Chapter

Research on Partial Nitritation and Anaerobic Ammonium Oxidation Process

Wenqiang Wang, Dong Li, Shuai Li, Huiping Zeng and Jie Zhang

Abstract

In recent years, the partial nitritation and anaerobic ammonium oxidation (PN/A) process has been widely appreciated by many countries around the world. As an autotrophic nitrogen removal process, this process can save more than 60% of the aeration energy consumption, reduce 80% of the residual sludge yield, and do not need to add additional carbon sources. However, this process is faced with several kinds of problems. This paper summarizes several effects of operating parameters on the inhibition of NOB in municipal wastewater treatment, implications of the reactor configuration and operation, and fixed film processes vs. suspended growth systems. The fixed film processes based on Anammox granular sludge and AOB flocculent sludge are alternative. Finally, a new strategy of continuous flow PN/A process with partial nitrification flocculent sludge and Anammox granular sludge was proposed.

Keywords: Anammox, wastewater treatment, PN/A, granular sludge, mixed reactor

1. Introduction

Anaerobic ammonia oxidation (Anammox) bacteria play a key role in the Earth's nitrogen cycle [1]. Compared with Anammox, the traditional biological denitrification technology widely used today has some shortcomings, such as high energy consumption, the need for additional organic carbon sources, and the inability to control the production of greenhouse gases [2]. Therefore, compared with the traditional nitrification and denitrification systems, Anammox technology has the advantages of no aeration, extra organic carbon source, and low surplus sludge yield, making Anammox a research hotspot for environmental protection. In the application of actual municipal wastewater [3], it is found that the lack of nitrite electron acceptor in actual wastewater is the main bottleneck of the application of Anammox in mainstream wastewater treatment. In addition to the artificial addition of nitrite, most of the current Anammox coupling processes focus on partial nitritation and anaerobic ammonium oxidation (PN/A) [4]. In practical application, partial nitritation (NH_4^+-N → NO_2^--N) can provide NO_2^--N for Anammox, thus forming a PN/A process. First, about 55% of the ammonia nitrogen in the wastewater is oxidized to nitrite under the action of ammonia oxidizing bacteria (AOB), and then the generated nitrite and the remaining ammonia nitrogen generate nitrogen under the action of anaerobic ammonia oxidation bacteria (AnAOB), to achieve the removal of TN. The total reaction equation [5] is:

$$NH_4^+ + 0.85O_2 \rightarrow 0.11NO_3^- + 0.44N_2 + 0.14H^+ + 1.43H_2O \quad (1)$$

In recent years, PN/A process has been widely appreciated by many countries around the world. As an autotrophic nitrogen removal process, this process can save more than 60% of the aeration energy consumption, reduce 80% of the residual sludge yield, and does not need to add additional carbon sources [6, 7]. However, this process is faced with the problems of long age and insufficient retention capacity of AnAOB sludge, competition of AOB from NOB, and high C/N ratio leading to massive reproduction of HB in sludge.

This paper summarizes several effects of operating parameters on the inhibition of NOB in municipal wastewater treatment, implications of the reactor configuration and operation, and fixed film processes vs. suspended growth systems. Finally, a new strategy of continuous flow PN/A process with partial nitrification flocculent sludge and Anammox granular sludge was proposed.

2. Effects of operating parameters on the inhibition of NOB in municipal wastewater treatment

2.1 Dissolved oxygen (DO)

Continuous aeration mode keeps DO at a low level in the CANON process reactor. However, Liu et al. found through experiments that under long-term low DO (0.16 ~ 0.37 mg/L) operation, the dissolved oxygen affinity coefficient Ko_2, AOB will be higher than Ko_2, NOB, that is, NOB is more competitive than AOB. As a result, part of NO_2^--N in the reactor is further converted to NO_3^--N, and the lack of stable nitrite supply greatly endangers the overall nitrogen removal performance of autotrophic nitrogen removal process [8]. In view of this phenomenon, Regmi et al. believed that Nitrobacter would increase significantly more than Nitrospira in a long-term state of low DO [9]. Nitrospira is the strategy-K (low specific proliferation rate, high matrix affinity), while Nitrobacter is the strategy-R (high specific proliferation rate, low matrix affinity). As a result, Nitrospira is more amenable to compete with DO. The previous thought that Ko_2, NOB was higher than Ko_2, AOB might be due to the dominance of Nitrobacter. Controlling DO concentrations of medium (<1.0 mg/L) and low (<0.5 mg/L) is indeed beneficial to Nitrosomonas, but it inhibits the Nitrobacter of strategy-R rather than the Nitrospira of strategy-K (which grows at a rate close to the maximum).

2.2 Transient hypoxia

Transient hypoxia caused by on/off aeration has been proven to be an effective method to inhibit NOB. The lag time of NOB activity at the beginning of aeration section is due to the following two reasons: (1) Lack of one or two substrates (nitrite and oxygen) [10]. (2) In the aerobic environment after a brief period of hypoxia, compared with AOB, NOB faces metabolic mechanism inactivation and adaptive lag in the recovery period [11]. The delay of nitro Spirillum activity after anoxic period (5–15 min) effectively inhibited NOB in PN/A process based on SBR [11]. Intermittent aeration is also effective in integrated fixed-film activated sludge (IFAS) process [12]. However, intermittent aeration is not conducive to the stability of effluent quality in continuous flow process and frequent opening and closing of blower will increase the failure rate of equipment. However, in a continuous system that consumes nitrous oxide in time, an aerobic/aerobic alternating strategy can effectively carry out partial nitrification [11, 13].

2.3 Starvation process

Studies have shown that nitrite accumulation occurs when nitrification system is restarted after being idle for a period of time. The attenuation rate of AOB is smaller than that of NOB in the starvation process [14, 15]. Jia et al. [16]) found that AOB has a unique hunger response strategy, and its cells are in a state of readiness at any time. Once the substrate appears, it can produce substrate invertase (gene transcription speed is fast), so that AOB can quickly recover its activity from starvation. However, NOB does not have this ability, so AOB has a stronger ability to adapt to environmental changes than NOB.

2.4 Aerobic sludge residence time

In the side-flow anaerobic process, the growth rate of AOB is higher than that of NOB, so short-time aerobic SRT is used to inhibit and flush NOB [17]. In the activated sludge process with temperatures between 28 and 30°C, aerobic SRT of 2.5 d is one of the main factors to ensure stable nitrogen removal in the Singapore Changi Regenerating water plant [18]. The control aerobic SRT of large-scale activated sludge denitrification process in the Southwest Wastewater Treatment Plant in St. Petersburg was 3.5 d, which is another reference case of this operation mode [19]. In the mainstream process, Blackburne and Oleszkiewicz found that shortening SRT was beneficial for AOB growth [19, 20]. Stinson et al. used short-term aerobic SRT as an intervention to achieve inhibition of NOBs at moderate and low temperatures [21].

2.5 Real-time aeration control

A variety of real-time aeration control strategies have been developed and applied to suppress NOBs by controlling DO or aeration volume. Response parameters related to DO or oxygen supply include ammonia nitrogen flux and dpH/dt [22]. In addition, frequent opening and closing of mechanical equipment such as blowers or pumps can increase the failure rate and cause serious operational problems, indicating that the reliability of key equipment is very important to A stable mainstream PN/A process.

3. Implications of reactor configuration and operation

3.1 Carbon pretreatment process

In view of the high carbon-nitrogen ratio of municipal sewage, carbon pretreatment is usually introduced. At present, there are three carbon pretreatment processes at home and abroad: (1) High-rate activated sludge (HRAS). For example, in the Strass sewage treatment plant, A stage of activated sludge process (SRT ≈ 0.5d, HRT ≈ 0.5 h) can guarantee the removal rate of COD of 60% [23]. (2) Chemical-intensive pretreatment can remove about 80% ~ 90% TSS and 50% ~ 70% COD; (3) Methanogenic fermentation pretreatment, designed to maximize energy recovery in UASB reactors [24]. Generally, the three reasonably designed pretreatment processes can satisfy the PN/A influent COD/N ≤ 2 ~ 3.

3.2 One-stage and two-stage processes

The one-stage PN/A process performs PN/A in one reactor, while the two-stage PN/A process separates the PN/A reaction in two reactors. The combination of PN and Anammox reactions in a reactor significantly reduces infrastructure and operating costs compared to a two-stage process [25]. One-stage reactors tend to operate under nitrite restriction and low DO concentrations.

One-stage PN/A process is also known as CANON (Completely autotrophic nitrogen removal over nitrite, CANON) granular sludge has a regular shape and compact, dense structure, high sludge concentration, good settling performance, etc. Winkler et al. believed that in typical CANON granular sludge, AOB bacteria were usually distributed in the outer layer of particles permeable by dissolved oxygen, while AnAOB bacteria were distributed in the inner anaerobic zone of particles [23]. However, with the in-depth study of CANON granular sludge, some scholars found that AOB and AnAOB bacteria co-existed in CANON granular sludge, without specific spatial distribution rules, the two bacteria interleave each other, and the nitrite matrix produced by AOB ammonia-nitrogen does not need to be transferred through a long chain, and is degraded as the substrate of AnAOB bacteria in a short time. The whole autotrophic nitrogen removal process can be efficiently completed [26, 27]. Chen's research shows that the combination of AnAOB and AOB forms a special olivar-shaped structure: (1) AnAOB mainly gathers inside the particle to form the kernel of the particle, AOB forms a thick wall in the outer layer of the particle, (2) AnAOB gathers into multiple clusters, and AOB is relatively evenly distributed in the whole particle without any clusters. (3) The many cracks clearly observed in the Anammox particles are likely conduits through which substrates and wastes flow. In this special structure, part of influent NH_4^+-N is oxidized to NO_2^--N by AOB in the particle surface layer, and Anammox in the particle core uses residual NH_4^+-N and generated NO_2^--N. In addition, the consumption of O_2 by AOB covered by the outer layer of particles provides protection for AnAOB from inhibition of O_2 and other environmental factors [27]. Statistics show that more than 50% of PN/A reactors operate in SBR mode, 88% of wastewater plants operate using single-stage systems, and 75% are used to treat sideflow municipal wastewater. Solid film substrate transport, aeration control, and nitrate generation are major operational difficulties [28]. Moreover, the single-stage CANON is mostly used in side-flow processes.

4. Fixed film processes vs. suspended growth systems

4.1 Suspended sludge reactor

The Changi Reclaimed Water Plant in Singapore and the Strass Sewage Treatment Plant in Austria are two existing PN/A processes using suspended sludge reactors. In both cases, AnAOB is not affected by oxygen in the anoxic zone, and heterotrophic denitrification makes an important contribution to nitrogen removal at high C/N influent ratios. One of the most common problems of flocculent sludge is poor settling [29]. Small floc cannot settle and separate well, resulting in increased turbidity of effluent [30].

4.2 Biofilm reactor

Biofilm reactor includes biological drip filter, fixed membrane biofilm reactor, fluidized bed reactor, biological rotary table, and moving bed biofilm reactor. The typical problem with biofilms is mass transfer restriction, in which only the bacteria in the outer layer of the biofilm can promote substrate removal [31]. The biofilm mainly grows on the surface of the filler, and the filler is prone to clogging during the actual operation, which is not conducive to the long-term operation of the process [32]. In addition, the cost of biofilm carriers is also a limitation of their application in large-scale wastewater treatment plants [33].

4.3 Granular sludge reactor

Bacterial aggregation in granular sludge reactors increased biomass concentration [34], as well as biomass retention [35] and tolerance to environmental stress [36]. Granular sludge can fix more AnAOB population under aeration conditions [37, 38]. Compared with floc and biofilm, particles have the advantages of dense structure and do not need to be attached to the surface of the carrier, so they are favored by the engineering field. However, the disadvantage of Anammox granules is that the low cell yield and growth rate of AnAOB lead to long sludge age, and HB grows excessively on autotrophic bacteria under long sludge age conditions.

4.4 Mixed reactor

The mixed reactor has a high concentration of suspended sludge in the liquid phase. The biomass of liquid and solid (biofilm or granular sludge) phases plays an important role in microbial transformation. Based on the theory that AnAOB mainly exists in particles or biofilms, while NOB and HB mainly exist in floc [39]. Compared with the biofilm reactor, AOB, NOB, and HB are mainly suspended in the liquid phase, while AnAOB mainly exists in the biofilm. It has been reported that 60% of aerobic reactions are achieved in the liquid phase, while AnAOB activity occurs almost exclusively in biofilms (>96.5%) [24]. The high suspended sludge concentration in the liquid phase of the mixed reactor significantly reduces the diffusion limit compared with the single particle or biofilm reactor, thus inhibiting the competition of AOB by controlling the low concentration level of DO in the liquid phase. In addition, the sludge age of suspended sludge can be controlled independently of particles or biofilms, which facilitates the washing of HB and NOB, and can tolerate higher influent COD/N [40].

It has been reported that the nitrogen removal capacity of IFAS process co-existing with flocculent sludge and biofilm is three to four times higher than that of MBBR process consisting of biofilm only [37, 41]. Compared with biofilms, particles have the advantage of dense structure and do not need to be attached to the surface of the medium. However, the process of coexisting Anammox particles with continuous flow flocculent sludge has not been reported. If the flocculent sludge with AOB as the main body and Anammox granular sludge is integrated into a continuous flow system, the nitrogen removal effect can be ensured, and the excess AOB and NOB short sludge age bacteria can be eliminated through the flocculent sludge to retain AnAOB, and the NOB can also be washed. Studies have shown that at low concentrations, intermittent anaerobic/aerobic = (15 ~ 20 min)/(5 ~ 15 min) alternating can effectively inhibit NOB [10]. Therefore, continuous flow anaerobic/aerobic alternating operation can inhibit NOB.

In addition to the difficulties of NOB suppression and panning, internal reflux and external reflux are often needed in continuous flow. In this process, the granular sludge of Anammox will inevitably be broken and disintegrated, which will also face the problem of AnAOB loss. If the problem of reflux is not solved, granular sludge can not be used effectively in the reactor with continuous push flow. At present, the methods of retaining granular sludge include membrane screening method and settling selection method, which represent the reactor membrane reactor and granular sludge selector respectively. Compared with membrane reactor, granular sludge selectors can pass flocculent sludge, not easy to clog, and is easy to maintain. If the granular sludge selector based on sedimentation selection is installed in the aerobic zone to retain Anammox particles and ensure the circulating flow of flocculent sludge, the reflux problem can be solved.

To sum up, in order to run the continuous autotrophic nitrogen removal process stably, Anammox granular sludge can be retained in the aerobic zone to participate in nitrite degradation but not reflux according to the anaerobic/aerobic process, so as to ensure the integrity of Anammox particles and effective retention of AnAOB while consuming most nitrite in time. The AOB in the floc is pumped back to alternate anaerobic/aerobic operation for nitrosation reaction. Of course, due to the mixed reactor, a small amount of AnAOB will exist in the floc, and the amount of AnAOB will not be too high because of the short floc sludge age. A small amount of AOB will also adhere to the Anammox particles to form a protective layer to consume dissolved oxygen.

5. Conclusions

This paper comprehensively describes the effects of operating parameters on the inhibition of NOB in municipal wastewater treatment, implications of reactor configuration and operation, and focuses on the discussion of fixed film processes versus suspended growth systems. A mixed urban sewage continuous flow PN/A process based on Anammox granular sludge is proposed. This process seems to have many advantages in theory, and it will be validated in experiments next.

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Conflict of interest

The authors declare no conflict of interest.

Author details

Wenqiang Wang[1*], Dong Li[1], Shuai Li[1], Huiping Zeng[1] and Jie Zhang[1,2]

1 Key Laboratory of Water Science and Water Environment Recovery Engineering, Beijing University of Technology, Beijing, China

2 State Key Laboratory of Urban Water Resource and Environment, Harbin Institute of Technology, Harbin, China

*Address all correspondence to: wangwenqiang@bjut.edu.cn

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