BICT biological process for nitrogen and phosphorus removal

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Abstract An updated biological nitrogen and phosphorus removal process – BICT (Bi-Cyclic Two-Phase) biological process – is proposed and investigated. It is aimed to provide a process configuration and operation mode that has facility and good potential for optimizing operation conditions, especially for enhancing the stability and reliability of the biological nutrient removal process. The proposed system consists of an attached-growth reactor for growing autotrophic nitrifying bacteria, a set of suspended-growth sequencing batch reactors for growing heterotrophic organisms, an anaerobic biological selector and a clarifier. In this paper, the fundamental concept and operation principles of BICT process are described, and the overall performances, major operation parameters and the factors influencing COD, nitrogen and phosphorus removal in the process are also discussed based on the results of extensive laboratory experiments. According to the experimental results with municipal sewage and synthetic wastewater, the process has strong and stable capability for COD removal. Under well controlled conditions, the removal rate of TN can reach over 80% and TP over 90% respectively, and the effluent concentrations of TN and TP can be controlled below 15 mg/L and 1.0 mg/L respectively for municipal wastewater. The improved phosphorus removal has been reached at short SRT, and the recycling flow rate of supernatant between the main reactors and attached-growth reactor is one of the key factors controlling the effect of nitrogen removal.

Keywords Attached-film; BICT; denitrification; nitrification; phosphorus removal; sequencing batch reactor

Introduction

Biological processes are widely accepted as an effective and economical nutrient removal method. However, many of existing biological nitrogen and phosphorus removal processes have met certain problems with respect to either treatment efficiency and stability or operational economy and reliability. The single-sludge suspended-growth systems, as the most widely applied biological nutrient removal processes, make use of the same mixed-culture of microorganisms in the system to accomplish the bio-oxidation of COD, nitrification/denitrification and enhanced biological phosphorus removal (bio-P removal). The coexistence of different featured and functioned microorganisms, and their complicated interactions and possibly conflicting requirements result in the difficulties in process controls and limitation of system performances. For a good nitrification and maximum availability of COD for denitrification, a long SRT is required (van Loosdrecht et al., 1998). However, for bio-P removal a higher sludge production or a short SRT is more advantageous (Smolders et al., 1997; Brdjanovic et al., 2000). Despite numerous efforts having been made in order to understand the biological phosphorus removal fundamentals, it seems that there are still a lot of studies to perform to better understand the exact mechanisms of the biological phosphorus removal due to their complexity, especially in the case of the concurrent biological nitrogen and phosphorus removal. In the early studies, it was assumed that the phosphorus accumulating organisms (PAOs, the major performers of biological phosphorus removal) could not use nitrate as an electron acceptor and, hence, could only grow and accumulate phosphate under aerobic conditions (Wentzel et al., 1989). Since then, many reports have claimed that a significant fraction of PAOs could take up
phosphate in the anoxic phase. It was hypothesized that the biological phosphorus removal population comprises at least two groups: one group capable of utilizing only oxygen (aerobic PAOs) and the other group capable of utilizing either oxygen or nitrate as an electron acceptor (denitrifying PAOs, or DPBs) (Kerrn-Jesperson and Henze, 1993; Meinhold et al., 1998; Mino et al., 1998). This implies if the DPBs dominate to take up and store phosphate using nitrate as electron acceptor, then the organic carbon substrate can be used simultaneously for both phosphorus and nitrogen removal. Since a lower cell yield value was reported for DPBs compared to aerobic PAOs, employing DPBs in the biological nutrient processes also makes it possible to reduce sludge production and aeration demand (Copp and Dold, 1998). In the single-sludge system, the mixed sludge goes through all stages such as anaerobic, aerobic, and anoxic. A long aerobic period is needed to maintain a sufficient amount of nitrifiers in the mixed sludge for accomplishing good nitrification, but this is known to inhibit the growth and activity of DPBs. For a good accumulation of DPBs, it is necessary to recycle the sludge through anaerobic and aerobic conditions (Kuba et al., 1996a). It is not the case for all types of continuous-flow biological nutrient removal (BNR) processes; none in SBR typed BNR processes. It is considered that, the long SRT, low organic loading rate and long aeration period, which are all required for ensuring nitrification, are the major factors that restrict the efficiency and stability of simultaneous nitrogen and phosphorus removal in the common practices of the single-sludge system, whereas the mixed-culture is the key factor (Li, 2001). The two-sludge systems have also been studied, e.g. nitrifiers are separated from the PAOs in a nitrification SBR (Kuba et al., 1996b) and in a nitrification biofilm reactor (Sorm et al., 1996). Here, an updated two-sludge process, BICT biological process, is proposed to improve the performance of the BNR process. In the system, nitrifying bacteria grow in an attached-growth reactor and heterotrophic organisms grow in suspended-growth SBR reactors. The intention of the process modification is not only simply to add a unit to the conventional biological nutrient removal system to provide more beneficial growth environments to adapt the different functioned microorganisms, but also, probably more important, to develop a better mechanism or potential based on current fundamental understandings for biological nutrient removal to overcome the disadvantages of the single-sludge system. In this paper, the concept of the BICT biological process and its overall performances obtained from lab-scaled experiments are introduced and discussed.

**Process concept and principles**
The BICT (Bi-Cyclic Two-Phase) biological process consists of a set of suspended-growth sequencing batch reactors, an attached-growth reactor, an anaerobic biological selector and a secondary clarifier. In the main reactors, i.e. the suspended-growth SBRs, the operation conditions are provided to promote the dominant biomass to be the heterotrophic organisms, including the phosphorus accumulative organisms (PAOs) and denitrifying bacteria. In the different batch operations, the alternating operation conditions enable us to accomplish COD removal, phosphorus uptake and/or denitrification. In the attached-growth reactor, which features long SRT, continuous aeration is applied to provide good conditions for growth of aerobic autotrophic organisms, mainly nitrifying bacteria. The attached-growth reactor receives the aerated and clarified effluent from the clarifier during the internal recycling. At this time, denitrification occurs in the main reactor, and possibly the excessive uptake of phosphorus by DPBs can be expected providing the required condition is met. In the selector, the high organic loading gradient caused by the short hydraulic retention time (HRT) compared to the main reactors produces a “selective pressure” suitable for selection of the biomass that has good flocculability and therefore a good settling property (Goronszy et al., 1996). The anaerobic conditions in the selector due to the high organic
loading and mixing of influent and returned sludge without aeration makes an adequate environment for PAOs to release phosphate from the bacterial cells.

In this experimental study, 4 major operation stages in an operation cycle are arranged in sequence for each SBR tank and related to the other component units of the BICT system, shown in Figure 1. The first stage is fill/aeration. In this operation stage, raw wastewater is pumped through the biological selector, here mixed with returned sludge, to the aerated SBR. Afterwards, the second stage is anoxic mixing/recycling. At this time, the SBR tank accepts the nitrified flow from the attached-growth nitrification reactor, while the overflow mixed liquor from the outlet weir of the tank is recycled back to the biofilm reactor after separating the biomass from it through the clarifier. The third stage, re-aeration in the tank, is optional, and aimed to blow off the fine nitrogen bubbles produced by denitrification during the last stage, and meanwhile the excessive uptake of phosphorus by the PAOs may be enhanced. The final stage is settling/sludge wasting/decanting. The excessive sludge wasted at this time is P-enriched so the phosphorus removal is achieved. The denomination of the process is to characterize the operation modes of the system, which distinguish the proposed BICT process and existing biological nutrient removal processes: the first cycle of so-called “Bi-cyclic” indicates the operation cycle of the SBR tanks described above, and the second cycle implies the flow recycling of supernatant and nitrified liquid between the main reactors and the biofilm reactor. The suspended and attached growth of the microorganisms make up the “Two phases” in the system.

According to the microbiological/biochemical and process fundamentals on biological nitrogen and phosphorus removal, the characteristics of the BICT process are expected as following:

- separate culture of heterotrophic and autotrophic microorganisms provides the suitable growth conditions for each group of bacteria, so that the interference and limits can be minimized;
- attached-growth and continuous aeration is favorable to life for slow growing nitrifying autotrophs, resulting in better nitrification and consequently more efficient removal of nitrogen in the system;
- providing that a good sludge settling property is obtained, the independent nitrification instead of nitrification with mixed culture enables sufficient utilization of volumes of the SBR reactors;
- phosphorus removal may be enhanced if application of short SRT does not affect the COD and N removal performance of the system.

Materials and methods

Experimental BICT system

The study has been carried out in a lab-scaled experimental system with total volume of
70 L. The working volume of SBR reactor is 30 L, the biofilm reactor is 10 L with supporting media. The clarifier was designed to have a HRT of 2 hours at 100% recycling rate. The experimental system was kept at 20°C in a water bath. Influent wastewater and returned sludge were pumped with peristaltic pumps. And overflow of the clarifier was led to a biofilm reactor with an aquarium pump. Aeration was undertaken when needed by compressed air through aquarium type diffusers fixed at the bottom of the SBR and the biofilm reactor. A mechanical agitator was used to mix the reactor content in the SBR during anoxic mixing.

**Experiment materials**

In the experiments both municipal wastewater and synthetic wastewater were used. The municipal wastewater was the grit chamber effluent from Suzhou New District Wastewater Treatment Plant, which was of 200–550 mg/l COD, 25–80 mg/l TN and 5–25 mg/l PO₄³⁻−P. Note that the higher values for N and P were the results of adding carbamide and KH₂PO₄. Synthetic wastewater consisted of 90%(V/V) river water from the canal in the campus of USTS and 10%(V/V) macronutrient solution with 0.5 ml/l trace element solution. Compositions of the macronutrient solution are soluble starch (400–500 mg/l as COD basis), NH₄Cl (25–80 mg/l as NH₄⁺−N basis), KH₂PO₄ (5–10 mg/l as PO₄³⁻−P basis), 200 mg/l MgSO₄•7H₂O, 30 mg/l CaCl₂, 30 mg/l FeCl₃•6H₂O. The seeding sludge was taken from an oxidation ditch in Suzhou New District Wastewater Treatment Plant.

**Experimental methods**

Extensive lab-scale experiments have been carried out over two years to investigate the feasibility, performance and the factors influencing the efficiency of COD and nutrient removal. The four stages of unit operation mentioned above were accomplished in sequence in an operation cycle. In the experimental study, the duration of an operation cycle for the SBR reactor was set to 4 hours, so 6 cycles were applied in one day. There were three different operation modes used in the experiments according to the time arrangements for each operation stage in operation cycle: M1 – 1.0 hour for filling/aeration (F/A), 1.0 hour for mixing/recycling (M/R) and 2.0 hours for sedimentation/decanting (S/D); M2 – 1.5 hours for F/A, 1.0 hour for M/R and 1.5 hours for S/D; M3 – 1.0 hour for F/A, 1.0 hour for M/R, 0.5 hours for re-aeration and 1.5 hours for S/D. The loading rates in terms of COD, TN and TP were changed by means of controlling the influent concentration of the corresponding compounds and the so-called filling rate, i.e. the decanting/filling proportion of the volume of the main reactor. The filling rates of 1/3 and 2/3 were applied. The sludge retention times (SRT) of 5, 10 and 20 days were applied by controlling the wasting sludge quantity from the mixed liquor of the SBR reactor. The experiments under different SRT were accomplished in an earlier stage of the study at cooperation mode M1 and filling rate of 1/3 so that the more effective operation conditions with respect of SRT had been determined (that is SRT = 5 d). Afterwards, under SRT of 5 days, variation of recycling rate of clarifier overflow to the influent flow from 0.5 to 1.8, and sludge return rate of 0.3 and 0.6, as well as the filling rate of 1/3–2/3 were also tested in order to investigate the effects of these factors on performance of the system.

The experimental results presented in this paper are taken from the experimental runs after over a week of every change of operation conditions, which was considered to represent the steady state performance of the system. Analyzed parameters for influent and effluent were COD, pH, NH₄⁺−N, NO₃⁻−N, NO₂⁻−N, TN, PO₄³⁻−P, TP and Alkalinity determined according to Standard Methods (APHA 18th edition, 1992). MLSS, SVI were determined at the end of the experiment under the same operation conditions.
Results and discussion

Removal of COD in the system

In all operation conditions used in the experiments, the system maintains quite good COD removal rate. For municipal wastewater, COD removal was over 80% in most cases, with effluent COD concentrations ranging from 32 to 48 mg/l. When different SRT was applied, there were no evident influences for COD removal. The COD removal rate increased to some extent with the increase of organic volumetric loading rate. For synthetic wastewater, COD removal rate was kept over 90% with effluent COD concentration of 24 to 40 mg/l. It was obvious that metabolism and conversion of organic matter in the system was not subject to the changes of operation mode and the process control parameters. It is easy to understand that the effective and stable removal of COD is due to the favorable conditions, such as relatively long hydraulic retention time (HRT), and multiple mechanisms, such as assimilation and dissimilation of organic carbon in both the aeration stage and anoxic denitrification stage. It is also possible that the remaining COD was removed in the biofilm reactor during the internal recycling.

Nitrogen removal in the system

The experimental results indicated that in the BICT system, as shown in Figure 2, the nitrogen removal did not diminish as quite short SRT was used, whereas the removal efficiency of nitrogen under SRT of 5 days was higher than that under SRT of 20 days. With increase of the N loading, despite the nitrogen removal rate slightly increasing under the same SRT, the effluent TN concentration was also apparently increased. Operation with different modes did not show significant change in term of N removal (Figure 3). The experimental results with different recycling rate (the ratio of recycling flow over influent flow) displayed apparent improvement of N removal efficiencies at a high recycling rate for both municipal and synthetic wastewaters. In circumstances of recycling rate not yet beyond 110%, controlling the N loading less than 0.15 kgN/m³.d, the effect of TN concentration lower than 15 mg/l could be obtained for municipal wastewater. In case of synthetic wastewater, under recycling rate of 180%, the nitrogen removal efficiency exceeded 80% in most cases, with all effluent TN concentration below 10 mg/l (Figure 4, Figure 5).

It is revealed that good nitrogen removal can be achieved under quite short SRT (e.g. 5 days) in the proposed system. This is significantly important for improvement of the biological nutrient removal process. Due to the nitrification being completed in the separated

Figure 2  Nitrogen removal at different SRT for municipal sewage. Operation modes = M1, filling rate = 0.33, sludge return rate = 0.3, recycling rate = 1.0; SRT: (●) 5 d; (■) 10 d; (▲) 20 d; (●) Effluent TN
Figure 3  Nitrogen removal at different operation modes for municipal sewage. SRT = 5 d, filling rate = 0.33, sludge return rate = 0.6, recycling rate = 1.8, operation modes: (◆) M1, (■) M2, (▲) M3; (●) Effluent TN.

Figure 4  Recycling rate vs. nitrogen removal for municipal sewage. Operation modes = M1, SRT = 5 d, filling rate = 0.6, sludge return rate = 0.3, recycling rate: (◆) 0.5, (■) 0.8, (▲) 1.1; (●) Effluent TN.

Figure 5  Recycling rate vs. nitrogen removal for synthetic wastewater. Operation conditions = M1, SRT = 5 d, filling rate = 0.33, sludge return rate = 0.6; recycling rate: (◆) 1.0, (■) 1.5, (▲) 1.8; (●) Effluent TN.
attached-growth reactor, the requirements for accumulation of nitrifying bacteria could be readily met. In this way, the close interaction and therefore the restriction of different groups of microorganisms in the single sludge system could be avoided. The evident influence of recycling on N removal performance indicates the importance of the nitrification reactor in the system. The large recycling rate is favorable to bring the nitrified content of the biofilm reactor to the main reactor to promote sufficient denitrification under anoxic mixing condition. However, just because of this, the benefits for nitrogen removal by increasing recycling flow were limited. From Figure 4 and Figure 5 it is seen that when recycling rate was increased from 50% to about 100%, the nitrogen removal rate was evidently improved; but for increase in recycling rate from 150% to 180%, there were no substantial differences with respect to N removal. According to the actual operation circumstance of the lab study, it seemed that there was still a certain potential to enhance the effect of nitrogen removal through improving the design and operation.

Consequently, it is easy to understand that the operation modes used in the experiments had very limited impact on system performance in terms of N removal effect since the M/R stage in all 3 modes lasted 1.0 hour. However, the reasons for high N removal efficiency under short SRT remain to be further investigated.

**Phosphorus removal in the system**

From Figure 6 it can be seen that the phosphorus removal efficiency of the system for municipal waste water could reach over 90% if suitable loading and operation conditions were fulfilled. When P loading was kept around 0.01 kg P/m³.d and influent phosphate concentration ranged from 6 to 8 mg/l, PO₄³⁻ concentration in effluent could be lower than 1.0 mg/l. The experiments demonstrated that SRT significantly affected the efficiency of phosphorus removal in the biological nutrient removal process. The P removal rate under SRT of 5 days was evidently higher than that under SRT of 10 and 20 days in all cases of varied influent concentrations. Comparing with the cases of SRT of 5 days and 20 days, the increase of phosphorus removal efficiency could be expected to an extent of 20% (Figure 7). Despite the inconsistent reports in the literature that have been found (Tremblay et al., 1999), the experimental results in this study supported the opinion that the short SRT is favorable to biological removal of phosphorus. It is further indicated by the experimental results that in the BICT system this could be accomplished without interfering or even benefiting the removal of COD and nitrogen. Nevertheless, it is obviously indicated that the
Figure 7  Phosphorus removal at different SRT for municipal sewage. Operation modes = M1, filling rate = 0.33, sludge return rate = 0.3, recycling rate = 1.0; SRT (◆) 5 d, (■) 10 d, (▲) 20 d; (●) Effluent PO$_4^{3-}$

Figure 8 Phosphorus removal at different operation modes for synthetic wastewater. SRT = 5 d, filling rate = 0.67, sludge return rate = 0.3, recycling rate = 1.0; operation modes: (◆) M1, (■) M2, (▲) M3; (●) Effluent PO$_4^{3-}$

Figure 9 Phosphorus removal at different HRT of selector for synthetic wastewater. Operation modes = M2, SRT = 5 d, filling rate = 0.33, sludge return rate = 0.3, recycling rate = 2.0; Selector HRT: (◆) 0.25 h, (■) 0.5 h, (▲) 0.75 h, (●) 1.0 h, (○) Effluent PO$_4^{3-}$
high P loadings and/or high influent P concentrations could result in quite high effluent P concentrations whatever the other operation conditions were in the system. In these cases, additional chemical precipitations should be considered in order to meet the strict nutrient discharge criteria.

In the experiments with synthetic wastewater, it seemed that the operation modes had little effect on P removal. Even in the case of influent concentration ranging from 12 to over 14.5 mg P/l, the phosphorus removal efficiency in all applied operation modes reached over 90% (Figure 8). It was different from what is shown in Figure 8 in the case of municipal wastewater. When M3 was applied, i.e. a re-aeration stage was added following the anoxic mixing stage, the P removal was better than that when M1 and M2 were applied, with a best increase of 10%. This might imply that re-aeration provided more favorable conditions for excessive uptake of phosphorus by aerobic PAOs. At the same time, aeration was beneficial to blowing off the fine gas bubbles produced in denitrification and facilitating settling of the suspended sludge.

HRT of the biological selector also influenced phosphorus removal of the system. The variation of the P removal rate for different values of HRT of the selector is shown in Figure 9. The biological selector functioned in the system mostly for phosphate release of PAOs. Therefore, the influence of selector HRT on P removal of the system was probably caused by the sufficiency of P release during the stay of the returned sludge. In the earlier period of the study, the experimental apparatus was so designed that at the time of recycling, the outflow from the biofilm reactor had to pass through the selector before entering the main reactor. After modification of the configuration of the system, turning the selector to a separate unit, the P removal was obviously improved.

**Sludge settling property in the system**
The sludge in the BICT system, in fact in the main reactor, had quite good settling properties in most cases of experimental operation. The SV value was normally kept around 20% and SVI around 80 to 120, not subject to change of the operation conditions. Hopefully, this indicates the possibility in practice to increase the loading rate by applying the large filling proportion in the SBR reactors. In the experiments, the largest filling proportion applied was 0.67, which did not result in flushing out of the sludge.

**Conclusion**
• The BICT biological process is of positive performance of COD, nitrogen and phosphorus removal. According to the lab-scale experimental results, the process has strong and stable capability for COD removal. At the most experimental conditions, the removal rate of COD is over 80% and 90%, and COD concentration in effluent is lower than 50 mg/l and 40 mg/l for municipal and synthetic wastewater respectively. By controlling the suitable N loading and internal recycling rate, the removal efficiency of nitrogen can reach over 85%. For the municipal wastewater, at the condition of TN loading below 0.15 kg N/m³·d, the effluent TN concentration can be lower than 15 mg/L, whereas at the condition of phosphorus loading controlled around 0.01 kg P/m³·d, P removal in the system may approach 90%, or higher; for the TP concentration of influent between 6–8 mg/l, effluent PO₄³⁻–P concentration may be controlled below 1.0 mg/l.

• The investigation reveals that the well-operated biofilm reactor plays an important role for nitrogen removal. The internal recycling rate is a key operational factor that controls the nitrogen removal but not evidently influences the COD and phosphorus removal.

• For phosphorus removal, the key operational factors are sludge retention time (SRT) of the SBR reactors and HRT of biological selector. Properly short SRT is favorable for
both TP and TN removal. Comparing the experimental results under SRT of 5 days to that under SRT of 20 days, the phosphorus removal efficiency increases by 30%.

• The sludge in the SBR reactor had quite good settling properties in most cases of experimental operation.

References


