Development of sequencing batch reactor with step feed and recycle


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Abstract SBR process shows high nitrogen and phosphorus removal in countries where separated sewers are used. On the other hand, removal efficiency is low in countries where combined sewers are used though the same SBR is applied. This is because the organic concentration (as BOD), which is used as carbon source for denitrification, of combined sewers is much lower than that of separated sewers. Almost all sewers in Korea are combined, and their BOD is low by about 1/2 over the level needed for denitrification. In this study, a SBR process that can optimise organic usage by step feed and recycle is thus developed to increase the removal efficiency of nitrogen and phosphorus, and the results show that the removal rates of BOD, T-N and T-P are 95.4, 81.4 and 86.1%, respectively, though influent BOD is low.

Keywords Anoxic or aerobic state; denitrification; nitrification; phosphorus release and uptake; SBR; sewers; step feed and recycle

Introduction

According to PAI (Population Action International), Korea is one of the water shortage countries. If water pollutants enter into the rivers and streams continuously and exceed the limit of natural purification capacity, there is a possibility that Korea will also fall into the category of water deficit nations by the decrease of water resources having good quality due to the acceleration of water pollution with the reduction of self-purification capacity. Also, the cost to treat the water supplied for home, industry and agriculture will then be higher.

The eutrophication in lakes and bays is caused by nitrogen and phosphorus that come mostly from domestic wastewater (Lee and Kim, 2001). Nitrogen and phosphorus themselves are water pollutants and also nutrients for algae growth, so they make water quality much worse. Thus, the development of high efficiency and low cost technology that can remove nitrogen and phosphorus in wastewater is necessary to solve the problem of water deficiency in Korea and preserve the water quality of lakes and bays. In Korea, nitrogen and phosphorus were included in the effluent quality standard for sewage treatment plants in 1996 and the standard was reinforced by elevating standard for nitrogen and phosphorus from 60 and 8 mg/L to 20 and 2 mg/L, respectively, in 2002.

A sequencing batch reactor (SBR) process has been widely applied in Korea recently, but its efficiency is relatively low compared with that of other countries. That is, the removal efficiency of nitrogen and phosphorus by SBR process is high in countries where separated sewers are used but low in countries, including Korea, where combined sewers are used though the same SBR is applied. This is because combined sewers have low strength wastewater that contains organic material (BOD) not high enough for denitrification. Theoretical C/N ratio for nitrogen removal is 2.0, but the C/N ratio of most Korean
combined sewer wastewater is less than 1.0 (Lee et al., 2003). This indicates that most of BOD in the influent of wastewater treatment plants is necessary to be used as carbon source for denitrification (nitrogen removal). Therefore, the purpose of this study is to develop a SBR process to maintain high treatment efficiency of nitrogen and phosphorus through the optimum usage of influent BOD.

**Materials and methods**

Figure 1 shows the schematic of the JASSFR (JA sequencing batch reactor with step feed and recycle) developed in this study. JASSFR process consists of pre-anoxic reactor (0.5 \( \times \) 1.0 \( \times \) 2.0 m) and SBR (1.0 \( \times \) 1.0 \( \times \) 2.0 m) in series, and there are a feed pump and a recycle valve between the two reactors. Influent flows into the pre-anoxic reactor continuously, but the mixed liquor from pre-anoxic reactor is pumped to SBR by a step feed. The step-recycle of the mixed liquor from SBR to pre-anoxic reactor is made via electric valve that regulates open/close according to the control time schedule set by considering water level in both reactors. Also, a remote operation and maintenance system, including automatic measurement sensors of flow, pH, DO, ORP and water temperature, is installed for allowing managers to monitor, analyse and control the real-time operation information transmitted from on-site system to any place (laboratory of researcher, office of cooperative enterprise, etc.) via web server located at the university that performs this study.

The reactors shown in Figure 1 are a single body system made of iron plate. Their treatment capacity is 2.4 m\(^3\)/day, and hydrological detention time is 24 hours. To use real domestic wastewater as influent, a temporary building is constructed in the area of domestic wastewater treatment plant with the capacity of 25,000 m\(^3\)/day, and the reactors are placed inside the temporary building.

**Pre-anoxic reactor design and its features**

The JASSFR process places a pre-anoxic reactor in front of the SBR in order to remove nitrogen by denitrifying nitrate in the mixed liquor recycled from SBR, and also increase phosphorus release by accelerating the hydrolysis of organic material and the production of organic acid. It is known that phosphorus is released under anaerobic condition, but its release is obstructed when nitrate exists because microorganisms use nitrate as a final electron acceptor (Hamamoto et al., 1997; Kim and Han, 1999). If nitrate is removed in the pre-anoxic reactor, this concentration in SBR can thus be decreased, and then it can lead to the increase of phosphorus removal efficiency. Also, because denitrifiers such as *Pseudomonas* compete for substrate intake with *Acinetobacter* that shows high...
phosphorus removal efficiency, if nitrate concentration is high during unaerated period in SBR, *Pseudomonas* growth is facilitated, while *Acinetobacter* growth is depressed. Thus, *Acinetobacter* should be the dominant species in SBR to maximise phosphorus removal efficiency (Kim and Han, 1999).

SBR processes with continuous inflow type of influent (no flow equalisation tank) show unstable effluent quality, while intermittent inflow SBR processes show stable effluent quality but a flow equalisation tank should be placed in it. The JASSFR process consists of continuous inflow/step-feed/intermittent effluent and has flow equalisation capacity within pre-anoxic reactor. Nonetheless, JASSFR shows stable effluent quality like other intermittent SBR processes. In addition, the pre-anoxic reactor not only treats part of pollutants but also decreases the anoxic operation time in SBR for nutrient removal. However, it does not increase the whole volume of JASSFR including pre-anoxic reactor, that is, the increased volume is insignificant compared with the volumes of conventional SBRs. The volumes required in conventional SBRs range from 0.85–1.0 m³/m³ of influent wastewater in Korea (Lee et al., 2003), and that of JASSFR is 0.95 m³/m³, including the volume of SBR and pre-anoxic reactor, of influent.

**SBR design and its features**

Operating mode in one cycle of SBR preceded by pre-anoxic reactor consists of feed/anoxic/aerobic/.../ anoxic/aerobic/settling/decant, and nitrogen is then removed by denitrification under anoxic conditions. BOD in the influent is not only removed under anoxic conditions, but also under aerobic conditions. Therefore, if influent BOD is low, BOD should not be removed under aerobic conditions of SBR, and instead BOD has to be available for denitrification under anoxic conditions that the removal of nitrogen occurs. JASSFR makes most of influent BOD available for denitrification during anoxic periods by controlling step-feed time. On the other hand, in case that influent BOD is high as in separated sewer areas, it is necessary to control step-feed time (for example, continuous feed is chosen instead of step feed) to remove BOD during both anoxic and aerobic periods.

Under anoxic conditions in SBR preceded by pre-anoxic reactor, organic material and nitrogen are removed, and phosphorus can be released. The removal of residual organic material, the nitrification of NH₃, and the uptake of phosphorus occurs under aerobic conditions when no influent is added to SBR. The low concentration of organic compound will make nitrifier dominant under aerobic conditions in SBR.

**Operating conditions of SBR**

The experimental apparatus of this study has been operated for about 10 months, including 55 days start-up period; several operating modes of SBR are shown in Table 1. Operating modes from phases 1 to 6 are not set up beforehand, but these are adjusted to raise the removal capacity of SBR and the removal efficiency of pollutants, specifically nitrogen and phosphorus, throughout the feedback from the test results by each phase. As shown in Table 1, the operating time of SBR is generally set to 6 hours/cycle and 4 cycles/day, and six phases are tested with the variety of inflow, aerobic reaction, anoxic reaction, and settling time.

In phase 1, total anoxic and aerobic periods in a cycle are 140 and 160 minutes, respectively. If anoxic time of pre-anoxic reactor is included, total anoxic reaction time becomes 200 minutes per cycle. It is known the longer anoxic reaction period makes for higher removal efficiencies of nitrogen and phosphorus (Gerber and Winter, 1984).

In phase 2, the duration of anoxic periods is increased, while the frequencies of alternate anoxic/aerobic state is decreased. The increase of each anoxic reaction time by 10–15 minutes is made because it is measured at the end of phase 1 that high denitrification
Table 1 Operational modes of SBR

<table>
<thead>
<tr>
<th>Reactor's state</th>
<th>Phase 1</th>
<th>Phase 2</th>
<th>Phase 3</th>
<th>Phase 4</th>
<th>Phase 5</th>
<th>Phase 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerobic 1</td>
<td>20 (SF = 15)</td>
<td>30 (SF = 23)</td>
<td>30 (SF = 23)</td>
<td>30 (SF = 25)</td>
<td>30 (SF = 30)</td>
<td>–</td>
</tr>
<tr>
<td>Anoxic 1</td>
<td>30 (SR = 5)</td>
<td>40 (SR = 10)</td>
<td>40 (SR = 10)</td>
<td>40 (SR = 10)</td>
<td>40 (SR = 11)</td>
<td>45 (SF = 60, SR = 60)</td>
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<tr>
<td>Aerobic 2</td>
<td>30 (SF = 15)</td>
<td>30 (SF = 17)</td>
<td>30 (SF = 17)</td>
<td>30 (SF = 20)</td>
<td>30 (SF = 17)</td>
<td>50</td>
</tr>
<tr>
<td>Anoxic 2</td>
<td>30 (SR = 5)</td>
<td>40 (SR = 5)</td>
<td>40 (SR = 5)</td>
<td>40 (SR = 5)</td>
<td>40 (SR = 4)</td>
<td>45 (SF = 40, SR = 40)</td>
</tr>
<tr>
<td>Aerobic 3</td>
<td>30 (SF = 10)</td>
<td>30 (SF = 10)</td>
<td>30 (SF = 10)</td>
<td>30 (SF = 5)</td>
<td>30 (SF = 3)</td>
<td>50</td>
</tr>
<tr>
<td>Anoxic 3</td>
<td>25 (SR = 5)</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>45</td>
</tr>
<tr>
<td>Aerobic 4</td>
<td>25 (SF = 10)</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>50</td>
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<tr>
<td>Anoxic 4</td>
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<td>Aerobic 5</td>
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<td>–</td>
<td>–</td>
<td>–</td>
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<tr>
<td>Anoxic 5</td>
<td>30</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Aerobic 6</td>
<td>30</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Settling</td>
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<td>40</td>
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<td>40</td>
<td>50</td>
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<td>Outflow</td>
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<td>20</td>
<td>10</td>
<td>15</td>
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</tbody>
</table>

SF, step feed time; SR, step recycle time
Units are in minutes
and phosphorus release occur after about 25 minutes from the start of anoxic reaction. The first step-feed time in phase 1 is 15 minute/cycle, but that in phase 2 is 20 minute/cycle because step-feed quantity has to be increased due to the decrease of alternate step-feed/recycle frequencies in this phase.

The operating mode of phase 3 is the same as phase 2 except for MLSS concentration in SBR. Phase 3 is operated in winter and thus low water temperature, and this makes microbes inactive. MLSS concentration in phase 3 is 4,000–4,500 mg/L, increased by about 1,000 mg/L compared with that of phase 2. The operating time of phases 1–3 is 6 hours/cycle, but that of phases 4 and 5 is 5 hours/cycle by deleting the final anoxic/aerobic periods. Because the operating time of phases 4 and 5 after the third step feed is shorter than that of phases 1 to 3, the duration (amount) of the third step feed is decreased, and thus that of the first step feed is increased. In phase 5, the duration of the third step feed is further decreased to reduce the amount of the pollutant that should be removed during the remaining time in one cycle after the third step feed, and then the first step feed is further increased compared with that of phase 4. In addition, the settling time is increased from 40 to 50 minutes, but the decant time of effluent is decreased from 20 to 10 minutes.

In phase 6, a cycle time is increased to 6 hours in order to sufficiently stabilise the efficiency of pollutant removal. A feed pump is used in phases 1 to 5, but it is replaced with a new apparatus that functions as both mixer and feed pump in phase 6. However, the feeding volume per hour by the new apparatus is lower than that by the feed pump, so the durations of step feed and recycle are increased. The mixing of mixed liquor in SBR is performed in all phases by air blower during each aerobic period, while it is only performed in phase 6, but not phases 1 to 5, by the new apparatus during each anoxic period.

In phases 1 to 4, the step recycle is performed after the step feed. But the first step feed and recycle time in phase 5 is partly overlapped, that is, the step feed and recycle occur simultaneously in the latter half of the step-feed time. But the first step-feed and recycle time is fully overlapped in phase 6. MLSS from pre-anoxic reactor is transported to SBR with influent organic matters by feed pump when SBR is anoxic period and MLSS from SBR is recycled to pre-anoxic reactor through recycle valve at the same time. This simultaneous feed and recycle operation under anoxic conditions can maximise the usage of influent organic matter for denitrification. The first reaction of one cycle of SBR in phase 6 should then be anoxic but not aerobic a in phases 1 to 5, because the recycle of mixed liquor in SBR when the state of SBR is aerobic can lead to the increase of DO concentration in the pre-anoxic reactor. DO in SBR is about 2.5 mg/L and 0 mg/L under aerobic and anoxic conditions, respectively. If DO is high when aerobic reaction is converted into anoxic reaction, conversion time to anoxic is longer and thus anoxic reaction time is shorter, so DO should be regulated not to be high.

In addition, the beginning of the repetition in anoxic state in phase 6 differently from phases 1 to 5 can achieve the early removal of nitrate in the reactor by denitrification and thus increase the removal rate of phosphorus. The end of the repetition in aerobic state can also increase the removal rate of phosphorus by withdrawing the microorganisms (sludge) that absorb phosphorus in aerobic state but they release phosphorus in anoxic state (Lin et al., 2003).

Results and discussion
BOD removal efficiency
Figure 2 shows BOD removal characteristics by each operational phase. From phases 1 to 6, each influent BOD is 119, 133, 117, 199, 112 and 172 mg/L, respectively, and each effluent BOD is 8, 7, 3, 12, 5 and 8 mg/L, respectively. Average removal efficiency is 94.8%. Average removal efficiency of phase 3 operated in winter is 97.4%, which is
higher than that of phase 2. This is because influent BOD is a little low and MLSS is maintained to be high (4,000–4,500 mg/L). Therefore, if MLSS is increased when water temperature is low, wastewater treatment plant can be operated even in winter without the decrease of removal efficiency.

Operation time per cycle in phases 4 and 5 is shortened to 5 hours, but BOD removal efficiency is 93.9 and 95.5% respectively. BOD removal in phase 5 is higher than that in phase 4, because total influent organic material load is increased in the first step feed and also the reaction time for BOD removal is increased by as much. But if more BOD is removed during early stage, it causes organic material for denitrification to be deficient and eventually T-N removal is decreased. BOD removal in phase 6 is high as 95.3%, since the first and second step-feed quantities are increased due to concurrent feed/recycle.

**Nitrogen removal efficiency**

Figure 3 shows nitrogen removal characteristics by each operational phase. Average influent T-N, NH₃-N and NO₃-N are 39.7, 9.7 and 2.7 mg/L, respectively, and most nitrogen is organic nitrogen. T-N removal in phase 2 is higher than that in phase 1. This indicates that total anoxic reaction period should be increased to improve nitrogen removal, but aerobic/anoxic reaction period should be regulated according to influent T-N concentration.
The highest T-N removal efficiency (81.4%) is shown in phase 6. From phases 1 to 5, the first reaction of one cycle is aerobic reaction and first step recycle is performed during anoxic reaction preceded by aerobic reaction, so pre-anoxic reactor cannot take NO₃-N from SBR during first aerobic reaction time. But the first reaction in phase 6 is anoxic and mixed liquor is recycled concurrently from SBR, so NO₃-N in the recycled mixed liquor is denitrified in pre-anoxic reactor. Since the first anoxic reaction time is 45 minutes in phase 6, so NO₃-N in the recycled mixed liquor is denitrified 45 minutes earlier than other phases. In phase 6, organic acid can be produced at the beginning of cycle in SBR and also denitrification can be facilitated, because one cycle of SBR starts with anoxic reaction.

Phosphorous removal efficiency

Figure 4 shows phosphorus removal characteristics by each operational phase. Influent T-P and PO₄-P are 3.7 and 2.7 mg/L, respectively, and 73% of T-P is PO₄-P. Average T-P removal efficiency in phase 2 is 76.0% higher than that of phase 1. At this time, effluent T-P is 0.9 mg/L. Compared with phase 1, aerobic reaction time is shorter but anoxic reaction time is longer in one cycle. As a result, phosphorus removal is improved. Because of the increased anoxic reaction time, NO₃-N is decreased and organic acid production is increased, which can lead to the increase of phosphorus removal efficiency.

T-P removal efficiencies of phases 4 and 5 are 70.1 and 71.0%, respectively, lower than other phases. This is because operating time per cycle is shortened to 5 hours. T-P removal efficiency in phase 6 is the highest at 86.1%. The mixed liquor recycled with high NO₃-N is added to pre-anoxic reactor and then denitrified from the beginning of the cycle, so NO₃-N can be maintained as low within the reactors from an early stage of the cycle. Organic material dissociation and organic acid production are facilitated earlier too, because the first period of cycle in phase 6 is anoxic.

Internal profiles of nitrogen and phosphorus

The anoxic and aerobic states are alternatively repeated in a cycle of SBR, and then the internal profiles of nitrogen and phosphorus represent a wave motion with the passage of time (Figure 5). NO₃-N is increased by nitrification during aerobic reaction but decreased by denitrification during anoxic reaction, while T-N is generally decreased in length of time, but increased whenever the step feed occurs from pre-anoxic reactor to SBR with high content of T-N. On the contrary, T-P is increased during anoxic reaction but decreased during aerobic reaction. As mentioned earlier, microorganisms absorb phosphorus in aerobic state, but release it in anoxic state.
Conclusions

1. JASSFR shows that effluent BOD, T-N and T-P are 8, 6.9 and 0.76 mg/L, respectively, and their removal efficiencies are 95.4, 81.4 and 86.1%, respectively, under the operating condition of phase 6. But other phases also meet the effluent quality standards for nitrogen and phosphorus.

2. High T-N removal of JASSFR is because BOD in influent is fed for denitrification at each anoxic time, and thus most of the BOD can only be used as carbon source for denitrification (nitrogen removal).

3. To improve the removal efficiency of T-N and T-P, anoxic reaction time should be as long as possible when allocating anoxic/aerobic reaction time within a cycle, and also the first and last reactions of cycle in SBR should be anoxic and aerobic, respectively.

4. Each anoxic or aerobic time in a cycle should be over 30 minutes for high removal of nitrogen and phosphorus, but the repetition frequencies of alternate anoxic/aerobic state may be insignificant in removal efficiency.

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