Research on the Optimal Operation of Inverted A2/O & MBR Process for Rural Domestic Sewage Treatment

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Abstract. A new integrated device—inverted A2/O–MBR process for rural domestic sewage treatment was designed and investigated in this study. The device consisted of three components orderly referred to the anoxic zone, anaerobic zone and aerobic zone where a MBR membrane group was arranged. Results showed that the device was favorable to treat rural domestic sewage. Optimal influent percentage of influent to anoxic zone was 70%, with TN, TP removal ratio approaching to 69% and 89%. Reduction of NH4+-N and TN enhanced with the increase of sludge age, but that of TP decreased. 15d was determined to be the best sludge age for simultaneous removal of NH4+-N, TN and TP. Moreover, when DO was 3.0mg/L, NH4+-N, TN and TP reduction reached up to 96%, 70% and 88% respectively. These data verified the good performance of the integrated system, and the quality of effluent could well meet the direct emission standard of Outdoor Drainage Design Specification in China (GB50014-2006) (edition 2014).

1. Introduction

Rural domestic sewage was mostly originated from the daily life of farmers and poultry. This kind of sewage was high-dispersely, intermittently and asymmetrically discharged, so effective collecting systems were extraordinarily deficient in countrysides. Contents of organic matters, nitrogen as well as phosphorus in the sewage were steady and C/N ratio was relatively low, and no toxicants existed (Li. 2009). At present, most sewage was directly discharged to Surface River without any treatment, and this incurred many damages to ambient environment. Not only the safety of rural drinking water faced the threat, but also the fertility of farmland soil was seriously slashed. What’s worse, the existing abundant nitrogen and phosphorus would lead to eutrophication like large-scale outbreak of cyanobacteria in Taihu Lake, P.R China, which caused massive death of fish and exacerbation of water quality (Xu et al. 2007). According to the report [1] of Chinese Ministry of Construction, Chinese national rural domestic sewage was estimated to 9.86 billion tons in 2008, sadly it would continually grow with the rapid development of modern economy and society. Unfortunately, only 2.6% villages in China had established relevant proceeding facilities by the year 2007 (Hou et al. 2012). For these reasons, high-efficiency disposal of rural domestic sewage was thereby an urgent mission for contemporary environmental scientific researchers.

Numerous typical technologies had been exploited and widely employed in the past few years, mainly including anaerobic digestion, waste stabilization ponds, constructed wetland, soil infiltration
and earthworm ecological filter technology. Regrettably, when they were put into practical use, many problems emerged unexpectedly. The anaerobic digestion technology, sealed domestic wastewater in an anoxic circumstance for a long time, was merely available to convert organic matters to methane, signifying the difficult elimination of retained nitrogen and phosphorus (Zaiat M. et al. 2001). According to the IRC (International Water and Sanitation Centre), waste stabilization ponds (anaerobic, facultative and maturation pond) was the most cost-effective wastewater treatment technology for removing pathogenic microorganisms [3]. In addition, the performance of stabilization ponds to a large extent suffered from season changes and large land usage (Dalu J. M. et al. 2003). All of the constructed wetlands, soil infiltration and earthworm ecological filter technology were confronted with challenges like low organics load, high operation cost, tough daily maintenance and easily being blocked (Bavor H. J. et al. 1995) (Liang et al. 2008) (Wang et al., 2010), especially when used to treat chinese rural domestic sewage. Aimed at avoiding the disadvantages of these technologies, a new integrated device—inverted A²/O–MBR process for rural domestic sewage treatment was designed and investigated. (Adam C. at el. 2002; Lee at el. 2009)

2. Materials and Methods

2.1. Bioreactor configurations and mechanisms

Schematic of the inverted A²/O–MBR configuration were shown in Fig.1. The A²/O–MBR bioreactor was mainly divided into three components referred to the anoxic zone, anaerobic zone and aerobic zone (membrane zone). Unlike traditional A²/O process, anoxic zone was put in ahead anaerobic zone, and the influent was divided two share to flow into them respectively. Meanwhile, the liquid mixture with abundant nitrate and high-concentration sludge was backwashed from aerobic zone to anoxic zone. Reflux ratio (R) was 250%, and the details of each component were described following.

**Figure 1.** Schematic of the inverted A²/O–MBR configuration

**Anoxic zone**

The anoxic zone was particularly designed for nitrogen removal. Denitrification transformation of nitrate to N₂ was accomplished by denitrifying bacteria using organic matters serving as electron donors and backwashed nitrate as electron acceptors. Compared with traditional A²/O process, the inversion of anaerobic zone and anoxic zone not only guaranteed the dominance of denitrification bacteria and efficiency of nitrogen removal, but also avoided the anaerobic environment breaking by the dissolved oxygen carried by backwashed mixture from the anaerobic zone. Moreover, high phosphorus removal could be achieved based on literature (Liu et al. 2008).

**Anaerobic zone**

The anaerobic zone was used for biological phosphorus removal. Phosphorus in mixture was firstly taken in by phosphorus accumulating bacteria and stored as polyphosphates. The intracellular
Polyphosphates were then decomposed and concomitantly produced ATP and inorganic phosphate. The generated ATP was used for the adsorption of low molecular fermenting product such as volatile fatty acid (VFA) in effluent by phosphorus accumulating bacteria and stored as poly-β-hydroxybutyrate (PHB) or other organic particles in microbial cells. Produced inorganic phosphate was released out the cell and in turn made a good preparation for the excess phosphorus intake in the subsequent aerobic zone. Furthermore, if influent was only pumped into anoxic zone, available VFA for phosphorus accumulating bacteria would be insufficient due to low C/N ratio of rural domestic sewage. In comparison, if influent was appropriately distributed, namely partial sewage flowed directly into anoxic zone and the other into anaerobic zone, it would be a great benefit for phosphorus accumulating bacteria to intake enough VFA and make use of the energy generated from decomposition of intracellular polyphosphates.

**Aerobic zone (membrane zone)**

In aerobic zone, many further pollutants removing reactions including removal of organics by heterotrophic bacteria, ammonia nitrogen by nitrifying bacteria and phosphorus by accumulating bacteria were concurrently taken place owing to the existence of high-concentration dissolved oxygen. The membrane group was arranged in the aerobic zone. On the one hand, the arranged membrane group in aerobic zone of inverted A2/O&MBR process intercepted the zoogloea and thus obtaining a higher concentration of activated sludge and microorganisms compared with that of A2/O process without membrane group. On the other hand, higher speed of phosphorus absorption, ammonia nitrogen oxidation and organic matters removing were also achieved (Adam C. et al. 2002; Lee et al. 2009).

In addition, continuous stirring of roots blower could hydraulically clean the membrane group and slow down the membrane pore blocking. The effluent of aerobic zone was directly discharged to receiving waters and no settling tank was needed, which greatly reduced the land usage. Moreover, the mixed liquid with high-concentration sludge was continuously returned to the anoxic zone at a reflux ratio of 250%, and the excess sludge containing rich phosphorus was drained at regular intervals.

### 2.2. Characteristics of experimental wastewater

Experimental wastewater was a kind of rural domestic sewage collected from a village of Jiangsu Province P.R China. The sewage treatment could reach 50 m³/d. Parameters of influent and standards of effluent quality were described as Table 1.

| Parameters | CODc(mg/L) | BOD5(mg/L) | NH3-N(mg/L) | TN(mg/L) | TP(mg/L) | SS(mg/L) | pH |
|------------|------------|------------|-------------|-----------|----------|----------|----|
| Influent   | ≤380       | ≤200       | ≤38         | ≤38       | ≤3.40    | ≤185     | 5.5~6.5 |
| Effluent standard | 50       | 10         | 5           | 15        | 0.50     | 10       | 6~9 |

### 2.3. Operating conditions

Operating parameters of different zones in integrated device-inverted A2/O&MBR process were shown in Table 2.

| Parameters | Anoxic zone | Anaerobic zone | Aerobic zone |
|------------|-------------|----------------|--------------|
| Working volume (m³) | 6.3         | 3.2            | 12.6         |
| Hydraulic retention time (hrs) | 3.0         | 1.5            | 6.0          |
| Membrane material | —          | —              | Polyethylenea |
| Membrane surface area (m²) | —          | —              | 120          |
| Membrane pore size (μm) | —          | —              | 0.45         |
2.4. Analytical methods

Influent ratio

3. Results and Discussions

3.1. Optimal influent percentage of anoxic and anaerobic zone

Organics in anoxic zone was served as the electrons donors when NO$_3^-$ was converted to N2, and it had a great influent on nitrogen removal. Enough VFA existing in sewage was a necessity for PHB generation in phosphorus accumulating bacteria cells in an anaerobic environment. To ensure that there was enough organics in anoxic zone and enough VFA in anaerobic zone, it was necessary to redistribute the carbon source for denitrifying bacteria and phosphorus accumulating bacteria by changing the influent percentage of anoxic zone and anaerobic zone. The TN and TP removal efficiencies changing with influent percentage were presented in Fig.2. The other influencing factors like C/N ratio, reflux ratio, SRT, DO, nitrogen and phosphorus loading were kept constant.

![Figure 2. TN and TP removal efficiencies under different influent percentages](image)

As was exhibited in Fig.2, when influent percentage of anoxic zone was lower than 50%, TN and TP removal ratio was pretty low with average at about 60%, which reflected the inhibition of nitrogen and phosphorus removal efficiencies. Owing to lower influent percentage of anoxic zone, organics used for nitrate denitrification was insufficient, consequently plentiful unreacted nitrate was carried to the anaerobic zone with sewage flowing. Unfortunately, the nitrate denitrification in anaerobic zone was incomplete because of short hydraulic retention time. What’s more, denitrifying bacteria reaped a benefit from the plentiful unreacted nitrate and became the dominated microorganisms for VFA competition with phosphorus accumulating bacteria. Meanwhile, part of nitrate was used as final electrons acceptors by phosphorus accumulating bacteria in intracellular PHB decomposition. As a result, energy provided by remaining PHB used for phosphorus uptake was reduced.

When influent percentage increased from 50% to 70%, TN removal ratio was slightly grown from 63% to 67%, and TP removal ratio was marginally decreased from 96% to 94%, which indicated the steady removal efficiencies in the influent percentage range of 50-70%. However, when influent percentage of anoxic zone exceeded 70%, organics was adequate but VFA was deficient. TN removal ratio was nearly kept the same due to the limiting of reflux nitrate amount, but TP removal ratio was dramatically dropped down (Liu et al. 2008).

Taken together, optimal influent ratio of anoxic zone was 70% (anaerobic zone 30%). Removal ratios of TN, TP were 69%, 89% respectively. Effluent quality well met the requirements in Outdoor Drainage Design Specification in China (GB50014-2006) (edition 2014).
3.2. Optimal sludge age of aerobic zone (membrane zone)

The generation time of phosphorus accumulating bacteria was much shorter than that of nitrifying bacteria. Comparatively speaking, generation time was largely depended on sludge age. Therefore, sludge age has significant impact on nitrogen and phosphorus removal. The sludge age was set from 5d to 25d at the step of 5d. Other conditions were controlled as table. Relationships between SRT and NH3-N, TN, TP removal ratio were depicted below.

According to Fig.3, removal ratios of NH3-N, TN were gradually increased from 38% to 96% and 24% to 75% respectively when sludge age was ranged from 5d to 25d. Nevertheless, in contrary to the removal of NH3-N and TN mentioned above. TP removal ratio gradually decreased from 94% to 72%. These results showed that in a certain range, the longer the SRT was, the higher the removal ratio of NH3-N and TN would be. It was analyzed that when SRT was lower, much nitrifying bacteria were still in their growing and immature stage. These immature bacteria would be taken away with sludge recycle. As a result, the conversion of NH4+-N to NO2-N or NO3-N was restricted and denitrification was at low level, which induced worse TN and NH4+-N removal effect. When SRT was relatively longer, sludge concentration in aerobic zone was enhanced. An anoxic or anaerobic micro-environment was created so as to successfully accomplish simultaneous nitrification and denitrification process.

Unlike TN and NH4+-N reduction, TP removal ratio was decreased with the increased SRT. In general, generation time of phosphorus accumulating bacteria was short, so lower SRT had no negative effect on phosphorus removal. However, the longer sludge age remained some disadvantages. Compound substances like glycogen, stored in the cells of phosphorus accumulating bacteria, were oxidized and thereby reducing the organics which offered energy for cell growth. Besides, longer sludge age would arise the degradation of phosphorus accumulating bacteria and released the dissolved polyphosphate, which brought about a second phosphorus release and increased TP concentration of effluent (Liu et al. 2008; Fu et al. 2009).

Comprehensively, it could be concluded that 15d was the optimal sludge age for simultaneous nitrogen and phosphorus removing. Meanwhile, the NH3-N, TN, TP removal ratio were 92%, 69%, 87% respectively. All of them were enough to meet the requirement of wastewater treatment.
3.3. Optimal DO value of aerobic zone (membrane zone)

DO concentration was an especially critical factor in NH$_3$-N oxidation and phosphorus uptake in aerobic zone. The removal ratio of NH$_3$-N, TN and TP under different DO concentrations were depicted in Fig.4. When DO was less than 3.5mg/L, the removal ratio of NH$_3$-N increased remarkably with the increasing DO value of aerobic zone and it reached the peak 98%. Yet with the further increase of DO value, NH$_3$-N removal ratio began to fall. Likewise, the TN removal ratio reached up to 72% when DO value was 2.5mg/L. Nevertheless it descended when DO was more than 2.5mg/L. That was because higher DO strengthened the activity of nitrifying bacteria [4]. The stronger activity of nitrifying bacteria gained more NO$_2$-N, NO$_3$-N which would bachwash to anoxic zone and consequently enhanced the denitrification. Unfortunately, once DO concentration was supplied overdose, many adverse forces came up. On the one hand, activated sludge was more easily aged. Thus the bacteriolyis was aroused and content of effluent NH$_3$-N was ascended. On the other hand, DO with concentration exceeding 2.5mg/L in aerobic zone resulted in a higher DO level which was carried in backwashing mixture. After entering in anoxic zone, the higher backwashing DO destroyed the perfect anoxic environment. It could be explained that denitrifying bacteria preferentially utilized dissolved oxygen as electron acceptors and organic compounds as electron donors for respiration, so the excess dissolved oxygen competed for electron donors with NO$_2$-N, NO$_3$-N in anoxic zone, which seriously weakened the denitrification in anoxic zone. Furthermore, the higher DO was characterized with stronger ability of penetrating sludge flock. As a consequence, the anoxic micro-environment in anoxic zone was gradually vanished and TN removal ratio was undoubtedly declined.

It also could be seen from Fig.4 that the TP removal ratio increased firstly from 33% to 91% with the increase of DO concentration. The reason was that the increasing DO enlarged the oxygenolysis of intracellular PHB and other organic matters, with producing more energy for phosphorus accumulating bacteria to intake excessive phosphorus in anaerobic zone. At the same time, the anoxic micro-environment in the activated sludge of anaerobic zone was more completely ruined by the intense penetration of dissolved oxygen with DO increase. However, TP removal ratio was decreased to 88% when DO was sequentially grown to 4.0 mg/L. Dissolved oxygen surpassed 3.5mg/L would cause attenuation death of phosphorus accumulating bacteria, so TP concentration of effluent was aroused and TP removal efficiency was cut down (Lee et al. 2009; Fu et al. 2009).

Briefly summarizing, to concurrently achieve good removal effect of both nitrogen and phosphorus, optimal DO concentration was selected as 3.0 mg/L in accordance with Fig.4 and the analysis above. The NH$_3$-N, TN, TP removal ratios were 96%, 71%, 88% respectively, apparently satisfying the wastewater treatment standard. Comprehensive performance of the integrated process under all optimal conditions was shown in Table3.
Table 3. Performance of the integrated process under all concluded optimal conditions

| Item     | COD cr/(mg/L) | BOD 5/(mg/L) | NH3-N/(mg/L) | TN/(mg/L) | TP/(mg/L) | SS/(mg/L) | PH |
|----------|---------------|--------------|--------------|-----------|-----------|-----------|---------|
| Influent | 352           | 198          | 34           | 37        | 3.20      | 184       | 6.2     |
| Effluent | 27.8          | 8.2          | 2.4          | 9.9       | 0.38      | 5.4       | 7.1     |
| Reduction| 92%           | 96%          | 93%          | 72%       | 88%       | 97%       | —       |

Footnote:

4. Conclusion

1. The integrated process, combining inverted A2/O with MBR, greatly strengthened the removal effects of nitrogen and phosphorus. Besides, the integrated device was small in size and easy to install, which was in line with the need for regional treatment of rural domestic sewage.

2. Optimal influent ratio of anoxic zone and anaerobic zone were 70% and 30%. Optimal sludge age and DO concentration of aerobic zone was 15 d and 3.0 mg/L respectively.

3. Comprehensive performance of the integrated process was good. COD cr, BOD 5, NH3-N, SS removal ratio reached as high as 92%, 96%, 93% and 92% respectively, while TN and TP removal rate reached 72%, 88% with effluent water quality meeting the design requirements. In a word, the parameters of the effluent all met the design requirement.

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