ONE-STEP ANAMMOX®-PROCESS
A SUSTAINABLE WAY TO REMOVE AMMONIACAL NITROGEN
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Abstract

There is an increasing interest in anaerobic digestion of sewage sludge, organic waste and industrial effluents. Dewatering liquors and effluents derived from anaerobic digestion processes contain significant amounts of nutrients. Although small in volume sludge dewatering liquors can represent up to 30% of the nitrogen and phosphorous load on the overall wastewater treatment works. Dedicated separate treatment of these sludge liquors by the so-called one-step ANAMMOX® process and PHOSPAQ® (struvite) process reduce energy consumption and allow nutrient recovery. These technologies can also effectively be applied on digestates from organics waste digesters and nutrient rich effluent streams from industry (e.g. fermentation industry, food industry). Long term operations have shown stable process performance of the One-Step Anammox® process achieving ammonia removal in excess of 90%.

Key words

Anammox, Ammonia Removal, Sludge Liquor, Partial Nitritation, Anaerobic Digestion, Phospaq

Introduction

The Anammox Conversion

The anammox (anaerobic ammonium oxidation) conversion is an elegant short cut in the natural nitrogen cycle (see figure 1 - left). The anammox process is characterized by removing ammonia (NH_4^+) using nitrite (NO_2^-) rather than nitrate (NO_3^-) requiring less oxygen (O_2). The anammox conversion was discovered at a pilot plant of yeast and antibiotics producing company Gist Brocades (now DSM) in Delft, The Netherlands. The anammox process is a fully autotrophic process, meaning it does not require any carbon source. The anammox process was developed in partnership with the Technical University of Delft and the University of Nijmegen in The Netherlands.

The One-Step Anammox® Process

Paques bv from The Netherlands has developed the so called one-step-Anammox® reactor in which partial nitritation (equation 1) and the anammox reaction (equation 2) occurs simultaneously in one single process unit. It should be appreciated that in the one-step Anammox® only partial (50 %) nitritation is required to oxidized ammonia to nitrite to allow the reaction with the residual 50 % of ammonia (anammox reaction) to occur. The overall simplified conversions occurring in a one-step-Anammox® reactor can be described as follows:

Partial-Nitritation : \[ \text{NH}_3 + \text{O}_2 \rightarrow \text{NO}_2^- \]  
(1)

Anammox : \[ \text{NO}_2^- + \text{NH}_4^+ \rightarrow \text{N}_2 \]  
(2)
Overall reaction: \[ \text{NH}_3 + 0.85\text{O}_2 \rightarrow 0.11\text{NO}_3^- + 0.44\text{N}_2 + 0.14\text{H}^+ + 1.43\text{H}_2\text{O} \] (3)

Figure 1 schematically presents the anammox reaction as part of the nitrogen cycle (derived from Jetten et al., 1997) and the one-step Anammox® process combining partial nitritation with the anammox process.

![Figure 1](image1)

Figure 1: The anammox conversion as part of the overall natural nitrogen cycle (left) and the One-step ANAMMOX® process combining partial nitritation and anammox (right)

Figure 2 presents a comparison between conventional nitrification-denitrification and the one-step Anammox® process (combination of partial nitritation and anammox). In comparison to conventional nitrification-denitrification for the conversion of ammoniacal nitrogen, the one-step Anammox® process does not require any organic carbon source (BOD) and uses a minimum amount of energy. As a result addition of an external carbon source (or bypass of effluents), as required for conventional denitrification, is not needed. As only 50 % of ammoniacal nitrogen needs to be oxidized to nitrite (partial nitritation) up to 60 % savings on aeration energy can be achieved when using the one-step Anammox® process.

![Figure 2](image2)

Figure 2: The One-step Anammox® as compared to conventional nitrification-denitrification
Overall advantages of the One-step ANAMMOX® process combining partial nitritation and anammox are:

- No addition of organic carbon source (BOD) required
- Saving on aeration energy up to 60%
- Reduction of sludge production up to 75%
- Easy process control in one single continuously operated reactor unit

**Granular Biomass**

As the anammox bacteria have a relatively slow growth rate, effective biomass retention is essential for a sustainable process. The biomass generated in the Paques’ one-step-Anammox® process is of a granular nature and has a typical red-brown colour caused by specific enzymes. The granules consist of a mixture of nitritation and anammox bacteria. While the oxygen utilizing nitritation bacteria are concentrated at the outer granule, the anammox bacteria are more concentrated within the centre of the granule. The one-step Anammox® reactor is continuously fed and aerated and can be controlled by measurement of nitrite and ammonium.

The granules have a high settling velocity and are therefore easily retained in the reactor. The one-step-Anammox® reactor is equipped with a unique patented biomass separator mounted at the top of the reactor ensuring effective biomass retention.

Granular biomass has shown to be less susceptible for incidents with high solids or COD. Due to the special settler design solids in the influent and flocculent biomass growth are selectively washed out of the reactor, while the granular biomass is retained (Abma et al, 2010). The granules showed to be resilient in coping with potential inhibiting components. Prolonged exposure of granular anammox biomass to nitrite levels up to 50 mg/l did, in contrast to flock-type biomass, not result in inhibition of the bacteria (Abma et al, 2010). The granular anammox biomass has been used to inoculate other reactors facilitating the biological start-up. Depending on the amount of granular anammox biomass used for inoculation start-up times of newly built Anammox® reactors have been reduced significantly.
Figure 3: Granular biomass from One-Step-Anammox® reactors (courtesy Paques bv and TU Delft)

Applications

The one-step-Anammox® process is in principle suitable for treatment of anaerobic digestion liquors which are highly loaded with ammoniacal nitrogen and have relatively low concentrations of BOD, e.g.:
- Reject liquors from sewage sludge digestion
- Reject liquors from (Thermal) Hydrolysis Plants
- Organic resource digester liquors
- Anaerobic effluents from industry

Returning untreated sludge dewatering liquors directly into the wastewater treatment works (WwTW) will adversely affect the overall capacity of the WwTW as it will require large sums of aeration capacity and decrease the sludge age. Especially when the WwTW’s capacity is limited this would require additional aeration capacity and additional aeration basin volumes (Driessen and Reitsma, 2011).

Dedicated separate treatment of sludge dewatering liquors by the anammox process can overcome these issues saving power and space. In case existing basins can be utilized, footprint can be minimized even further and utilization of assets is maximized.
Pilot testing

In order to check the sustainability and performance of the one-step-Anammox® process test work can be conducted by on-site mobile, transportable pilot plants, which are equipped with pre-treatment (if required), an One-step Anammox® reactor, dosing equipment and automation. On-site test work has been conducted at several sludge treatment works (e.g. Netherlands, UK) and industry (especially, food industry, fermentation industry) to verify applicable loading rates and efficiency.

The anammox conversion is optimal at temperatures between 30-38 °C. Recently, research work has been started to investigate the anammox process performance at relatively low temperature.

Figure 4: Containerized ANAMMOX® pilot plant on-site

Full-scale Installations

To date there are 12 full-scale Anammox® projects. The Anammox® installations built vary in capacity from 60 to 11,000 kg/d. The first granular biomass based Anammox® installation was built at the Dokhaven WwTW in Rotterdam, The Netherlands in 2003. After an extensive start-up period, long term operation has demonstrated the Anammox® reactor at Rotterdam to achieve removal on ammoniacal nitrogen of 95-99 % consistently. Although originally designed for a load of 500 kgN/d (anammox reaction only) the Anammox® reactor (70 m³) at Dokhaven has been loaded up to 700-750 kgN/d without compromising the overall performance. The reactor produces granular sludge in excess, which is utilized for start-up of other Anammox® installations.

Beside sewage sludge dewatering liquors one-step Anammox® reactors have also been constructed to treat anaerobic effluents from industry (e.g. tannery, fermentation and food industry). The One-step-Anammox reactors are generally 8-10 m tall and can be built as rectangular (concrete) or round structures (concrete or steel). Table 1 presents the full scale applications of Anammox® installations built and currently under construction.
Table 1: Full-scale ANAMMOX® installations

<table>
<thead>
<tr>
<th>Source of liquor</th>
<th>Country</th>
<th>Design Capacity (kg N/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sludge liquor WwTW</td>
<td>Netherlands</td>
<td>700</td>
</tr>
<tr>
<td>Semiconductor Industry</td>
<td>Japan</td>
<td>220</td>
</tr>
<tr>
<td>Tannery</td>
<td>Netherlands</td>
<td>325</td>
</tr>
<tr>
<td>Sludge liquor WwTW</td>
<td>Switzerland</td>
<td>60</td>
</tr>
<tr>
<td>Sludge liquor WwTW</td>
<td>Netherlands</td>
<td>1,200</td>
</tr>
<tr>
<td>Yeast factory</td>
<td>China</td>
<td>1,000</td>
</tr>
<tr>
<td>Fermentation industry</td>
<td>China</td>
<td>11,000</td>
</tr>
<tr>
<td>Fermentation industry</td>
<td>China</td>
<td>9,000</td>
</tr>
<tr>
<td>Yeast industry</td>
<td>China</td>
<td>7,000</td>
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<tr>
<td>Distillery</td>
<td>Poland</td>
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<tr>
<td>Sludge liquor WwTW</td>
<td>Netherlands</td>
<td>660</td>
</tr>
<tr>
<td>Sludge liquor WwTW</td>
<td>UK</td>
<td>4,000</td>
</tr>
</tbody>
</table>

**Case 1: Olburgen WwTW- The Netherlands**

At the Olburgen WwTW in The Netherlands a blend of sludge dewatering liquors from the sludge treatment plant and industrial effluent from a nearby food factory are treated by the one-step Anammox® process. The sludge liquor treatment plant at Olburgen is financed and operated by the DBFO company Waterstromen, who selected the Anammox process on basis of lowest-cost-of-ownership. The one-step Anammox® reactors at Olburgen WwTW have a design capacity of 1,200 kg N/d.

The ammoniacal nitrogen concentration at Olburgen WwTW is around 300 mg/l on average. The relatively low nitrogen concentration did not compromise the performance of the installation as outlet concentrations was 30 mgN/l on average. Since its start-up in 2006, long term operation has demonstrated the Anammox® installation achieving removal of ammoniacal nitrogen well above 90 % (Abma, et al). As the anammox process does not require BOD, no bypass of industrial wastewater is needed allowing valorization of the complete effluent generating the maximum possible amounts of biogas (Driessen et al, 2010). Long term operational experience of the Phospaq® struvite reactors and the Anammox® reactors at Olburgen WwTW are extensively described by Abma et al (2010) and Driessen et al (2010).
At the Olburgen WwTW the one-step Anammox® installation is preceded by a Phospaq® struvite reactor to remove and recover phosphorous in the form of magnesium-ammonium-phosphate (MAP). The inlet and outlet concentration of the struvite reactor were 85 mgPO$_4$-P/l and 17 mgPO$_4$-P/l respectively. The struvite is harvested as crystalline particles having an average particle size of around 0.7 mm. Analyses proved the produced struvite to be in compliance with EU limits for usage as a slow-release fertilizer (Abma et al, 2010; Driessen et al, 2011).
At a fermentation industrial complex in China anaerobically treated effluent with ammoniacal nitrogen concentrations of over 600 mg/l is treated in a one-step Anammox reactor. The plant has a design capacity of 11,000 kgN/d treating effluent from monosodium-glutamate production. The Anammox® reactor in China was inoculated with granular biomass sourced from Anammox® installations in The Netherlands. A second Anammox® reactor with a capacity of 9000 kgN/d is in the process of start-up and a third is soon under construction.

Figure 7: Full-scale ANAMMOX® installation (11,000 kgN/d) at fermentation industry in China.

Case 3: Minworth WwTW – United Kingdom

In 2011 pilot test work was conducted to investigate the feasibility of the one-step Anammox® technology treating sludge dewatering liquors from sewage treatment works Severn Trent Water in the UK. After successful pilot trials the one-step Anammox® process was selected to treat the sludge dewatering liquors at Severn Trent Water’s Minworth WwTW. Minworth is Severn Trent Water’s largest sewage treatment works serving a population equivalent (PE) of 1.75 million from the city of Birmingham, UK.

The projected ANAMMOX® installation at Minworth WwTW is designed to treat a total maximum flow of 6000 m³/d and an ammoniacal N-load of maximum 4000 kgN/d. The one-step Anammox® installation will be built by retrofitting existing aeration basins. One aeration basin with a volume of 1750 m³ will be equipped with special patented Anammox® reactor internals and process control systems, ensuring efficient biomass retention and optimal process control. Other existing basins will be utilized for
buffering. By retrofitting existing aeration tanks utilization of existing assets is maximized. The installation is planned to be commissioned in 2012.

Figure 8: Existing basins at Minworth WwTW which will be converted into an ANAMMOX® plant (photograph by courtesy of Severn Trent)

Conclusions

1. The one-step ANAMMOX® process has proven to be an effective method to treat liquors with high ammoniacal nitrogen concentrations like sludge dewatering liquors from sewage plants as well as anaerobically treated industrial effluents.

2. Long term operational experience has proven stable performance achieving removal efficiencies on ammoniacal nitrogen well above 90 %.

3. The one-step ANAMMOX® process is characterized by relatively low energy consumption, low sludge production and is in no need of any carbon source

References

