(42) Nitrate Disappearance during Batch Settling in Sequencing Batch Reactor Activated Sludge Process

回分式活性汚泥法における沈殿過程での硝酸塩除去

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ABSTRACT; Nitrate disappearance during settling was quantified and correlated with the sludge settling characteristics in an small size intermittently aerated sequencing batch reactor. For 2770 mg/L initial MLSS sludge with zone settling velocity 2.52 cm/min, the percentage of nitrogen removed during settling to that removed in the system was 30% compared to 19% for initial MLSS 1270 mg/L with zone settling velocity 6.56 cm/min. In order to predict the fate of nitrate during settling, rate of endogenous denitrification considering biomass stratification is essential. A simple batch-settling model was proposed, which can provide stratified biomass concentration profile for predicting nitrate disappearance during settling in SBR. Furthermore, model simulations highlighted different factors affecting settler denitrification such as mass transfer limitations and residual DO.
KEYWORDS; Endogenous denitrification, Reactive settling, Sequencing batch reactor, Settling model

1. Introduction

Sequencing batch reactor technology has gained widespread popularity for the activated sludge treatment at small size treatment plants. The alternating anaerobic and aerobic conditions in a single tank simultaneously remove nitrogen, phosphorus as well as organic matter (Hayakawa et al., 1986). But under low organic loading conditions nitrate-nitrogen is not removed completely after the final phases of settling and decantation. The remaining nitrate from the preceding cycle adversely affects the phosphorus removal processes in the next filling phase. The existence of nitrate leads to prolonged anoxic conditions rather than anaerobic conditions, preventing the release of phosphate from biomass and bio-P removal is gradually lost (Furumai et al., 1997). The biological phosphorus removal can be achieved if the settled sludge is sufficiently denitrified prior to the next filling phase (Rusten et al., 1993). This can be achieved by increasing the settling period for higher endogenous nitrate respiration.

There have been a few studies conducted on denitrification during settling in a continuous clarifier. Seigerist et al., (1995) and Filos et al., (1996) reported that enhanced denitrification can be made possible by maintaining a higher sludge blanket through controlling the speed of scrapers. Henze et al., (1993) reported that under high temperature and more than 6-8 mg NO_3-N/L influent to settler leads to sludge rising. Kim et al. (1994) made attempts to predict nitrate disappearance in batch settling columns using a settling model. Their main objective was to investigate factors affecting sludge rising time and corresponding critical nitrate concentrations rather than quantification of settler denitrification. It is still difficult to quantify the nitrate disappearance during batch settling considering biomass stratification.

Although there have been many studies conducted related to the principal reaction processes of SBR, the settling part has been neglected. If the operational mode of SBR consists of a long settling period, the contribution of denitrification and phosphorus release cannot be ignored. The purpose of this study was to quantify the denitrification during settling for SBR. Field investigations during settling were conducted onsite in different seasons to study the factors affecting denitrification during settling. In addition, a simplified batch-settling model for SBR was proposed, which accounts for the biomass stratification during settling. The settling model in conjunction with endogenous denitrification reaction was used to explain nitrate disappearance during sludge settling. The results of this study may be useful in defining the optimal operational mode of SBR for nitrogen removal considering reactions during settling.

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2. Experimental Methods

2.1 Description of SBR plant

Field and experimental investigations were made on an intermittent aeration SBR activated sludge plant for 940 persons with design flow rate of 250 $m^3.day^{-1}$. The reactor operating on two tanks in parallel of capacity 5.75 x 5.75 x 5 m^3 each. A process cycle consists of two steps: three hours intermittent aeration and three hours settling and drawing. The intermittent aeration has three cycles of 30-min aeration and 30-min mixing. Influent flows into the tank for 3 hours of intermittent aeration. It was followed by three hours of settling. The decantation started after one hour during settling by a movable decanter.

2.2 Sampling and Analysis

The samples were collected for two hours of settling at an interval of 20 minutes at specified depths of the reactor by lowering down 6-mm diameter polyethylene tubes. The tubes were fixed to angle iron in order to avoid disturbance for collecting in situ MLSS samples from the reactor. One end of the tubes were open and positioned at 0.5m, 1.5 m, 2.5 m, 3.5 m, 4.5 m and 5 m depth, while the other ends were connected with specially prepared 100 ml syringe for withdrawing samples. A part of the collected samples was reserved for MLSS measurement, while the remaining was filtered and used for the analysis of nitrate, nitrite, phosphate and TOC. Immediately after collection, all samples were packed in icebox and transported to the laboratory for analysis. Nitrite, nitrate and phosphate were measured by ion chromatography, using a single channel ion chromatograph (IC) equipped with chemical conductivity suppressor. The response was quantified by comparing peak areas to three point calibration curves. The analyses of TOC and MLSS were performed in accordance with Standard Methods (1989). During sampling, sludge blanket height was also measured by a sludge interface detector.

2.3 Batch Experiments

A batch experiment was conducted on SBR sludge collected on 26 Dec.1997 to determine the specific endogenous denitrification (EDN) rate. A 500-ml flask was filled up to three-fourth of its volume with the sludge, added NO_3-N to 5-7 mg/L and placed in a water bath maintained at 20°C. Before starting the experiment and during sample collection, nitrogen gas was flushed through headspace, to prevent oxygen contamination. During the experiment the flask was sealed with rubber stoppers and the sludge was maintained in suspension. Samples for analysis were obtained at every 20 minutes interval, by a syringe attached to a glass tube reaching down below the liquid surface. The rate of EDN was determined from the gradient of the straight-line portion of curve.

3. Results and Discussions

3.1 Batch Settling in SBR

Field investigations were commenced from 4 September 1997 to 14 May 1998, during settling in an intermittent aeration SBR plant. The results are summarized in Table 1. Initial MLSS concentration varies from 1270-2770 mg/L and the corresponding Zone Settling Velocity (ZSV) in the range of 2.52 to 6.56 cm/min. Zone Settling Velocity (ZSV) was calculated for each case by measuring the slope of the straight-line section of the interface versus height curve. The recorded sludge interface profile for all field surveys were shown in Fig. 1. The ZSV obtained are lower than those observed in full-scale activated sludge plants (Huang and Hao 1993). The relationship between ZSV to MLSS is shown in Fig. 2. It is clear that sludge of lower MLSS concentration settles faster. The correlation is similar to that reported by Katoh et al., (1997). The ZSV and MLSS relationship could be assumed to follow the logarithmic or exponential function (Vesilind 1974), but the number of field survey data is limited to predict any mathematical relationship.

3.2 Denitrification during batch settling in SBR plant

To investigate the effect of initial MLSS and ZSV on denitrification, vertical profile of nitrate with time are depicted in Fig. 3, for two different settling sludge with initial MLSS 1270 mg/L with ZSV 6.56 cm/min and 2770 mg/L with ZSV 2.52 cm/min. In the case of initial MLSS 1270 mg/L sludge, nitrate profile does not changes at depth upper than 2.5m, but at the lower depths nitrate concentration decreased significantly. While for the case of initial MLSS 2770 mg/L sludge, a significant shift in nitrate profile was noted at depth upper than 2.5 m.

Table 1 Average Conditions during settling in SBR

Parameters	4 Sept. 1997	30 Oct. 1997	26 Dec. 1997	23 Apr. 1998	14 May 1998
Temp. (°C)	21	24	17	19	19
MLSS (mg/L)	1700	1270	2770	1805	1750
Initial NO_3-N (mg/L)	4.7	6.8	5.1	1.1	2.2
TOC (mg/L)	12.4	12.3	11	24.2	30
SV_{30} (%)	*	29	97	30	37
SVI (ml/g)	*	228	350	166	211
ZSV (cm/min)	4.15	6.56	2.52	3.40	4.51

* = not measured

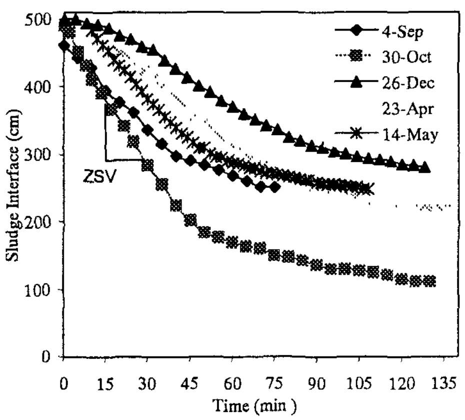

Fig. 1 Sludge interface profiles during settling in SBR plant

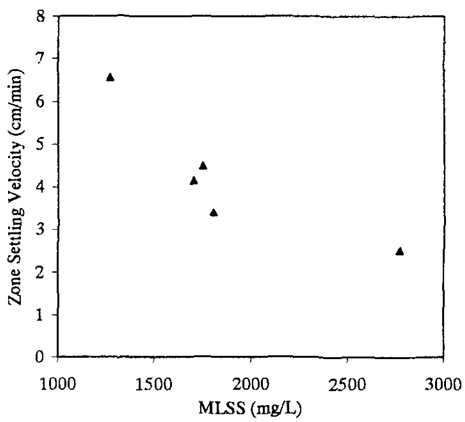

Fig. 2 Relationship between initial MLSS and ZSV

It can be interpreted that higher initial MLSS with lower settling velocity is more favorable to remove larger amount of nitrate during settling. Under lower settling velocity conditions, nitrate has more contact time with biomass resulting in more denitrification. Total nitrate removal during settling for the two cases was calculated by taking the difference between the initial and each time period nitrate profile provided in Fig. 3. The calculation results are shown in Fig.4. In calculations, only nitrate form of nitrogen was considered, since observed ammonium and nitrite nitrogen during settling was below detection limit, and the change of organic nitrogen was assumed to be negligible. The total influent nitrogen per cycle was 1446 g, on the assumption of 35 mg-N/L influent nitrogen. It is seen that for, nitrogen removed during settling was 270 g and 438 g for MLSS 1270 mg/L and MLSS 2770 mg/L respectively. These amounts are equivalent to 19% and 34% of the total input nitrogen. It is clear that total percentage of nitrogen during settling is significant, and could not be neglected.

3.3 Settling Model

It has been discussed that initial MLSS and settling velocity play important roles in denitrification during settling. Previous investigators assumed the constant biomass in sludge blanket for continuous flow type secondary settling tank (Henze et al. 1993 and Seigerist et al., 1995). However this assumption can not be applied to the case of batch settling. A biomass concentration profile varies during settling and compression of sludge. Biomass concentration profile in reactor over time is precondition for estimating nitrate disappearance. Therefore, it is necessary to develop a batch-setting model that can account for biomass concentration profile.

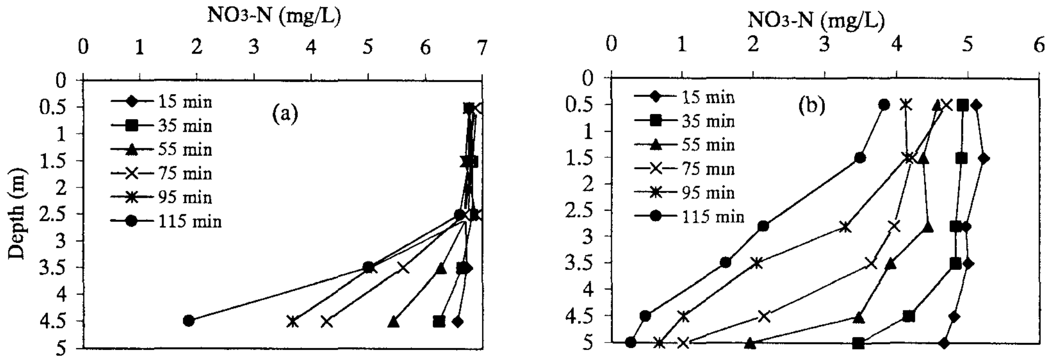

Fig. 3 Nitrate concentration during settling. (a) Initial MLSS 1270 mg/L, Temp 24°C, (b) Initial MLSS 2770 mg/L, Temp 17°C.

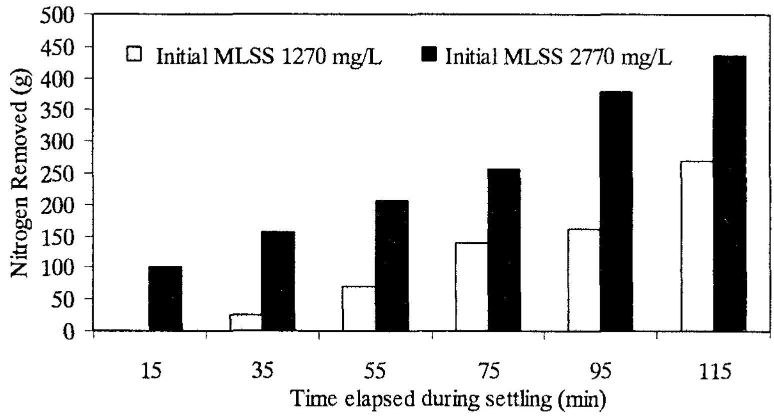

Fig. 4 Nitrogen removed during settling of SBR

The batch sludge settling in SBR is divided into three phases as shown in Fig. 5,

1. Period of constant interface-settling velocity (Constant velocity phase = Phase I)
2. Period of first decreasing interface-settling velocity (Transition phase =Phase II)
3. Period of second decreasing interface-settling velocity (Compression phase = Phase III)

Settling sludge interface and a sediment surface are considered to express sludge profile in the model shown in the Fig. 5 (a). The sediment zone is formed on the bottom from the commencement of settling, where the sludge particles are in mechanical contact with each other. During the constant interface velocity phase, the MLSS concentration at the sludge interface (X_H) is constant and it is same as the initial MLSS concentration (X_{H0}). For the transition phase, the sludge concentration (X_H) on the interface can be obtained by drawing a tangent on the sludge interface curve and by using the following formula proposed by Kynch.

$$X_H = \frac{X_{H0} H_o}{H_i} \qquad [1]$$

Where; X_{Ho} is the initial MLSS concentration [mg L^{-1}]
H_0 is the initial sludge height [cm]
H_i is the tangent intercept [cm]

The compression phase started when the descending sludge interface merges with the ascending sediment surface. The concentration on the sludge interface is same as the constant concentration on the sediment surface in compression phase. However it is very difficult to define the variation of sediment surface for flocculent suspensions like activated sludge. Fitch (1983) proposed a method for determination of sediment surface for non-opaque suspensions by conducting several batch tests on different heights. For each batch test, the determined or measured distinct height at which a considerable change in settling velocity were observed. Locating and joining the heights with time should evolve the sediment surface curve for the suspension. Although we conducted several batch tests on different heights for the same activated sludge during our study, it was impossible to locate and define the height of sediment surface.

Font (1988) defined the critical concentration (X_C) on sediment surface that is assumed to be constant in terms of time. It can be expressed by the following equation.

$$X_c = \frac{X_{H0} H_0}{H^*} \qquad [2]$$

Where H^* is the ordinate of the transition point (t_c). The characteristic line, which arises tangentially to the sediment surface at origin, intersects the sludge interface curve at transition point as shown in Fig.5 (a). In order to simplify the model, we assumed that the transition point is coincident with the changeover point by Talmadge and Fitch (1955), as both are the characteristic points in transition phase.

Based on the observations of Font (1991), the sediment surface L (t) starts at origin and could be assumed to follow an expression similar to saturation function [$L=L_0*t/(K+t)$] where L_0 and K are constants. The equation has been valid until it merges to the upper sludge interface. Settling sludge enters into the pure compression regime when sludge interface merges with sediment surface. The constants L_0 and K of the sediment surface curve can be estimated by regression if sediment height with time is available. However, it is very difficult to obtain the sediment surface from batch test as discussed previously. Therefore, for simplification constant L_0 was assumed as the initial sludge height H_0, as it is the maximum possible height of sediments. The value of K can be estimated by the graphical method discussed herewith. The characteristic line is tangential to sediment surface at origin has slope "a" that is differential of [$L=L_0*t/(K+t)$], i.e., $(dL/dt)_{t=0.}=L_0/K$. Therefore, if slope "a" would be known by graphical construction K is estimated as L_0/a as shown in Fig. 5 (a). For the case of bad settling, sludge interface settles slowly causing higher value of "a" and lower K, while for good settling sludge the value "a " is lower, resulting in higher K value. Hence constant K can fairly represents the settling or compression characteristics of the sludge.

MLSS (X_b) at the bottom of the settler over time can be obtained from Roche et al. (1995).

$$X_b = \alpha\,(t + \Delta t)^\beta \qquad [3]$$

Where; $\Delta t = 0.086 * X_0^{2.234}$ [min]

$\alpha = 2.065 * X_0^{0.382}$ [-]

$\beta = 0.545 * SVI^{-0.152}$ [-]

X_0 (g/L) is initial MLSS, t (min) is time elapsed and SVI (mL/g) is sludge volume index. The Roche model has taken into account the effect of thickening and plant operation parameters. The parameter Δt (min) is the adjusting parameter for representing bottom concentration at time zero, which is found to be dependent on initial MLSS. The parameters α and β showed a high dependency on X_0 and SVI.

Specifically to obtain the MLSS profile, the following steps are necessary (Fig.5);

1. Plot the sludge interface curve and locate the transition point by graphical construction.
2. Draw the characteristic line joining origin to the transition point.
   Compute the slope "a" of the line.
3. Calculate constant $K = (L_0/a)$ for the sediment surface curve assuming $L_0 = H_0$.
   Draw the sediment surface curve.
4. Compute constant critical concentration Xc on sediment surface by equation 2.
5. At every time step compute the MLSS concentration at sludge interface by equation 1
   until sludge interface merges with sediment surface, and bottom concentration from equation 3.

Therefore for a batch test, if profile of sludge interface, SVI and initial MLSS are available, the MLSS concentration on sludge interface and sediment surface, variable MLSS at bottom can be estimated over time. Joining these three concentration points linearly, simplified MLSS concentration profile can be obtained as shown in Fig. 5 (b). Solids balance at each time step can be applied to check the validity of linear assumption of MLSS profile below sludge interface.

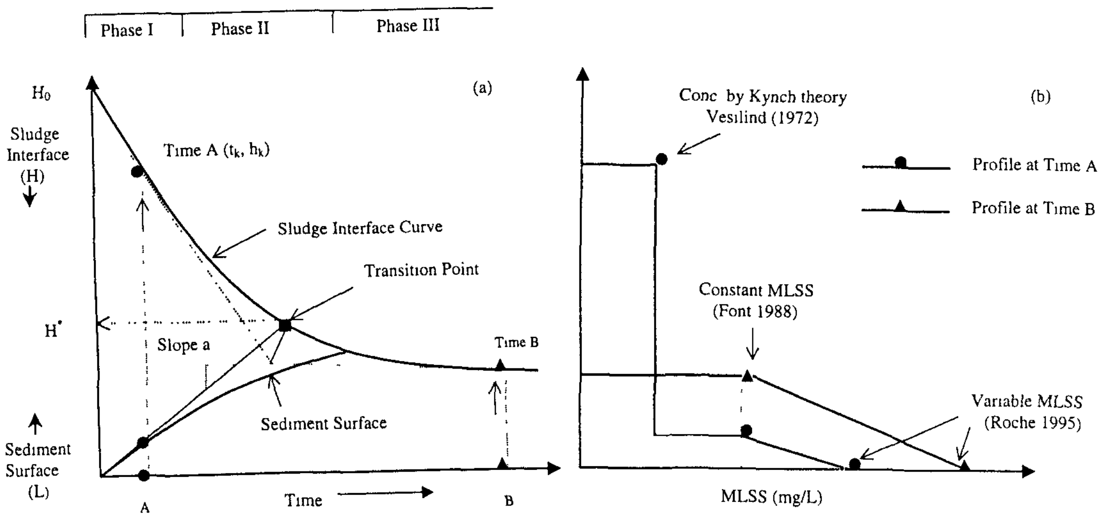

Fig. 5 Settling Model. (a) Sludge-Interface and Sediment-Surface profile
(b) Sludge Concentration profiles at time instants A and B

The presented settling model was verified for the in situ MLSS concentrations and sludge-interface profile obtained from field survey 23 April 1998. Model parameters were SVI=166, Initial MLSS 1805 (mg/L), L_0=500 (cm) and K = 125 (min). The time variable concentration profiles with the observed data are shown in Fig. 6. The simulated profile matched reasonably well for settling time 40 and 80 minutes. During settling, there is a sudden change in concentration near the top of sediment surface. Constant MLSS concentration (Xc = 3223 mg/L) on sediment surface is shown in Fig. 6. Solid balance for the simulated profiles at each time step was compared with the initial solid mass. It indicated that the variation was around 5-13 % that can be partly attributed to the linear assumption of MLSS profile below the sludge blanket.

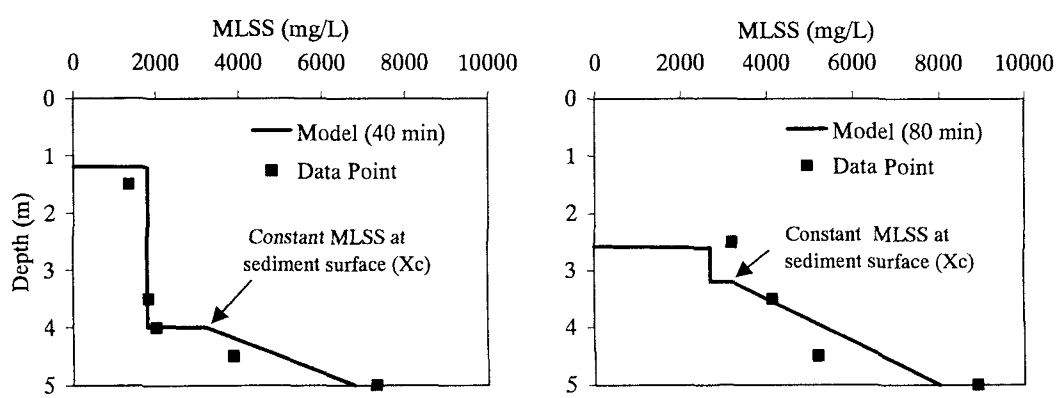

Fig. 6 Simulated and observed MLSS profiles for 40-min and 80-min of settling

3.4 Nitrate Disappearance during Settling in SBR

The rate of nitrate disappearance due to endogenous denitrification in a settler mainly depends on MLSS concentration below sludge blanket and temperature. Although sludge-liquid exchange and diffusion terms should be also taken into account in the nitrate balance equation, their effects are much smaller than the reaction terms. Considering first order denitrification rate with respect to biomass X and neglecting the effects of diffusion and liquid-sludge exchange, the change of nitrate concentration C_{NO_3} during settling can be expressed as follows;

$$\frac{dC_{NO3(z,t)}}{dt} = K_{EDN}X(z,t) \qquad [4]$$

Where specific endogenous denitrification rate K_{EDN} is constant and a function of temperature. Biomass concentration X (z, t) is variable with depth, z, over time and a function of settling characteristics such as SVI and ZSV. Therefore if stratified MLSS profile is given by the settling model and specific rate of K_{EDN} from a batch experiment is available, nitrate disappearance during settling can be predicted. Simulations were performed by dividing the reactor into vertical 10 layers with time steps of 10 minutes. Determined K_{EDN} 0.78 mg.NO_3-N/g.MLSS.h. at 20 °C in the batch experiment was compensated for the field temperature 17°C by the equation $K_{EDN\,(T)} = K_{EDN\,(20)} \times 1.09^{(T-20)}$ (Metcalf &Eddy 1991). Settling model parameters were SVI= 350, Initial MLSS 2770 (mg/L), L_0=500 (cm) K = 125 (min). Simulated and observed NO_3 profiles at 20 and 100 minutes sludge settling in the reactor are shown in Fig. 7.

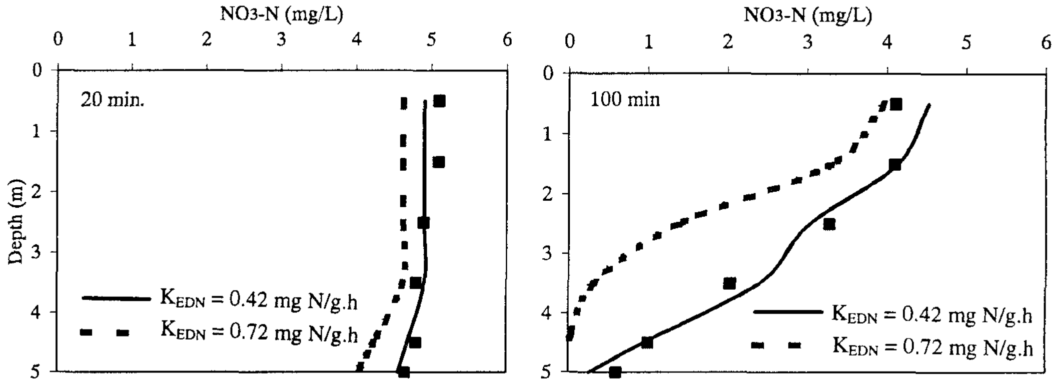

Fig. 7 Simulated and observed NO_3-N concentrations 20 and 100min of SBR settling

The dashed line refers to the simulations taking experimentally found K_{EDN} value. It is clear that simulation results based on the determined K_{EDN} do not agree with the observed one. The overestimated nitrate disappearance in the entire region was mainly due to the higher K_{EDN} value. Other sets of simulations were performed taking the lower K_{EDN} values to match the simulated results with the observed. The model yielded a good prediction on the fate of nitrate with K_{EDN} =0.42 mg. NO_3-N/g.MLSS.h. Thus, experimentally estimated EDN rates could not be taken directly to predict the nitrate disappearance during settling. In the batch settling of SBR, the mixing is minimum and the denitrification is mass transfer controlled, while regular EDN tests were conducted under higher mixing conditions to keep the sludge in suspension. Moreover the model presents the significance of stratified biomass concentration to predict the fate of nitrate during batch settling in SBR. Since the biomass has to be in contact with NO_3-N for denitrification to occur, a higher rate of nitrate disappearance was observed in the bottom zone of sludge blanket, while insignificant nitrate disappearance in upper zone of clear supernatant. The present simulations did not consider the effect of residual DO. For this case initial sludge concentration was sufficiently high to cause the rapid depletion of residual DO in the sludge blanket. But for lower initial MLSS, delay of denitrification will take place by the effect of residual DO. For field survey on Oct. 30 1997, under initial MLSS 1270 mg/L negligible nitrate disappearance was noted during the initial 35 min as shown in Fig.3 (a). The most probable reason would be the suppression and delay of denitrification by residual DO (Barnard 1977 and Crabtree 1983). Therefore the effect of oxygen, causing delay in denitrification should be considered in the present model for low MLSS cases.

4. Conclusions

The nitrate disappearance during settling was investigated in a full-scale SBR nutrient removal plant with intermittent aeration mode. The contribution of denitrification in settling sludge to the total nitrogen removal was evaluated by making total nitrate balances over the settling period of SBR. For initial MLSS 2770 mg/L, with ZSV 2.52 cm/min, 30% nitrogen was removed during settling to that removed in the system, compared to 19% for initial MLSS 1270 mg/L with ZSV 6.56 cm/min. Higher denitrification rates were observed in the bottom region during settling, compared to the top region of the reactor. The difference is involved with the sludge concentration profile induced by settling and compression of sludge. Total nitrate balance during settling showed that better denitrification was achieved for higher initial MLSS concentration that can be accomplished by controlling sludge wastage.

A simplified settling model was developed to provide stratified sludge concentration profile with time, which is prerequisite for predicting nitrate disappearance during settling in SBR. In the model, three important sludge concentrations are skillfully determined and a simple sludge concentration profile is given by joining them. The predicted sludge concentration profile by the model agrees well with those experimentally determined. Comparison of sludge mass for the simulated profile at each time step and the initial one indicated that the difference was only around 5-13 %. Furthermore, the settling model in conjunction with endogenous denitrification reaction was used to explain nitrate disappearance during sludge settling. The model simulations captured the basic trend of nitrate disappearance with an experimentally determined denitrification rate. The results also highlighted that the denitrification rate was overestimated in the batch experiment, because stronger mixing condition in batch test gave a higher specific rate under less mass transfer limitation.

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