Role of Solids Retention Time in Ammonia-Based Feedback Aeration Control

Guoqiang Liu[1] and Jianmin Wang[2]

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Abstract: Ammonia-based feedback aeration control could avoid an unnecessary air supply and, therefore, save energy. However, this control method could be impacted by many factors such as solids retention time (SRT), nitrite oxidation rate, dissolved oxygen (DO) variation, influent load, temperature, and regular low DO operation. This study indicated that, with an unlimited DO (DO $\geq$ 2 mg/L), the minimal SRT required to achieve complete nitrification was between 5 and 10 days. If the SRT was $\leq$ 20 days, reducing the DO could result in accumulation of nitrite. Nitrite could also accumulate under a peak ammonia load with a SRT of less than 15 days. In contrast, ammonia-based feedback control resulted in regular low DO operation. Because low DO enriches nitrifiers and selects nitrite-oxidizing bacteria (NOB) with a greater oxygen affinity, the required SRT to avoid the accumulation of nitrite can be substantially reduced. The authors recommend using a minimal SRT of 20 days to start a system. When the system reaches a stable condition, the minimal SRT can be reduced to 15 days, if needed. A pilot-scale field experiment indicated that the adverse effect of a low temperature can be overcome by extending the SRT. **DOI: 10.1061/(ASCE)EE.1943-7870.0001106.** © *2016 American Society of Civil Engineers.*

Author keywords: Nitrification; Ammonia-based aeration control; Solids retention time (SRT); Low dissolved oxygen (DO); Nitrite accumulation; Peak influent load.

Introduction

Dissolved oxygen (DO) is a critical control parameter for biological wastewater treatment processes because it directly relates to the effluent quality and operational cost. Energy used for aeration contributes to the majority of the energy consumption of a treatment plant (McCarty et al. 2011). Usually, the DO in an aeration tank needs to be maintained at 2 mg/L to ensure both biological oxygen demand (BOD) removal and nitrification (Metcalf and Eddy 2003; Ma et al. 2006). However, considering the fluctuation in wastewater flow and strength, BOD degradation and nitrification can be completed with a DO lower than 2 mg/L most of the time. In this case, maintaining a constant DO of 2 mg/L in the bioreactor is unnecessary.

Ammonia removal has become one of the most important goals in municipal wastewater treatment. Nitrifying bacteria are considered less competitive than heterotrophic bacteria under low DO conditions (Grady and Lim 1980; Metcalf and Eddy 2003); therefore, nitrification is much more sensitive to a low DO than BOD degradation is. When the DO is inadequate, the effluent ammonia or nitrite can provide a faster feedback than other effluent quality parameters, such as BOD, by increasing its concentration. As a result, ammonia or nitrite can be used to control the aeration intensity and avoid overaeration, which may save 15–25% of the aeration energy (Vrečko et al. 2011; Rieger et al. 2014).

Both ammonia-based feedforward and feedback controls have been implemented for the activated sludge process (Åmand et al. 2014; Rieger et al. 2014). Ammonia-based feedforward control is a model-based approach. Usually, the inflow rate and influent ammonia concentration are tracked to calculate the necessary DO level for treatment. The air flow is adjusted on the basis of the dynamic DO set point. Other parameters, such as mixed liquor suspended solids (MLSS) concentration and temperature in the aeration tank, are also monitored to determine this DO set point. The success of feedforward control is highly dependent on the reliability of various sensors, the mathematical models, and the kinetic parameters used in the models. However, the kinetic parameters used in the models vary with bacterial communities and are very difficult to determine (Cox 2004), which makes this control method difficult to use. Moreover, the calibration and maintenance of various sensors are also complex.

For ammonia-based feedback control, the ammonia concentration in the aeration tank is used to directly control the aeration (Fig. 1). When the ammonia concentration in the aeration tank is greater than the set point or range, the aeration is increased. When it is less than the set point or range, the aeration is decreased. It is essentially a real-time optimization process to keep the minimal DO needed for the treatment, and, therefore, improves oxygen transfer efficiency. Compared with the feedforward control, the feedback control is simple and more reliable to use.

The ammonia-based feedback aeration control relies on the direct correlation between operational DO and the effluent ammonia. The success of this control method is dependent on many factors or operational conditions, such as solids retention time (SRT), potential to accumulate nitrite, DO variation, peak ammonia and organic loads, temperature, and regular low DO operation caused by the ammonia-based control method. If incomplete nitrification was not caused by low DO, the ammonia-based feedback controller would give false information to increase aeration. Otherwise, a DO probe needs to be integrated to avoid increasing the aeration intensity if the DO reaches 2 mg/L (Rieger et al. 2014). High effluent nitrite concentration could also occur in a system with ammonia-based feedback control because nitrite-oxidizing bacteria (NOB) were thought to be more sensitive to low DO than

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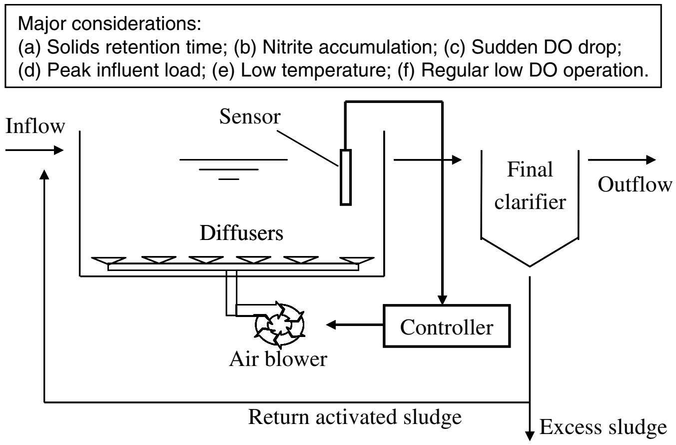

Fig. 1. Schematic of ammonia-based feedback aeration control

ammonia-oxidizing bacteria (AOB) (Laanbroek and Gerards 1993; Okabe et al. 1999; Sliekers et al. 2005; Blackburne et al. 2008; Park et al. 2010).

SRT is the most critical design and operational parameter for the activated sludge process, because it determines the nitrifier abundance and community composition (Metcalf and Eddy 2003; Liu and Wang 2014). The interferences of changes in temperature and peak influent loads for ammonia-based feedback control could be overcome by using an appropriate SRT, to ensure that effluent ammonia is the appropriate effluent quality indicator and that the operational DO directly correlates to the effluent ammonia concentration. The objectives of this research were to understand and determine an appropriate SRT, which is needed for the activated sludge process that uses ammonia-based feedback aeration control, and to avoid accumulation of nitrite and the adverse effects from other factors such as peak influent loads and low temperatures.

Materials and Methods

Lab Experimental Setup and SRT Effect

Four bench-scale complete-mix reactors of the same size (31.5 L) were fed continuously with synthetic wastewater to achieve a hydraulic retention time (HRT) of 12 h. To determine the effect of SRT on nitrification without DO limitation ($DO \geq 2$ mg/L), the reactors were operated at SRTs of 5, 10, 20, and 40 days, respectively. The regular influent chemical oxygen demand (COD) (from glucose) and ammonia nitrogen (ammonia-N, from ammonium carbonate) concentrations were 180 mg/L and 48 mg/L, respectively. In addition, trace elements were provided and the detailed constituents in the influent were shown in a previous study (Liu and Wang 2012). The pH in the reactor ranged from 7.0–7.5, maintained by a buffer containing K_2HPO_4 and Na_2CO_3. Reactor temperature was approximately 20°C. To achieve steady conditions, the 5- and 10-day SRT reactors were operated for more than 80 days, and the 20- and 40-day SRT reactors were operated for more than 100 days. The effluent 5-day biological oxygen demand (BOD_5), ammonia, nitrate, and nitrite were monitored. After an unlimited DO test, the 5-day SRT reactor was terminated because of its inability to achieve complete nitrification.

Low DO Shock Test

After all reactors were stabilized, the DO levels were reduced to various ranges for 8 h to determine the response of effluent quality. All other operational conditions, such as SRT, influent substrate concentration, HRT, and temperature, were maintained at the same level as before. The effluent COD, ammonia, nitrate, and nitrite were measured every 1 or 2 h after reducing the DO.

Ammonia and Organic Shock Load Test

After finishing low DO shock tests, all reactors were changed back to an unlimited DO condition. After stabilization, effects of ammonia and organic shock loads on reactor performance, especially nitrification, were tested. During ammonia shock load tests, the influent ammonia concentration was instantaneously increased to 1.5–6 times that of the regular concentration, although no change was made in the influent COD. Reactors were operated at the regular ammonia load for 24 h before changing to a different ammonia shock load. During organic shock load tests, the influent COD concentration was gradually increased to 6 times that of the regular concentration without changing any other operational parameters. In both shock load tests, the DO concentration was maintained above 2 mg/L and the pH was maintained at a range of 7.0–7.5. The concentrations of effluent ammonia, nitrate, nitrite, and COD were monitored after increasing the loads.

Field Pilot-Scale Test

A pilot-scale compete-mix activated sludge reactor was set up at the Southeast Wastewater Treatment Plant in Rolla, Missouri. The reactor was fed with raw municipal wastewater from a location between the fine screen and the grit chamber. The effective volume of the aeration tank was 20 m^3. To simulate the loading variation, the reactor was fed at different inflow rates (from 38 to 114 m^3/day), resulting in HRTs in the range of 4.2 to 12.6 h. Under each flow rate, the reactor was operated for 2 to 6 weeks. This field test was conducted during the period from June 2010 to February 2011, with the reactor temperature ranging from 7 to 27°C. The SRT was controlled and maintained at approximately 30 days before November 2010. Starting from the middle of November, the SRT was increased to 50 days to ensure good effluent quality. During the experiment, constant aeration was provided. Parameters were monitored approximately three times per week. These included operational parameters including aeration tank MLSS, mixed liquor volatile suspended solids concentration (MLVSS), pH, temperature, and DO, the influent parameters including inflow rate, COD, suspended solids (SS), and total nitrogen (TN), and the effluent parameters including COD, ammonia, nitrite, and nitrate. Composite samples were used for influent parameter analysis, and grab samples at the final clarifier were used for effluent parameter analysis.

The analysis methods for MLSS, MLVSS, COD, BOD_5, pH, DO, ammonia, nitrate, and nitrite are described in a previous study (Liu et al. 2012; Liu and Wang 2012).

Results

Effect of SRT on Nitrification without DO Limitation

Incomplete nitrification can be caused by a combination of many factors, such as short SRT, DO, low temperature, and shock influent load. If it is not caused by a low DO only, ammonia-based feedback control will not work. Table 1 shows the effect of SRT on effluent quality, without DO limitation, in a lab experiment with a constant temperature and an influent load. All reactors had low effluent BOD_5 concentrations, indicating that the organic degradation had been completed. The effluent ammonia and nitrite concentrations in the 10-, 20- and 40-day SRT reactors were below

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Table 1. Steady-State Effluent Quality with Different SRTs (Mean ± SD, $n \geq 15$) (DO ≥ 2 mg/L, pH = 7.0–7.5, Temperature = 20.5 ± 1°C)

SRT (day)	NH_4^+-N (mg N/L)	NO_2^--N (mg N/L)	NO_3^-N (mg N/L)	Total output N[a] (mg N/L)	BOD_5 (mg/L)
5	2.6 ± 2.3	9.2 ± 3.4	32.0 ± 4.1	50.6	4.3 ± 1.4
10	0.04 ± 0.01	0.15 ± 0.05	41.9 ± 0.9	48.1	2.2 ± 0.6
20	0.03 ± 0.007	0.04 ± 0.01	43.2 ± 0.8	48.4	1.6 ± 0.3
40	0.02 ± 0.003	0.01 ± 0.004	44.4 ± 1.4	48.1	1.7 ± 0.5

[a]Total output nitrogen = effluent ammonia nitrogen + effluent nitrate nitrogen + effluent nitrite nitrogen + organic N in wasted biomass.

0.5 mg N/L, indicating that complete nitrification was achieved in these reactors. For the 5-day SRT reactor, however, both the effluent ammonia and nitrite concentrations were greater than 2 mg N/L, suggesting that the 5-day SRT was too short to achieve complete nitrification under the loading imposed. Moreover, a nitrite had accumulated within the 5-day SRT reactor, indicating that nitrite oxidation was lower than ammonia oxidation, limiting the overall nitrification performance. As a result, to accomplish complete nitrification, it was estimated that the minimal SRT should be between 5 and 10 days. This estimation was verified by the authors' previous work (Liu and Wang 2014).

Effect of Low DO Shock

The principle of the ammonia-based feedback control is to use the effluent ammonia concentration to directly adjust aeration intensity. Therefore, the DO concentration in the activated sludge process varies with the fluctuations in the influent load and temperature. To avoid nitrite accumulation, ammonia oxidation needs to have at least the same rate as the nitrite oxidation during the DO change.

Historically, we perceive that NOB were more sensitive to the DO change than AOB were, which resulted in nitrite accumulation when the DO was inadequate (Laanbroek and Gerards 1993; Okabe et al. 1999; Sliekers et al. 2005; Blackburne et al. 2008). However, the authors' recent studies have indicated that both AOB and NOB contain diverse sublineages with different oxygen affinities, and their communities are impacted by SRT (Liu 2012; Liu and Wang 2014). Therefore, the responses of both AOB and NOB to the low DO were SRT dependent.

Low DO shock tests were conducted on the 10-, 20-, and 40-day SRT reactors to determine the effect of a sudden DO drop on effluent quality, with results shown in Fig. 2. For the 10-day SRT reactor, a DO drop to 1.5 mg/L resulted in a noticeable nitrite accumulation without impacting the ammonia concentration. For the 20-day SRT reactor, a DO drop to 0.8 mg/L resulted in a slight increase in nitrite concentration without impacting the ammonia concentration. Further reducing DO to 0.4 mg/L resulted in both a nitrite and an ammonia increase. For the 40-day SRT reactor, nitrite did not accumulate, even when the DO dropped to 0.23 mg/L, but the ammonia concentration increased significantly. As expected, the effluent COD did not significantly increase, even when incomplete nitrification occurred in all reactors, confirming that the nitrification process was more sensitive to the reduced DO than the heterotrophic biodegradation process was.

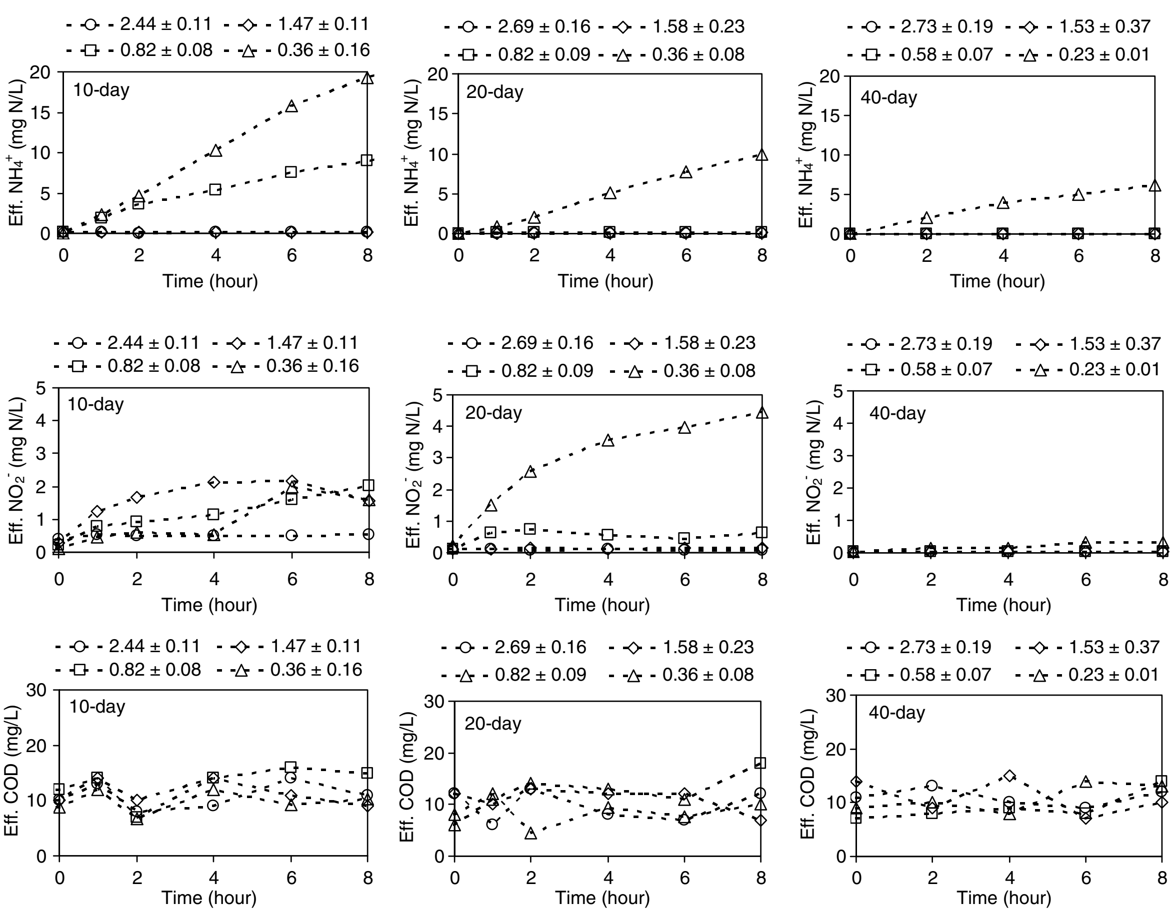

Fig. 2. Effect of sudden DO drops on effluent COD, ammonia and nitrite for reactors with 10-, 20-, and 40-day SRTs (pH = 7.0–7.5, temperature = 20.5 ± 1°C)

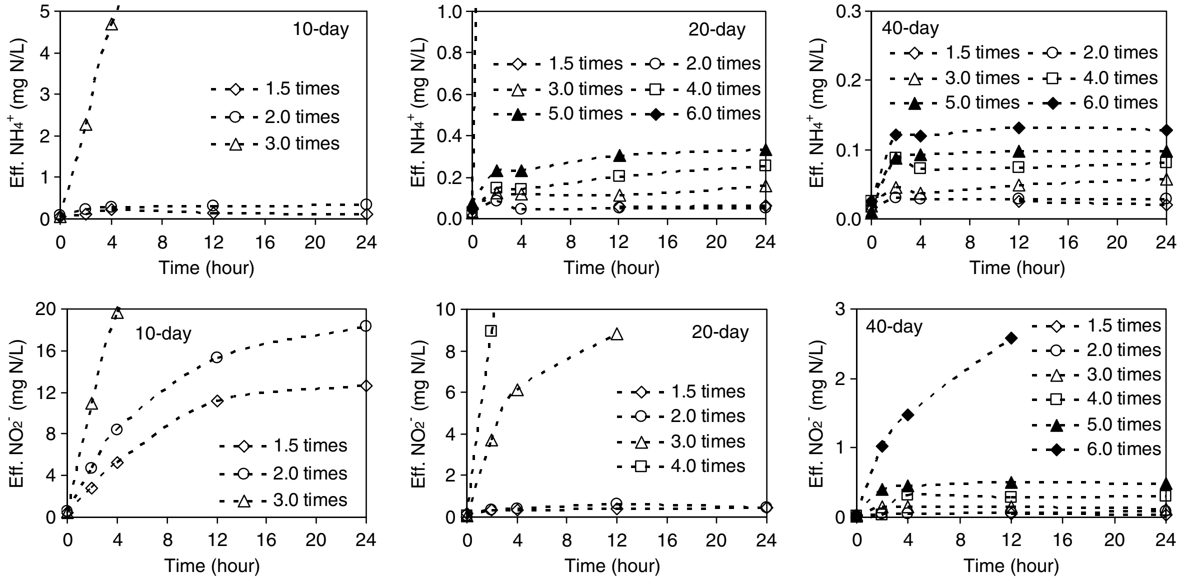

Fig. 3. Effect of ammonia shock loads on effluent ammonia and nitrite for reactors with 10-, 20-, and 40-day SRTs (DO ≥ 2 mg/L, pH = 7.0–7.5, temperature = 20.5 ± 1°C)

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The responses of 10- and 20-day SRT reactors to the DO drop were in agreement with the authors' previous understanding that NOB was more sensitive to low DO than AOB was. At the 40-day SRT, however, ammonia oxidation was more sensitive to low DO than nitrite oxidation was because only ammonia accumulated. This performance resulted from the difference in the nitrifier community. NOB contained both *Nitrobacter* and *Nitrospira*. Low SRT (<20 days) makes *Nitrobacter*-NOB, which have lower oxygen affinity, more competitive than *Nitrospira*-NOB (Liu and Wang 2013). In the 40-day SRT reactor, however, nitrite oxidation is primarily accomplished by *Nitrospira*-NOB that have a greater oxygen affinity (Liu and Wang 2014). Therefore, the dominance of *Nitrospira* in the 40-day SRT reactor made nitrite oxidation faster than ammonia oxidation at a low DO.

Fig. 2 also suggests that, to achieve complete nitrification and avoid nitrite accumulation, the 10- and 20-day SRT reactors need a DO of greater than 1.5 mg/L and 0.8 mg/L, respectively. However, for the 40-day SRT reactor, complete nitrification could be achieved at a DO of approximately 0.5 mg/L. Therefore, maintaining a DO of 2 mg/L for advanced wastewater treatment is not necessary.

Effect of Ammonia Shock Load

For municipal wastewater treatment plants, the typical peak hourly loads for BOD are less than four times the average load, and for total Kjeldahl nitrogen (TKN), the loads are less than three times the average (Metcalf and Eddy 2003). The peak TKN load could result in a greater effluent ammonia concentration if the nitrification capacity is not enough. In this situation, ammonia-based feedback control could result in intensive aeration without improving effluent quality.

Fig. 3 shows the results from the ammonia shock load test under unlimited DO conditions. For the 10-day SRT reactor, the effluent nitrite concentration increased to above 2 mg N/L after 2 h when the ammonia loading increased to one-and-one-half times, and greater increases in nitrite concentration were observed with a further increase in ammonia loading. However, the effluent ammonia concentration increased only when ammonia loading was raised three times. For the 20-day SRT reactor, a noticeable increase in nitrite concentration occurred after only 2 h when influent ammonia loading increased to three times the original value, although a high effluent ammonia concentration occurred only after the influent ammonia loading increased to six times the original loading. For the 40-day SRT reactor, the six times of ammonia loading only led to a slight nitrite accumulation. During the ammonia shock load tests, no significant change was observed in effluent COD concentration (data not shown).

Fig. 3 shows that reactors with a longer SRT had a greater capability for handling ammonia shock load and for reducing nitrite accumulation, because a longer SRT resulted in a higher nitrifying biomass concentration and, therefore, a greater nitrification capacity (Metcalf and Eddy 2003; Liu and Wang 2014). In addition, nitrite accumulated before ammonia during the ammonia shock load experiment in all reactors.

Effect of Organic Shock Load

It was thought that nitrification would be inhibited by a high BOD concentration in activated sludge processes (Sharma and Gupta 2004). As a result, incomplete nitrification could occur at the peak organic load. To test the hypothesis, an organic shock load was applied to all reactors. During the organic shock load test, the influent ammonia concentration remained constant. As shown in Fig. 4(a), when the COD concentration increased to 1,080 mg/L, an increase in effluent BOD concentration only occurred in the reactor with a 10-day SRT. As shown in Figs. 4(b and c), no significant change was found in the effluent ammonia and nitrite under various organic shock loads, indicating that an organic shock load had no impact on nitrification. The decrease in effluent nitrate concentration, with the increase in influent organic loading [Fig. 4(d)], was probably caused by the increase in ammonia assimilation to the biomass.

Pilot-Scale Test Data

Low temperature could also result in incomplete nitrification attributable to the reduced reaction rate, even when the DO is high. It was anticipated that the adverse effect of low temperature on

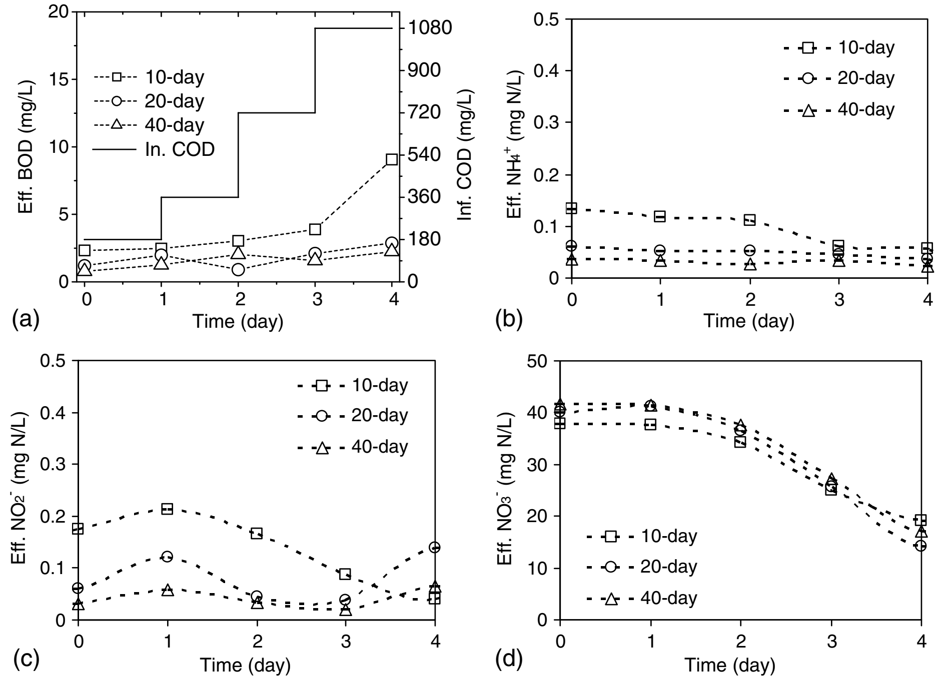

Fig. 4. Effect of organic shock load on (a) effluent BOD; (b) ammonia; (c) nitrite; and (d) nitrate in reactors with 10-, 20-, and 40-day SRTs ($DO \geq 2$ mg/L, pH = 7.0–7.5, Temperature =20.5 ± 1°C)

nitrification could be overcome by increasing the SRT. A field pilot-scale experiment was conducted to validate the findings obtained from lab bench-scale experiments and also to test the hypothesis that complete nitrification can still be achieved under a low temperature when the SRT is long enough.

Fig. 5 shows the changes in temperature, DO, MLSS, influent COD and TN loads, and concentrations of effluent COD, ammonia, and nitrite in the field pilot-scale reactor. Because there was no nitrate or nitrite in the influent, the total TN load was equivalent to the TKN load. During the experiment, the temperature ranged from 7 to 27°C. Because the pilot-scale reactor was fed with different flow rates over the experimental period, the influent organic and TN loads varied from 3.5 to 59.3 kg COD/day and 0.38 to 3.84 kg N/day, respectively. Constant aeration was provided, resulting in DO variations from 0.1 to 8.7 mg/L attributable to the fluctuation in the inflow rate, strength, and temperature. Before the middle of November, the SRT was approximately 30 days and the MLSS ranged from 1.8 to 6.3 g/L (with an average value of 3.9 ± 1.1 g/L). Starting from the middle of November, the SRT was increased to approximately 50 days, to overcome the effect of low temperatures on reactor performance, and the average MLSS concentration increased to 6.5 ± 1.3 g/L.

As presented in Fig. 5, there was no significant change in effluent COD concentrations (with an average of 26 ± 10.8 mg/L) under various loading, temperature, and DO conditions. The effluent nitrite concentration during the experiment varied slightly, from 0.02 to 1.8 mg N/L. However, the effluent ammonia fluctuated significantly, from 0.03 to 18.0 mg N/L. The highest effluent ammonia occurred during the period when the DO was very low.

As shown in Fig. 5, high effluent nitrite concentrations (higher than 1 mg N/L) were detected only in the first several days after the reactor start-up. This was because NOB grew slower than the AOB did. However, no nitrite accumulation was detected after July, even when the DO was lower than 0.5 mg/L. In addition, no nitrite had accumulated with a low temperature. This result indicated that, when the SRT was long enough, nitrite would not accumulate, even when the DO and temperature were low and even with a fluctuating influent load.

Fig. 6 shows the correlations of effluent ammonia and nitrite with the operational DO during the experimental period. A clear trend was evident when a high effluent ammonia concentration occurred if the DO was low, and the nitrite concentration was much lower than the ammonia concentration. The clear relationship between effluent ammonia and the operational DO suggested that, as long as the SRT was long enough, the low DO was the only factor that resulted in a high effluent ammonia, regardless of the temperature and influent load variations. Because the effluent ammonia was less than 1 mg N/L most of the time, as long as the DO was greater than 0.5 mg/L, maintaining a DO of 2 mg/L was determined to be not necessary. As shown in Fig. 6, when the DO was higher than 2 mg/L, the effluent ammonia and nitrite were always lower than 0.5 mg N/L, indicating that ammonia of 0.5 mg N/L could be used as the lower threshold value for aeration control. Once the effluent ammonia was lower than 0.5 mg N/L, aeration should be reduced.

Discussion

SRT Requirement

The bench-scale experiment indicated that, to achieve complete nitrification at a steady state with an unlimited DO, the minimal SRT should be between 5 and 10 days. A case study indicated that, if applying ammonia-based feedback control with a SRT between 5 and 10 days, the actual operational DO was generally higher than 1 mg/L, and effluent ammonia that was higher than 2 mg N/L occurred frequently (Åmand et al. 2014). Because the operational DO was still high, the energy savings were insignificant. In addition, nitrite, which was not monitored by Åmand et al. (2014) in their case study, is expected to accumulate in the effluent under these low

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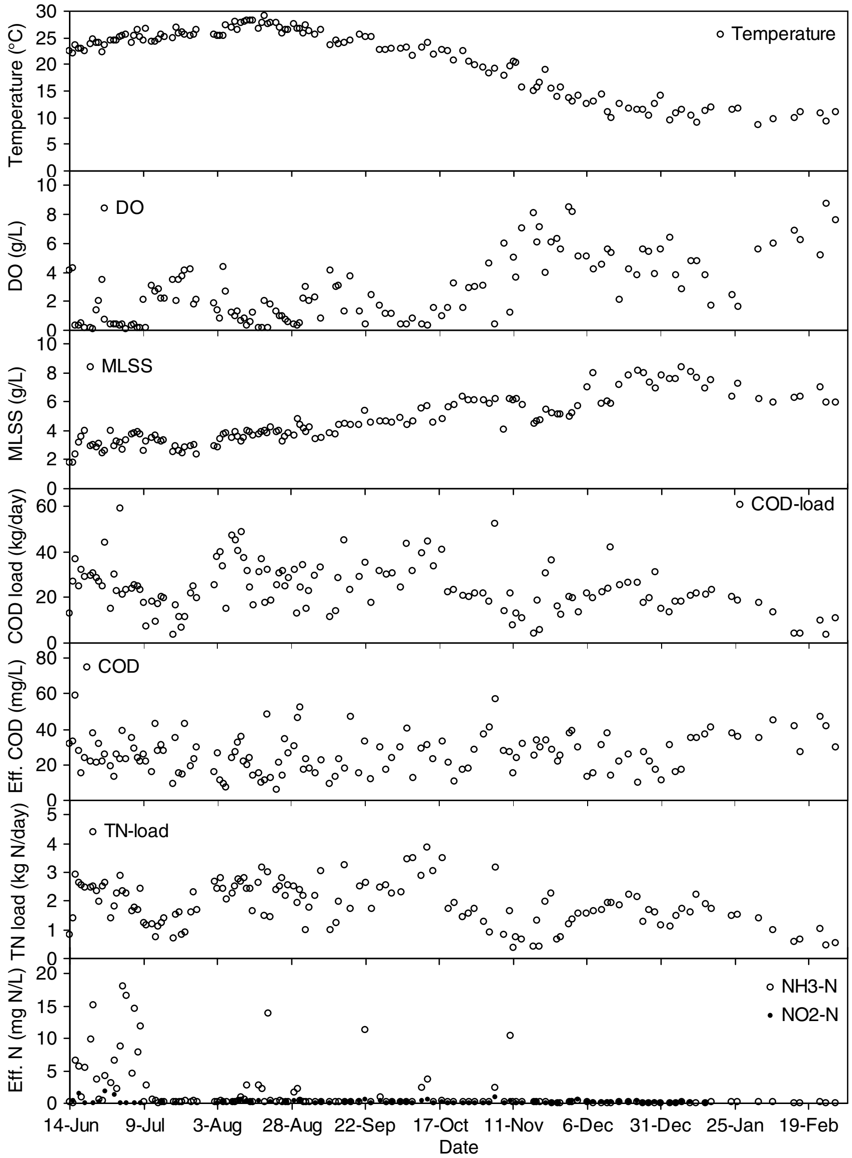

Fig. 5. Temperature, DO concentration, MLSS concentration, influent COD and TN loadings, and effluent COD, ammonia, and nitrite concentrations in the pilot-scale field reactor

SRTs, as indicated by this paper Therefore, the treatment process that uses ammonia-based feedback aeration control should have a SRT greater than 10 days.

Fig. 2 indicates that the responses of effluent ammonia and nitrite to low DO shock were SRT dependent. With the SRT between 10 and 20 days, the effluent nitrite accumulated before the effluent ammonia did when the DO became inadequate. For the 40-day SRT reactor, the effluent nitrite had no significant increase, even when the DO dropped to 0.23 mg/L, although the effluent ammonia increased significantly. On the basis of this information, the minimal operational SRT for a system with ammonia-based feedback aeration control should be greater than 20 days to avoid nitrite accumulation. However, ammonia-based feedback aeration control will result in regular low DO operation. If the chronic effects of low DO on nitrifier enrichment and NOB community shift are considered, nitrite will unlikely accumulate when the SRT is greater than 10 days (to be discussed in the "Nitrifier Enrichment and NOB Community Shift as a Result of Ammonia-Based Control" section).

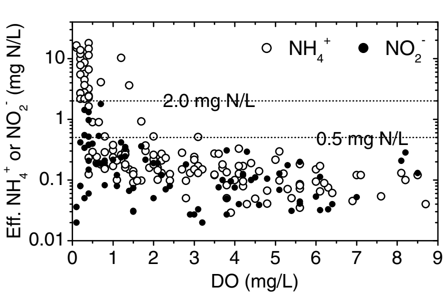

Fig. 6. Correlations of effluent ammonia and nitrite with DO

The ammonia shock load test indicated that nitrite accumulated significantly in the 10- and 20-day SRT reactors at one-and-one-half and three times the ammonia shock load, respectively, after 2 h of operation. In the lab ammonia shock load test, a high ammonia load was applied continuously. However, in the field

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condition, the peak hourly TKN load only occurred within the peak hour, and the operating TKN load was much less than the peak value before and after the peak hour. Considering the dilution effect within the aeration tank, the authors assumed that the treatment plant would be impacted by a realistic ammonia peak load equivalent to two times the average load for a period of 2 h. According to Fig. 3, the reactor with a 20-day SRT did not show nitrite accumulation under this load condition, and the estimated SRT to have nitrite accumulation under a realistic peak ammonia load condition should be less than 15 days. If the SRT $\geq$ 15 days, complete nitrification would be achieved, even under a peak ammonia load.

The field experiment supported the results from a bench-scale experiment, showing that no nitrite accumulated under low DO and peak ammonia load conditions if the reactor maintained a long SRT. In addition, the field experiment confirmed that low temperature (~7°C) did not negatively impact effluent quality when the operational SRT was extended. Therefore, the negative effect of low temperature can be compensated for by increasing the SRT.

Control Range

For ammonia-based feedback aeration control, controlling the effluent ammonia in a range instead of by a set point provides more flexibility and response time for the controller and the treatment process. The pilot-scale field test suggested that, when the DO was greater than 2 mg/L, the effluent ammonia was always lower than 0.5 mg N/L, regardless of influent load and temperature variations if the SRT was extended. Therefore, low effluent ammonia could indicate excessive aeration, and a concentration of 0.5 mg N/L could be used as the lower threshold value for aeration control. However, the lower threshold value will also be impacted by the detection limit of ammonia-monitoring instruments or sensors. When the effluent ammonia concentration is below the threshold value, the aeration intensity should decrease. However, the upper threshold value of ammonia needs to be determined on the basis of the discharge permit limit. A value that is slightly lower than the permit limit will provide some safety for the discharge quality.

Nitrifier Enrichment and NOB Community Shift as a Result of Ammonia-Based Control

The lab study was conducted on the activated sludge cultivated under unlimited DO conditions. In the activated sludge system with ammonia-based feedback aeration control, the actual operational DO varied from 0.1 to 2.5 mg/L (Rieger et al. 2014). The operational DO level would stay low most of the time, as long as the SRT was more than 10 days. The low operational DO has significant impact on the nitrifier community.

The authors' recent studies indicated that a low DO concentration inhibited the endogenous decay of both AOB and NOB (Liu and Wang 2013, 2015). As a result, regular low DO operation significantly increased both the nitrifier population size and the biomass nitrification capacity. For instance, compared with unlimited DO operation (DO $\geq$ 2 mg/L), a long-term low DO of 0.37 mg/L increased the biomass maximum ammonia oxidation rate and nitrite oxidation rate by 95% and 58%, respectively, under a 10-day SRT (Liu and Wang 2013). The increased nitrification capacity could alleviate effects of other unfavorable conditions, such as shock ammonia load and low temperature, on the overall nitrification performance. The authors' recent study also indicated that, under long-term low DO conditions, *Nitrospira*-NOB, which contained sublineages with high oxygen affinity, won the competition over *Nitrobacter*-NOB (Liu and Wang 2013). As a result, nitrite oxidation became more competitive than ammonia oxidation, resulting in no nitrite accumulation for systems operated with a low DO. For example, nitrite oxidation rate for a 40-day SRT sludge cultivated under a low DO was three times that of the ammonia oxidation rate under a low DO of approximately 0.2 mg/L (Liu and Wang 2013), and no nitrite accumulation was observed for all reactors (with SRTs of 10, 20, and 40 days) operated under low DO conditions (Liu 2012). It was expected that the ammonia-based feedback aeration control would result in regular low DO operation most of the time. Therefore, these positive effects of low DO on the nitrifier community have to be considered.

Because a 10-day SRT was sufficient to achieve complete nitrification when the reactor was continuously operated under a high DO (Table 1) and a low DO (Liu and Wang 2013), it should also be sufficient to achieve complete nitrification under fluctuating DO conditions resulting from ammonia-based feedback control. The actual range of DO is determined by changes in influent load (such as COD and ammonia) and operation conditions (such as SRT and temperature). It could be as low as 0.2 mg/L when the influent load is low and when the SRT is high. In addition, because low DO shifted the NOB community and resulted in a greater operating nitrite oxidation rate than the ammonia oxidation rate, nitrite was unlikely to accumulate at a SRT of 10 days. Moreover, because low DO enriched both AOB and NOB, the reactor operated with ammonia-based feedback aeration control should have better capability in alleviating the adverse effects from a shock ammonia load and low temperature than the one that operated under a continuous high DO condition. Therefore, the required SRT to handle the ammonia peak load should be less than 15 days.

However, a 10-day SRT is not recommended for actual operation because nitrite may still accumulate at a peak ammonia load. As indicated in the authors' previous study, the 10-day SRT sludge cultivated under a low DO increased its maximum nitrite oxidation rate by 58%, which was still lower than the maximum ammonia oxidation rate (Liu and Wang 2013). In addition, ammonia-based aeration control will result in a low DO condition not all the time (although most of the time). Therefore, the enrichment of nitrifiers in reactors operated with ammonia-based feedback aeration control would not be as good as that operated with consistently low DO conditions. Consequently, 10-day SRT would be too short to provide reliable treatment quality for a system operated with ammonia-based feedback control. On the basis of the above considerations and previously determined nitrification kinetics under low DO conditions (Liu 2012), the authors recommend that a minimal SRT of 15 days be used to operate a treatment plant that needs complete nitrification to ensure operational stability, if ammonia-based feedback aeration control is used.

It may need 1 to 2 months to enrich nitrifiers and select the NOB with the higher oxygen affinity under low DO conditions (Liu and Wang 2013). Therefore, when starting a treatment plant with ammonia-based feedback control, a minimal SRT of 20 days is recommended initially. A longer SRT will definitely reduce the operational DO. A lower operational DO will promote nitrifier enrichment and select the NOB community with high oxygen affinity. When the system attains a stable condition, the minimal operational SRT can be reduced to 15 days, if needed, to increase sludge production and reduce oxygen demand. The optional SRT needs to be increased in winter to compensate for the adverse effect of low DO on nitrification performance. Low DO operation of activated sludge process could promote the growth of filamentous bacteria and result in sludge bulking. Probably this issue could be solved using selectors, and further study is needed.

Conclusions

Effects of SRT, sudden DO drop, ammonia shock load, organic shock load, low temperature, and regular low DO operation on the overall nitrification performance were investigated in lab and field systems. Results indicated that complete nitrification was achieved with a SRT of between 5 and 10 days in lab bench reactors with unlimited DO, and a sudden drop of DO, to 0.8 mg/L or lower, caused nitrite accumulation for reactors with SRTs ≤ 20 days. Results also indicated that a peak ammonia load resulted in nitrite accumulation if the SRT was less than 15 days, even with unlimited DO. However, an organic shock load did not impact nitrification. Field pilot-scale study data indicated that effects of low temperatures, fluctuating influent loads, and DO variations could be overcome by extending the SRT. In contrast, ammonia-based feedback aeration control will result in regular low DO operation, and a low DO promotes accumulation of nitrifiers, and shifts the NOB community to those that have greater oxygen affinity. As a result, nitrite accumulation will not be expected in the stable system with ammonia-based feedback aeration control when the SRT is greater than 10 days. The authors recommend that a minimal SRT of 15 days be used for treatment plants that adopt ammonia-based feedback aeration control; however, this SRT needs to be extended if the temperature is less than 20°C.

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