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확장형칼만필터에 의한 연속회분식반응조의 탈질 적응제어

Adaptive Control of Denitrification by the Extended Kalman Filter in a Sequencing Batch Reactor

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Abstract

The reaction rate of denitrification is primarily affected by the utilization of organics that are usually limited in the anoxic period in a sequencing batch reactor. It is necessary to add an external carbon source for sufficient denitrification. An adaptive model of state-space based on the extended Kalman filter is applied to manipulate the dosage rate of external carbon automatically. Control strategies for denitrification have been studied to improve control performance through simulations. The normal control strategy of the constant set-point results in the overdosage of external carbon and deterioration of water quality. To prevent the overdosage of external carbon, improved control strategies such as the constrained control action, variable set-point, and variable set-point after dissolved oxygen depletion are required. More stable control is obtained through the application of the variable set-point after dissolved oxygen depletion. The converging value of the estimated denitrification coefficient reflects conditions in the reactor.

Key words: adaptive control, denitrification, extended Kalman filter, external carbon source, sequencing batch reactor

주제어: 적응제어, 탈질, 확장형칼만필터, 외부탄소원, 연속회분식반응조

1. INTRODUCTION

In the biological nutrient removal (BNR) processes, denitrification requires organics as an electron donor. However, organics are usually limited during the denitrification step because they are mostly oxidized during the preceding nitrification step. Operations such as internal recycle and split feeding have been used to utilize organic compounds in the influent, but these depend on C/N ratio of the influent and have a certain limit for nitrogen removal. An external carbon source should be added in such conditions for sufficient denitrification (EPA, 1993). As the concentration of nitrogen

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compounds in the influent varies, oxidized nitrogen is always in the dynamic state. The constant dosage of external carbon for denitrification may cause organics limited condition which leads to insufficient nitrogen removal, or organics excessive condition which leads to the considerable costs, deterioration of effluent water quality, and increase of sludge production. Therefore, it is necessary to automatically control the dosage of external carbon to achieve sufficient denitrification and to maintain a stable operation.

Proportional-integral-derivative control has been widely used in biological processes due to its simplicity. However, it requires time-consuming and trial-and-error procedures for the tuning of gains, and does not sufficiently reflect the nonlinearity and time-varying system of the BNR processes. Adaptive control can provide flexible approaches to uncertainty, nonlinearity, and time-varying characteristics, so it is a more suitable control algorithm for denitrification. Isaacs et al. (1995) applied adaptive control of denitrification by manipulating the dosage rate of external carbon to an alternating activated sludge process, and Lindberg and Carlsson (1996a) also used it in an activated sludge process. Especially the state-space model based on the extended Kalman filter (EKF) has the tracking ability for state and parameter variables. It can also estimate unknown state and parameter variables of the system which are difficult to measure experimentally using available measurements. Due to such advantages it has been applied to state and parameter estimation, process control, and data analysis in biological processes (Beck, 1981; Ayesa et al., 1991; Jeppsson and Olsson, 1993; Lindberg and Carlsson, 1996b; Ekman et al., 2003; Kim and Chung, 2003).

As a sequencing batch reactor (SBR) is a fill-and-draw, time-oriented, and periodic system, it has advantages such as equalization of shock loads, maintenance of high mixed liquor suspended solids, no requirement of return activated sludge pumping, good sludge settleability, and so on (Arora et al., 1985; Irvine and Ketchum, 1989; Ketchum, 1997). In particular, the flexibility of operation due to a time-oriented system can easily accommodate aerobic, anoxic, and anaerobic environments for the simultaneous removal of nitrogen and phosphorus through simple regulation of aeration in a single reactor. Because the SBR is operated in a batch system, a control strategy other than that for a continuous system may be required. In a batch reactor there is no flow during the anoxic period when an external carbon source is added, while a continuous system receives the continuous flow from a nitrification tank. In the continuous system such as a completely mixed flow reactor, overdosed carbon could be consumed by oxidized nitrogen that is in the flow from a nitrification tank. However, in a batch reactor there is no additional consumption for overdosed external carbon by supplementary oxidized nitrogen. It is very important to apply a suitable control strategy to the batch reactor to control denitrification properly. The purpose of this study is to investigate the optimal control strategy for denitrification in the SBR through simulations using adaptive control of the state-space model based on the EKF.

2. SIMULATION MODEL

2.1. Process Model

For the process model of the SBR system, a modified model based on Activated Sludge Model No. 2 (Henze et al., 1997; Henze et al., 2000) has been developed. To express nitrification and denitrification in detail, nitrification is expressed as two-step processes and denitrification is also separated into two-step processes. Particulate nitrogen and phosphorus are considered. Stoichiometric coefficients and kinetic parameters are chosen from literature and calibrated in simulations for experiments (Kim and Chung, 1999). The multistep predictor-corrector method of a variable step-size is adopted to solve vector nonlinear ordinary differential equations in computer programs. The four-step Adams-Bashforth method is used as a predictor and the three-step Adams-Moulton method as a corrector (Burden et al., 1986). The maximum step-size is set to 2.08×10^{-4} d and the minimum to 4.17×10^{-10} d. An allowable error is adjusted in proportion to the step-size: 0.02 × step-size for soluble components and 0.1 × step-size for particulate components.

Typical operating conditions are simulated in this study. Design flowrate of 1,800 m^3/d is consecutively treated in four reactors. Hydraulic retention time and solids retention time are 13.3 h and 30 d, respectively. Each reactor is operated with a cycle of 8 h (fill 2 h, react 4 h, settle 1.5 h, and draw and idle 0.5 h). The react period is composed of 2 h of aeration, 1.5 h of no aeration, and 0.5 h of aeration, and no air is supplied during the rest period of the cycle. Characteristics of municipal wastewater used in simulations are as follows. The concentration of total chemical oxygen demand (COD), nitrogen, and phosphorus in the influent is 250 mg COD/l, 25 mg N/l, and 4 mg P/l, respectively (Kim and Chung, 1999).

2.2. State-Space Model

A state-space model based on the EKF is adopted to manipulate the dosage rate of external carbon for the control of denitrification in the anoxic period. It can estimate state and parameter variables including those not easily measured, and reflect system nonlinearity. As denitrification by the dosage of external carbon is a dynamic state and time-varying system, the improved control can be obtained using the EKF, which can also reflect the nonlinearity of reactions.

To apply the EKF to the control, a simplified reaction rate equation for denitrification is established. The reaction rate of denitrification is primarily influenced by the concentration of oxidized nitrogen ($NO_X^- = NO_2^- + NO_3^-$) and organics. Therefore, considering the reaction mechanisms and easily measurable variables, the first order reaction for oxidized nitrogen and the dosage rate of external carbon, respectively, is assumed as follows:

$$\frac{dNO_X^-}{dt} = -k_{DN} NO_X^- U_Q \qquad (1)$$

where NO_X^- = oxidized nitrogen (mg N/l), k_{DN} = denitrification coefficient (m^{-3}), and U_Q = dosage rate of external carbon (m^3/d).

The state-space model of the continuous-discrete EKF (Gelb et al., 1979) is expressed as the prediction and correction form (Kim and Chung, 2003), which is as follows:

System:

$$\dot{\mathbb{x}}(t) = \mathbb{f}(x(t), \mathbb{u}(t)) + \mathbb{w}(t); \quad \mathbb{w}(t) \sim \mathrm{N}(\mathbb{0}, \mathbb{Q}(t)) \qquad (2)$$

Measurement:

$$\mathbb{y}(t_k) = \mathbb{h}(\mathbb{x}(t_k)) + \mathbb{v}(t_k); \quad \mathbb{v}(t_k) \sim \mathrm{N}(\mathbb{0}, \mathbb{R}(t_k)) \qquad (3)$$

where $\mathbb{x}$ = state vector, $\mathbb{u}$ = input vector, $\mathbb{y}$ = measurement vector, $\mathbb{f}$ = system function vector, $\mathbb{h}$ = measurement function vector, $\mathbb{w}$ = system noise vector which is Gaussian noise with zero mean and covariance $\mathbb{Q}$, and $\mathbb{v}$ = measurement noise vector which is Gaussian noise with zero mean and covariance $\mathbb{R}$.

Prediction:

$$\hat{\mathbb{x}}(t2 \mid t_{k-1}) = \hat{\mathbb{x}}(t_{k-1} \mid t_{k-1}) + \int_{t_{k-1}}^{t_k} \mathbb{f}(\hat{\mathbb{x}}(\tau), \mathbb{u}(\tau))d\tau \qquad (4)$$

$$\begin{aligned} \mathbb{P}(t_k \mid t_{k-1}) = \mathbb{P}(t_{k-1} \mid t_{k-1}) \\ + \int_{t_{k-1}}^{t_k} [\mathbb{F}(\hat{\mathbb{x}}(\tau), \mathbb{u}(\tau))\mathbb{P}(\tau) \\ + \mathbb{P}(\tau)\mathbb{F}^{\mathrm{T}}(\hat{\mathbb{x}}(\tau), \mathbb{u}(\tau)) + \mathbb{Q}(\tau)]d\tau \end{aligned} \qquad (5)$$

Correction:

$$\begin{aligned} \mathbb{K}(t_k) = \mathbb{P}(t_k \mid t_{k-1})\mathbb{H}^{\mathrm{T}}(t_k)[\mathbb{H}(t_k)\mathbb{P}(t_k \mid t_{k-1})\mathbb{H}^{\mathrm{T}}(t_k) \\ + \mathbb{R}(t_k)]^{-1} \end{aligned} \qquad (6)$$

$$\hat{\mathbb{x}}(t_k \mid t_k) = \hat{\mathbb{x}}(t_k \mid t_{k-1}) + \mathbb{K}(t_k)[\mathbb{y}(t_k) - \mathbb{h}(\hat{\mathbb{x}}(t_k \mid t_{k-1}))] \qquad (7)$$

$$\mathbb{P}(t_k \mid t_k) = [\mathbb{I} - \mathbb{K}(t_k)\mathbb{H}(t_k)]\mathbb{P}(t_k \mid t_{k-1}) \qquad (8)$$

where $\mathbb{P}$ = error covariance matrix, $\mathbb{K}$ = Kalman gain matrix, $\mathbb{F}$ = Jacobian matrix of $\mathbb{f}$, and $\mathbb{H}$ = Jacobian matrix of $\mathbb{h}$.

In the control of denitrification state vector, measurement vector, and input vector are as follows: $\mathbb{x} = [NO_X^- \ k_{DN}]^T$, $\mathbb{y} = [NO_X^-]$, and $\mathbb{u} = [U_Q]$. Initial conditions for parameter and error covariance matrix used in simulations are $k_{DN} = 25 \ m^{-3}$ and $\mathbb{P}_{ii}(0) = [100 \ 0.1]$, respectively. Covariance matrices for the system and measurement are $\mathbb{Q}_{ii}(t)$ = [10 0.1] and $\mathbb{R}(t_k)$ = [0.01], respectively. The step-size of time is 1 min. The differential equations are solved by the multistep predictor-corrector method described earlier in the process model. Gaussian noise with the zero mean and standard deviation of 0.1 is superimposed to the measurements.

2.3. Control Law

For the control of denitrification, the dosage rate of external carbon is manipulated in simulations. From Eqs. 1 and 4, the manipulated variable, U_Q, can be obtained by the minimum variance control law considering the set-point.

$$U_Q(t_k) = \frac{1}{k_{DN}T}\ln\left\{\frac{\hat{NO}_X^-(t_k \mid t_k)}{NO_X^{-*}(t_{k+1})}\right\} \qquad (9)$$

where $NO_X^{-*}(t_{k+1})$ is the one-step ahead set-point and T is the step-size of time. As in practice a control action is constrained by pump conditions, the dosage rate of external carbon actually used in simulations is limited as follows:

$$U_Q(t_k) = U_{Q,\min} \quad \text{if} \quad U_Q(t_k) < U_{Q,\min} \qquad (10)$$

$$U_Q(t_k) = U_{Q,\max} \quad \text{if} \quad U_Q(t_k) > U_{Q,\max} \qquad (11)$$

where $U_{Q,\min}$ and $U_{Q,\max}$ are set to 0 and 20 m^3/d, respectively.

Organic compounds that could be used as an external carbon source, are methanol, ethanol, acetic acid, supernatant of digester, and so on (EPA, 1993). Methanol of 100,000 mg COD/l is used as an external carbon source in this study. All the programs in simulations have been written in FORTRAN.

3. RESULTS AND DISCUSSION

Control strategies for denitrification in the SBR have been established to settle the occurring perplexity of control and to improve control performance during simulations. Considering the constraint of the control action and the variation of set-points, four control strategies have been examined. The initial concentration of oxidized nitrogen in the SBR is set to 12 mg N/l.

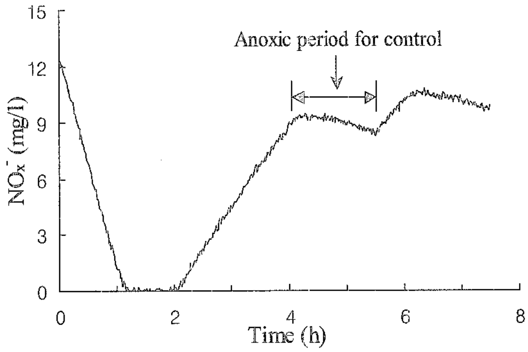

Fig. 1. Uncontrolled oxidized nitrogen and the anoxic period for control in the SBR.

In the case of no control, as shown in Fig. 1, though oxidized nitrogen during the anoxic period is very high, denitrification proceeds very slowly due to lack of organics. Consequently, it is necessary to add an external carbon source to achieve sufficient denitrification.

3.1. Constant Set-Point (S1)

In the control of processes a fixed set-point is commonly applied. When it is used in the SBR, the results are shown in Fig. 2. The constant set-point of NO_X^- = 1.0 mg N/l is used in the simulation. External carbon is continuously dosed until NO_X^- is under the set-point. However, dosed organics are not immediately consumed by denitrifying organisms. Though NO_X^- is maintained over the set-point, denitrification proceeds if there are organics remaining in the reactor. In this case the additive dosage of external carbon is not needed, but the dosage is continued because NO_X^- is over the set-point. Consequently, S1 causes overdosage of external carbon, and results in the accumulation of organics and deterioration of effluent quality.

3.2. Constrained Control Action (S2)

To suppress the overdosage of external carbon, the

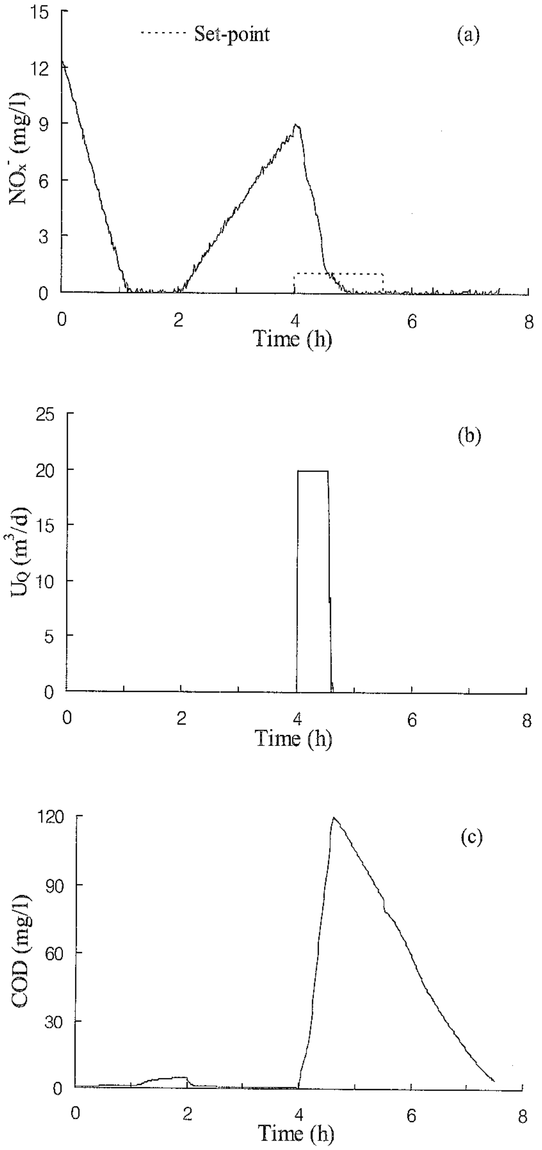

Fig. 2. Control by S1: (a) oxidized nitrogen, (b) dosage rate of external carbon, and (c) readily biodegradable organics.

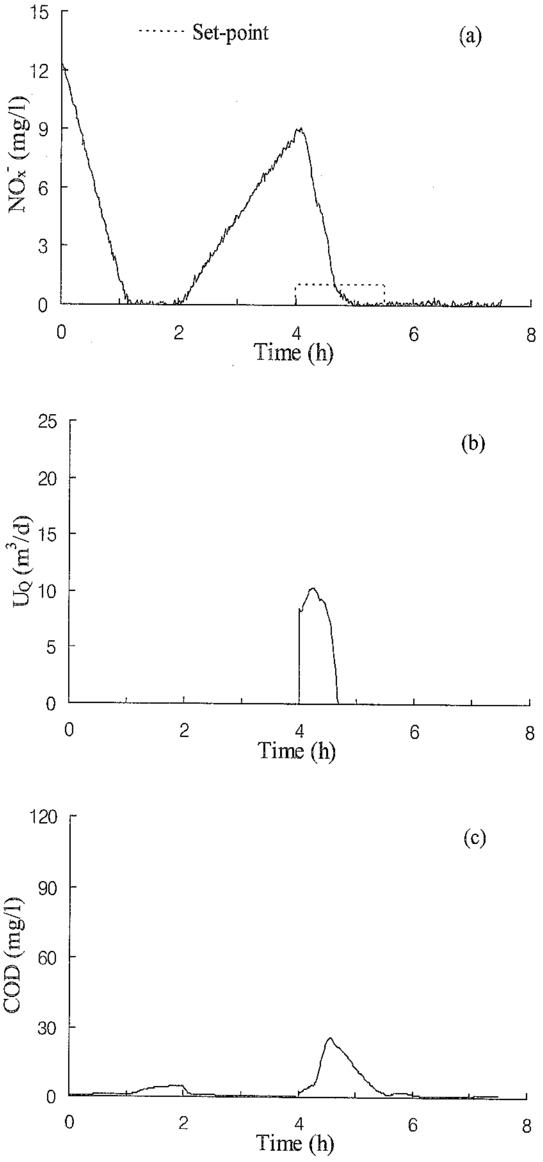

Fig. 3. Control by S2: (a) oxidized nitrogen, (b) dosage rate of external carbon, and (c) readily biodegradable organics.

control action is compulsorily constrained by increasing the step-size (T) in Eq. 9 of the control law to 15 min, while the original step-size for measurement and control is not changed. The control action is reduced to one-fifteenth of the calculated control action. The overdosage is diminished by constraint of the control action, as shown in **Fig. 3**, but S2 is an only temporary method and may not reflect the various dynamic states.

3.3. Variable Set-Point (S3)

In the constant set-point such as S1 and S2, denitrification is not properly controlled because the simplified reaction cannot completely reflect the environment of the SBR where organics remain and can be used for further denitrification. A variable set-point that is gradually decreased, as presented in Eqs. 12 and 13,

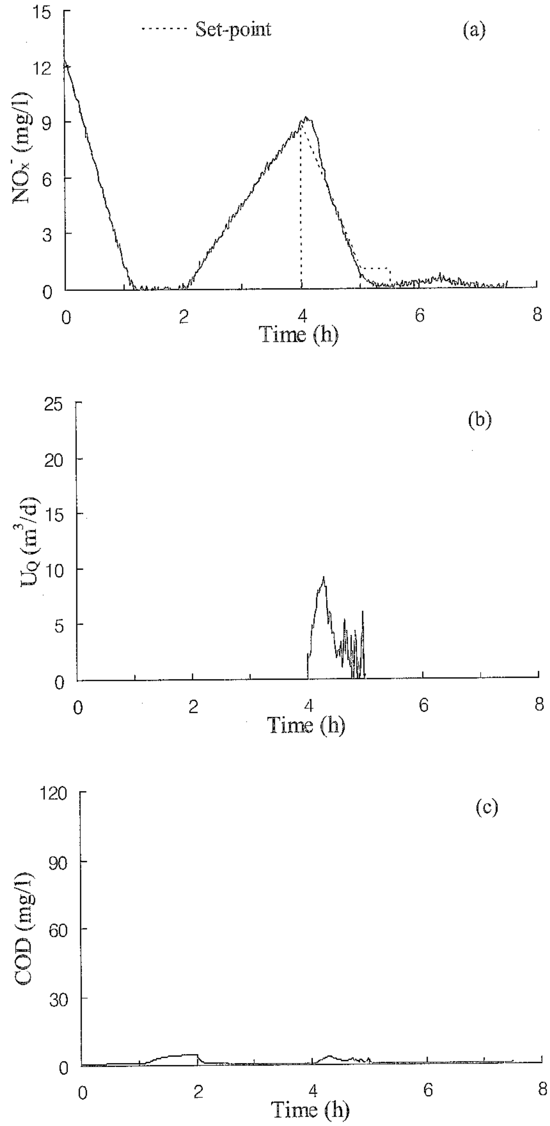

Fig. 4. Control by S3: (a) oxidized nitrogen, (b) dosage rate of external carbon, and (c) readily biodegradable organics.

is introduced to prevent the excessive control action and to utilize organics remaining in the reactor.

$$NO_X^{-*}(t) = NO_{X,i}^{-*} - \frac{(NO_{X,i}^{-*} - NO_{X,f}^{-*})}{T_{DN}}(t - t_i) \quad \text{if} \quad t_i \leq t < (t_i + T_{DN}) \tag{12}$$

$$NO_X^{-*}(t) = NO_{X,f}^{-*} \quad \text{if} \quad t \geq (t_i + T_{DN}) \tag{13}$$

where $NO_X^{-*}(t)$ = variable set-point, $NO_{X,i}^{-*}$ = initial condition of the variable set-point, $NO_{X,f}^{-*}$ = final condition of the variable set-point, t_i = initial time when S3 begins, and T_{DN} = period of S3. $NO_{X,i}^{-*}$ of the concentration at the beginning of S3 and $NO_{X,f}^{-*}$ of 1.0 mg N/l are used. T_{DN} is set to 60 min to accommodate the sufficient utilization of organics remaining in the reactor.

As the set-point is gradually decreased during T_{DN}, external carbon is dosed only when NO_X^- is over the set-point, and supplementary dosage is prevented during the control period (Fig. 4). The overdosage of external carbon can be prevented and organics remaining in the reactor is effectively utilized. As a result, S3 shows good performance of denitrification control.

3.4. Variable Set-Point after DO depletion (S4)

In the beginning period of control, dosed organics are not directly utilized by denitrifying organisms since there is dissolved oxygen (DO), as shown in Fig. 5c, in the reactor yet. NO_X^- scarcely decreases in that period because organics are consumed by heterotrophic organisms. This must lead to erroneous effects on the estimation of state and parameter variables though that period is short. To induce stable control, both the constant dosage during the period when DO is not depleted yet and the variable set-point after DO depletion are applied. Considering the sensitivity of a DO meter, the level of DO depletion is set to 0.5 mg/l. The dosage rate of external carbon is maintained at 5 m^3/d until DO is depleted. After DO is depleted, the control strategy of the variable set-point is applied. In this S4, the excessive control action during the period when DO is not depleted, is reduced, as shown in Fig. 5. In comparison with the other control strategies, the best control performance can be obtained.

3.5. Parameter Estimation

Fig. 6 depicts the estimated parameter of the denitrification coefficient converges rapidly to a constant value during the earlier control period. The converging value of S1 is smallest and that of S4 is largest, so the

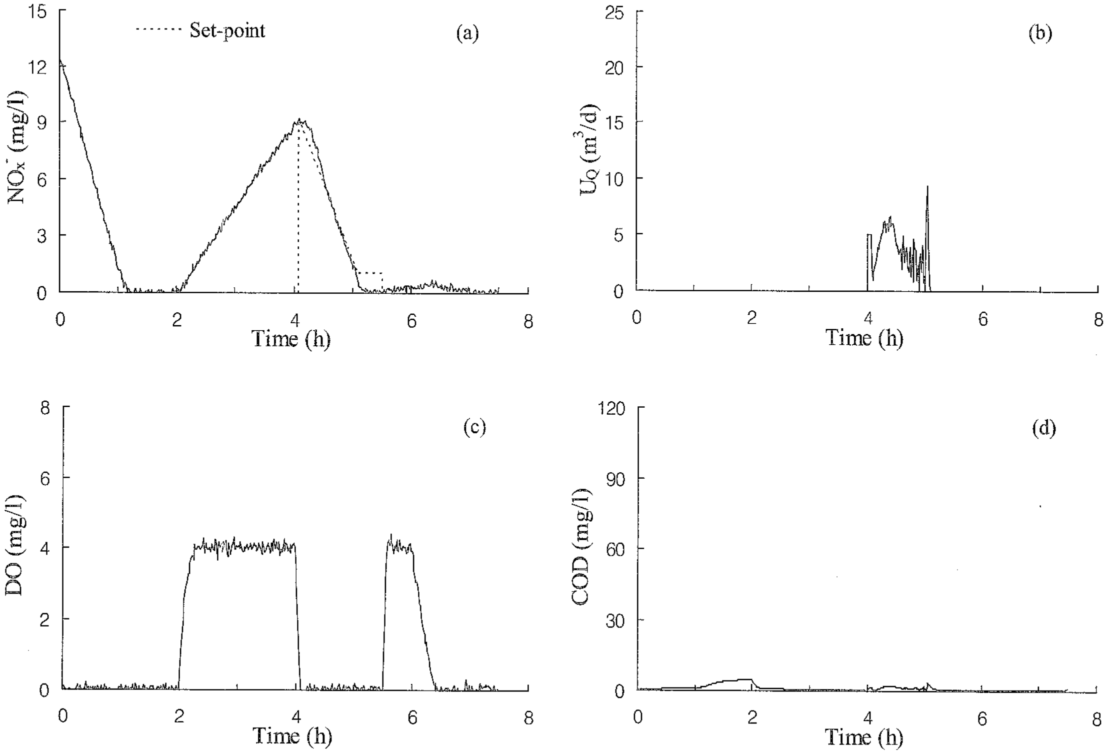

Fig. 5. Control by S4: (a) oxidized nitrogen, (b) dosage rate of external carbon, (c) DO, and (d) readily biodegradable organics.

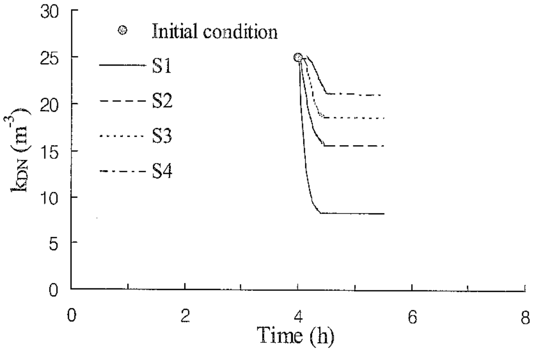

Fig. 6. Estimated denitrification coefficient in various control strategies.

converging value becomes smaller when organics remain high in the reactor. Therefore, it reflects the reactor conditions. As can be seen in Eq. 1, the smaller converging value means that the denitrification rate is a little affected by U_Q, which is caused by the fact that organics remain high in the reactor due to overdosage. In Eq. 9 the very small converging value also increases the control action and leads to the overdosage like S1. On the contrary, S4 shows the adequate coefficient value and control action, and results in very good control performance.

4. CONCLUSIONS

The bottleneck in the simultaneous removal of nitrogen and phosphorus is the denitrification step. As denitrification occurs after nitrification, organics are commonly limited during denitrification and it is necessary to add an external carbon source for successful nitrogen removal. In the continuous system of a completely mixed flow reactor, overdosed carbon can be consumed by oxidized nitrogen that is in the effluent from a nitrification tank. It means that the reactor of that type has the buffer capacity for overdosed carbon. However, in a batch reactor there is no consumer such as supplementary oxidized nitrogen for overdosed organics. As a batch reactor has no buffer capacity for overdosed carbon, it seems that more stable control strategies are required.

The state-space model based on the EKF is adopted for the control of denitrification by manipulating the dosage rate of external carbon. It can represent the reaction mechanisms based on the mass balance. The adaptive control algorithm using the EKF is able to estimate the parameters reflecting circumstances of the SBR. The normal control strategy of the constant set-point causes the overdosage of external carbon and results in accumulation of organics in the reactor. Improved control strategies such as the constrained control action, variable set-point, and variable set-point after DO depletion are required to reduce the overdosage of external carbon. It is possible to prevent the overdosage of external carbon by applying the variable set-point. It also appears that more stable control results are obtained through the application of the variable set-point after DO depletion. The converging value of the estimated denitrification coefficient effectively reflects conditions in the reactor. The presented control strategies might be effectively applied to the control of denitrification.

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