external pH (Satoh et al. 1992). In short, the presence of a ‘‘nitrate apex’’ would signify the possibility to shorten the fill cycle and initiate the mix cycle. In Phase III studies, the fill cycle was indeed reduced from 30 to 10 min.

Once aeration starts, the system pH sharply increases due to stripping of CO_2 out of the system. Thereafter, there are several factors affecting pH. Nitrification decreases pH, while ammonification and phosphorus uptake increase pH. Corresponding alkalinity increases and acidity decreases associated with aerobic phosphate uptake have been reported (Wentzel et al. 1986). As aeration proceeds, the pH decreases, because the consumption of the system alkalinity due to nitrification is higher than alkalinity generated from ammonification and *P* uptake. Once ammonia is completely consumed, the pH increases due to continued phosphate uptake, result in a distinct ‘‘ammonia valley’’ point [Fig. 3(b)]. After further *P* removal, there appears an inflection point on the pH profile [Point A in Fig. 3(b)] as the rate of pH increases slows down. This point has also been identified in a previous study (Chang and Hao 1996) and presents a useful tool for potential on-line control purposes to terminate the aeration cycle and initiate the next cycle.

During the first part of the idle period, a relatively constant ORP value was shown while pH dropped. The constant ORP values in this transient period are probably due to the consumption of the dissolved oxygen. The inflection point in the ORP profile [Point B in Fig. 3(c)] may indicate the beginning of endogenous nitrate respiration.

Model Calibration and Evaluation

The model parameters for both ASM2 and the linear model were first calibrated with the data set shown in Fig. 2. The

TABLE 4. Stoichiometric and Kinetic Parameters Used in ASM2 and Linear Model (LM)

Parameters (1)	Default (2)	ASM2 (3)	LM (4)
(a) Hydrolysis			
K_h	3.0	2.0	1.0
η_{NO3}	0.6	0.6	0.6
η_{fe}	0.1	0.1	0.3
K_{O2}	0.2	0.2	—
K_{NO3}	0.5	0.5	—
K_X	0.1	0.1	—
(b) Phosphorus Accumulating Organisms			
Y_H	0.63	0.63	0.63
f_{XI}	0.1	0.1	—
μ_H	6.0	5.0	6.0
q_{fe}	3.0	3.0	3.0
η_{NO3}	0.8	0.8	0.8
b_H	0.4	0.4	0.2
K_{O2}	0.2	0.2	—
K_F	4.0	4.0	—
K_{fe}	20	20	—
K_A	4.0	4.0	—
K_{NO3}	0.5	0.5	—
K_{NH4}	0.05	0.05	—
K_P	0.01	0.01	—
K_{alk}	0.1	0.1	—
(c) Phosphorus Accumulating Organisms			
Y_{PAO}	0.63	0.63	0.63
Y_{PO4}	0.4	0.45	0.4
Y_{PHA}	0.2	0.2	0.2
q_{PP}	1.5	2.5	1.5
q_{PHA}	1.5	2.5	1.5
μ_{PAO}	1.0	1.0	1.0
b_{PAO}	0.2	0.2	0.1
b_{PP}	0.2	0.2	0.1
b_{PHA}	0.2	0.2	0.1
K_{O2}	0.2	0.2	—
K_A	4.0	4.0	—
K_{NH4}	0.05	0.05	—
K_{PS}	0.2	0.5	—
K_P	0.01	0.01	—
K_{alk}	0.1	0.1	—
K_{PP}	0.01	0.01	—
K_{MAX}	0.34	0.34	—
K_{IPP}	0.02	0.15	—
K_{PHA}	0.01	0.01	—
(d) Nitrifiers			
Y_{ALT}	0.24	0.24	0.24
μ_{AUT}	1.0	0.8	1.0
b_{AUT}	0.15	0.1	0.1
K_{O2}	0.5	0.25	—
K_{NH4}	1.0	2.5	—
K_{alk}	0.5	2.0	—
K_P	0.01	0.01	—

Note: Values for J_1–J_{10} are 0.32, 10, 10, 3.3, 7, 3, 180, 26, 12, and 26, respectively.

simulation results from the full ASM2 model (solid lines) and liner model (dashed lines) are plotted along with the actual experimental data (rectangles). The numerical fitting was done by changing a few parameters in both the full and linear models, while other parameters were kept constant. The values of the stoichiometric and kinetic parameters used are presented in Table 4, with the "J" constants used in the linear model listed in the footnote of Table 4.

Remarkably, the default values in the ASM2 serve well; only 13 out of 46 parameters need to be changed and 11 of these 13 calibrated parameters are related to reactions involving PAOs and autotrophs. As would be expected, phosphate uptake/release are extremely sensitive to q_{PP} and q_{PHA} values. Other investigators also reported reasonable ASM2 predictions either with the use of a complete set of default values (Zhao et al. 1999) or adjustment of only nine parameters, mostly in decay terms (Furumai et al. 1999a).

Model calibration of the linear model took less time and effort than that of the full model. This is due to the small number of parameters used in the linear model (19 parameters as compared with 46 parameters in ASM2; Table 4), and the major task for model calibration is the adjustment of "J" values by using default values of the kinetic and stoichiometric parameters. As for decay terms (b_H, b_{PAO}, b_{PHA}, b_{PP}, and b_{AUT}), they need to be calibrated, since the original ASM2 expressions (Table 4) are used (no involvement of "J" terms).

Overall, the full model shows slightly better prediction for phosphate release, ammonia disappearance, and nitrate buildup profiles. In the case of phosphate uptake, the linear model appears better than ASM2. The ASM2 predicts a zero-order rate for phosphorus uptake, which is also reported by others (Furumai et al. 1999a; Zhao et al. 1999), whereas the writers' data and those of others (e.g., Meinhold et al. 1998; Petersen et al. 1998) indicate otherwise. In fact, Petersen et al. (1998) have demonstrated that phosphate uptake should be modeled with a first-order rate or a Monod equation for PHB (polyhydroxybutyrate), since the reaction is dependent on the amount of PHB available.

Further validation of both the full and simplified models was conducted using two additional data sets (Figs. 4 and 5). Overall, both models reasonably predict the general features (NH_4^+, PO_4^{3-}, and NO_3^- profiles) of the SBR system, albeit with some discrepancies. For real-time control purposes, however, any discrepancies between actual data and model predictions can be compensated by different techniques, such as neural networks, a fuzzy system, or a simple error feedback. With its easier model calibration and speed of modeling, the linear model can be implemented in a real-time, model-based control scheme for SBR systems. In an accompanying paper (Kim et al. 2001), the linear model is used to shorten the duration of the aeration cycle to save energy, while maintaining the effluent *P* requirement.

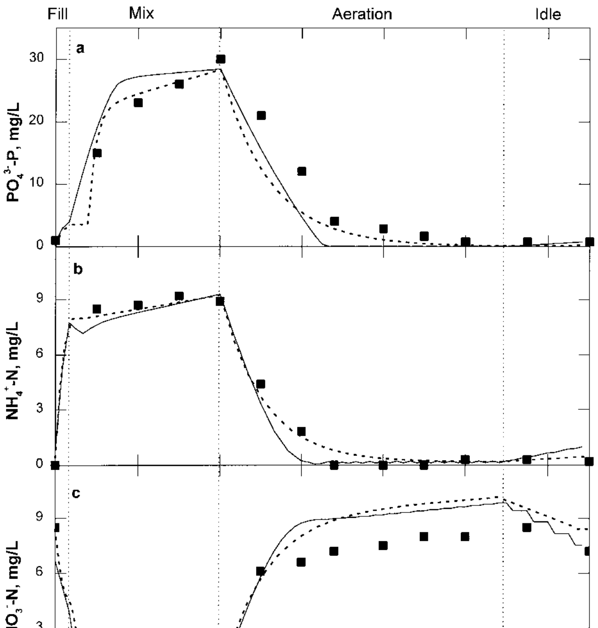

FIG. 4. Comparison of Full ASM2 (Solid) and Linear Model (Dotted) with Experiment Data (Phase III)

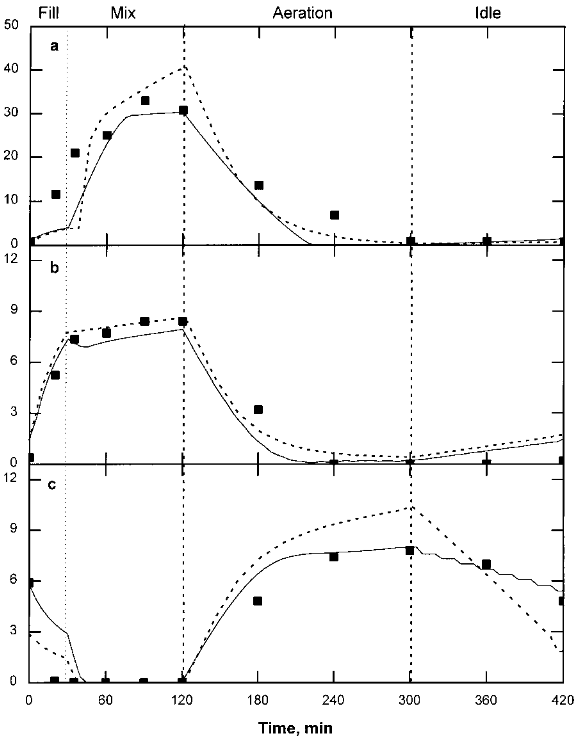

FIG. 5. Comparison of Full ASM2 (Solid) and Linear Model (Dotted) with Experiment Data (Phase II)

CONCLUSIONS

A laboratory scale SBR system was operated for over 8 months with various aeration ratios to observe their effect on nutrient removal and to derive kinetic constants. The system shows an excellent phosphate removal capability of 95% when a sufficient amount of acetate is provided. Throughout the entire study, the effluent NH_4^+ concentrations were lower than 0.5 mg N/L. The effluent nitrate concentrations, however, were rather high (7.2–9.1 mg N/L), due to a slow endogenous nitrate respiration rate in the idle cycle.

The full ASM2 model was simplified and linearized by excluding seven variables and replacing all the nonlinear hyperbolic terms with the "J" constants. Overall, both the ASM2 and the linear model reasonably predict the behavior of the system. The linear model significantly reduces the time and efforts for model calibration. The linear model could further be used for process control of SBR systems for minimizing energy saving by shortening the aeration cycle.

ACKNOWLEDGMENTS

The financial support from the NSF BBS-9625183 is acknowledged. The writers thank Dr. J. S. Anderson for the development of the linear model.

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