THE ANAMMOX®-PROCESS
DESIGN CONSIDERATIONS AND OPERATIONAL EXPERIENCE

Driessen, W., Ettinger van, M., Remy, M., Hendrickx, T. and Kruit, J.
Paques bv, P.O. Box 55, 8560 AB Balk, The Netherlands
Corresponding Author: Tel: + 31 514 60 8500, Email: w.driessen@paques.nl

Abstract

The Anammox® process is a biological treatment system for removal of ammoniacal nitrogen. The Anammox® process has been successfully applied on dewatering liquors from biosolids digesters and nutrient rich anaerobically treated industrial effluents (e.g. fermentation industry, food industry). Since the start-up of world’s first full scale Anammox® reactor in 2002 at Dokhaven WWTP in Rotterdam, 19 full-scale Anammox® plants have been built or are under construction representing a total installed capacity of over 65,000 kg N per day.

The Anammox® process is characterised by removal of ammoniacal nitrogen without the need of an organic carbon source (COD). The Anammox® process is a continuously fed biological process using granular biomass. Long term operations have shown stable process performance of full-scale Anammox® reactors achieving ammoniacal nitrogen removal in excess of 90% at various loading rates. Design considerations and long term operational experience are presented and discussed.

Keywords

Anammox, ammonia removal, anaerobic digestion, nutrient recovery, struvite, liquor treatment

Introduction

In recent years there has been an increasing interest in anaerobic digestion of sewage sludge, organic solids and industrial effluents. Although anaerobic digestion is an effective method to remove organic substances (COD), the removal of nutrients (N, P) is very limited. As a result, liquors derived from anaerobic processes have reduced COD content, but often still contain relatively high concentrations of ammoniacal nitrogen (NH₄⁺ + NH₃) and ortho-phosphate (PO₄³⁻).

Although small in volume sludge dewatering liquors of a sewage treatment work can represent up to 30% of the nitrogen and phosphorus load of the overall municipal wastewater treatment plant (WWTP). Returning untreated sludge dewatering liquors with high concentrations of ammonium (500-1500 mg/l) directly into the main wastewater treatment plant can adversely affect the overall capacity of the works as it will require a large amount of aeration capacity and decrease the sludge age. Especially when the WWTP’s capacity is limited this would require additional aeration capacity and additional aeration basin volumes (Driessen and Reitsma, 2011). Reduction of the nitrogen load in sludge dewatering liquors becomes even more important in case the main WWTP applies biological phosphorus removal (Shorrock et al., 2012).

Enhanced hydrolysis plants aim at extended degradation of biosolids, resulting in an increased release of nutrients. When biosolids are treated in thermal hydrolysis plants (THP), sludge dewatering liquors with elevated concentrations of ammonium (2000-3000 mg N/l) and phosphorus (150-350 mg P/l) are produced. Effective removal or recovery of nutrients from sludge dewatering liquors from anaerobic digesters involving THP treatment is crucial.

Dedicated separate treatment of sludge dewatering liquors can overcome the negative effects of returning untreated nutrient rich liquors to the main wastewater treatment plant. The Anammox® process is an
An effective way to remove ammoniacal nitrogen and phosphorus recovery is possible by precipitation of magnesium-ammonium-phosphate (MAP) by so called Phospaq™ reactors as demonstrated in full scale installations (Driessen et al, 2009). These processes can also effectively be applied on digestate dewatering liquors from organic solids digesters and nutrient-rich industrial effluents (e.g. food industry).

The Anammox® Process

The natural nitrogen cycle involves various biological processes. Nitritation \((\text{NH}_4^+ + \text{O}_2 \rightarrow \text{NO}_2^-)\) is the process where ammonium is oxidized to nitrite and nitrification is the process whereby ammonium is fully oxidized to nitrate \((\text{NO}_2^- + \text{O}_2 \rightarrow \text{NO}_3^-)\). Denitrification \((\text{NO}_3^- + \text{COD} \rightarrow \text{N}_2)\) is the process whereby nitrate with addition of an organic carbon source is converted to nitrogen gas. Anammox (anaerobic ammonium oxidation) conversion is an elegant short-cut in the natural nitrogen cycle whereby ammonium and nitrite are converted to nitrogen gas \((\text{NH}_4^+ + \text{NO}_2^- \rightarrow \text{N}_2)\). As the anammox process involves removal of ammonium over nitrite \((\text{NO}_2^-)\) rather than nitrate \((\text{NO}_3^-)\) less oxygen \((\text{O}_2)\) is required.

The Anammox® reactor as recently developed by Paques bv is a reactor system in which nitritation and anammox conversion occur simultaneously in one single process unit. These Anammox® reactor are continuously aerated reactors that use granular biomass. Figure 1 presents the biological reactions by the Anammox® process as part of the nitrogen cycle. The overall simplified conversions occurring in an Anammox® reactor can be described as follows:

\[
\text{NH}_3 + 0.85 \text{O}_2 \rightarrow 0.11 \text{NO}_3^- + 0.44 \text{N}_2 + 0.14 \text{H}^+ + 1.43 \text{H}_2\text{O}
\]

Figure 1: The Anammox® process combining (partial) nitritation and anammox as part of the N-cycle

In comparison to conventional nitrification-denitrification used for removal of ammoniacal nitrogen, the Anammox® process does not require any organic carbon source (COD). As a result addition of an external organic carbon source (or bypass of effluents) as required for denitrification, is not needed. In the Anammox® process only partial nitritation is required oxidizing 50% of the ammonium to nitrite. Subsequently the remaining 50% of ammonium reacts with the nitrite to nitrogen gas. Since 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.

Summarizing the advantages of the one-step Anammox® process combining partial nitritation and anammox conversion:
- 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

Construction

Treating the effluent from separate dedicated nitrification reactors the first Anammox® reactors built were designed to conducting the anammox reaction only. These Anammox reactors were built as tall tower reactors (steel) with typical heights of 12-16 m. The new Anammox® reactors that combine partial nitrification and the anammox conversion are built as rectangular (concrete) or round (steel, concrete) structures with typical heights of 6-10 m. Such Anammox® reactors are equipped with an aeration system at the bottom and a specially designed biomass separator in the top of the reactor to ensure biomass retention. The special Anammox® biomass separators can also be placed in existing tank structures converting existing assets to Anammox® reactors (Shorrock et al, 2012).

Figure 2: Photographs of various building concepts of Anammox® reactors

Granular Biomass

Granular anammox biomass shows analogies with anaerobic granular biomass. In the late 1970’s formation of granular anaerobic biomass was discovered in a ‘clarigester’ in South Africa. The advantages of using granular sludge for wastewater treatment was acknowledged and researched by the Wageningen University (Lettinga et al, 1980). Although the formation of granular biomass is a phenomena not yet fully understood, it has found widespread full scale application in so called anaerobic upflow sludge bed reactors (UASB). With more than 2200 installations built worldwide, anaerobic sludge bed reactors have become the most widely applied anaerobic technology for treating industrial effluents.
Similar to anaerobic sludge bed reactors that work with granular anaerobic biomass, Anammox® reactors also operate with biomass of a granular nature. The granules are aggregates of different micro-organisms that find synergy in living in direct proximity of each other. Whereas anaerobic granules contain strains of fermentative bacteria and methanogens, in Anammox® granules mixtures of ammonia oxidizing bacteria (AOB) and anammox bacteria are found. While Anammox® granules retain slow growing anammox bacteria, anaerobic granules contain slow growing methanogenic bacteria. Some characteristics of anammox bacteria and anaerobic bacteria are listed in table 1.

Table 1: Specific growth rates of micro-organisms in anammox granules and in anaerobic granules.

<table>
<thead>
<tr>
<th>Mesophilic</th>
<th>Substrate &amp; Conditions</th>
<th>Unit</th>
<th>Yield</th>
<th>Doubling times (d)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>UASB granular</td>
<td>Glucose</td>
<td>g VSS/g COD</td>
<td>0.11</td>
<td>3.3</td>
<td>Lettinga, 1995</td>
</tr>
<tr>
<td>UASB granular</td>
<td>VFA mix</td>
<td>g VSS/g COD</td>
<td>0.064</td>
<td>3.8</td>
<td>Lettinga, 1995</td>
</tr>
<tr>
<td>Anammox</td>
<td>T=30°C, DO=1mg/l</td>
<td>g VSS/g N</td>
<td>0.11</td>
<td>9.6</td>
<td>Hao et al., 2002a</td>
</tr>
<tr>
<td>AOB</td>
<td>T=30°C, DO=1mg/l</td>
<td>g VSS/g N</td>
<td>0.11</td>
<td>0.5</td>
<td>Hao et al., 2002a</td>
</tr>
</tbody>
</table>

Research has shown that the Anammox® granules consist of biofilms of nitritation and anammox bacteria to perform simultaneously various biological processes. While the oxygen utilizing nitritation bacteria are mainly concentrated at the outer layers of the granule, the anammox bacteria are more concentrated within the centre of the granule. The granular matrix protects the anammox bacteria in the inner core from extreme conditions in the bulk solution. As a result the Anammox® granules proved to be more resilient in coping with potential inhibiting components, than flocculent biomass. Prolonged exposure of granular anammox biomass to nitrite levels up to 50 mg/l did not result in inhibition of the bacterial activity (Abma et al, 2010).

![Figure 3: Schematic model of an Anammox® granule with nitritation in the outer biofilm and anammox within the core and the biological reactions (Hülsen et al, 2010)](image)

Granular biomass showed to be also less susceptible for incidents with high solids or COD. Due to the special design of the separator, solids and flocculent biomass present in the influent are selectively washed out of the reactor, while the granular biomass is retained (Abma et al, 2010). As the anammox bacteria have a relatively slow growth rate, effective biomass retention is essential for a sustainable process. The granules
have excellent settling properties and are therefore easily retained in the reactor. The Anammox® reactor is equipped with a unique patented biomass separator mounted in the top of the reactor ensuring effective biomass retention.

Examples of granular biomass from an Anammox® reactor and an anaerobic sludge bed reactor are presented in figures 4 and 5. The red-brown colour of the Anammox-granules is caused by specific iron containing enzymes, while the grayish/black colour of the anaerobic granules is caused by metal precipitates. The size of Anammox® granules typically varies between 0.5 and 4 mm.

Figure 4: Granular biomass from Anammox® reactor (l) and anaerobic Biopaq® sludge bed reactor (r)

Figure 5: Granular biomass from Anammox® reactor (l) and an anaerobic Biopaq® sludge bed reactor (r)

Any surplus of granular anammox biomass produced can be used to inoculate other reactors facilitating the biological start-up. Depending on the amount of granular anammox biomass used for inoculation, time for stating up new Anammox® reactors have been reduced significantly. In case of any calamities Anammox® reactors can be easily reseeded with granular biomass from other Anammox® reactors to allow a fast
recovery of the process. Due to the concentrated nature of the granular biomass high volumetric loading rates can be applied and relatively small reactor volumes are required.

**Full scale applications**

The 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.:

1. Sewage sludge dewatering liquors (also THP pre-treated biosolids)
2. Dewatering liquors from organic solids digesters
3. Condensates from biosolids drying plant
4. Industrial effluents (e.g. fermentation, food)
5. Leachate from aged landfills

Currently full-scale Anammox® reactors have been built to treat sewage sludge dewatering liquors and anaerobically treated effluents from industry (e.g. fermentation industry, food industry, semi-conductor industry, tannery, distillery). Table 2 presents a list of 19 full-scale Anammox® installations that have been built since 2002. As per September 2012 the total installed capacity of these installations is 66,000 kg N per day varying in capacity from 60 to 11,000 kg N/d.

**Table 2:** Full-scale Anammox® installations (n=19) and their daily design capacities

<table>
<thead>
<tr>
<th>Source of liquor</th>
<th>Country</th>
<th>Design Capacity (kg N/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biosolids reject</td>
<td>Netherlands</td>
<td>500</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>Biosolids reject</td>
<td>Switzerland</td>
<td>60</td>
</tr>
<tr>
<td>Biosolids reject &amp; Food industry</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>
</tr>
<tr>
<td>Distillery</td>
<td>Poland</td>
<td>1,200</td>
</tr>
<tr>
<td>Fermentation industry</td>
<td>China</td>
<td>6,100</td>
</tr>
<tr>
<td>Biosolids reject</td>
<td>Netherlands</td>
<td>660</td>
</tr>
<tr>
<td>Food industry</td>
<td>China</td>
<td>2,200</td>
</tr>
<tr>
<td>Fermentation industry</td>
<td>China</td>
<td>11,000</td>
</tr>
<tr>
<td>Biosolids reject</td>
<td>UK</td>
<td>4,000</td>
</tr>
<tr>
<td>Rendering plant</td>
<td>Netherlands</td>
<td>6,000</td>
</tr>
<tr>
<td>Distillery</td>
<td>China</td>
<td>900</td>
</tr>
<tr>
<td>Food industry</td>
<td>China</td>
<td>10,100</td>
</tr>
<tr>
<td>Winery</td>
<td>China</td>
<td>1,045</td>
</tr>
</tbody>
</table>
Return liquors from sludge dewatering plants are not only high in ammoniacal nitrogen concentration, but sometimes also contain relatively high levels on phosphorus. Dedicated phosphorus removal from these return liquors could significantly reduce the phosphorus load to the overall WWTP. A combination of phosphorus removal via recovery of magnesium-ammonium-phosphate (MAP) in a so called Phospaq™ reactor and nitrogen removal with the Anammox® process has been operational since 2006 at the Olburgen WWTP in The Netherlands (Driessen et al, 2009). The generated magnesium-ammonium-phosphate (MAP) is recovered as a coarse powder, easily blended with other additives to formulate a bespoke fertilizer. Test work on THP reject liquors is currently being performed to confirm treatment by the Anammox® process.

During the first years landfill leachate often contain high COD concentrations. However with increasing age of the landfill the biodegradable COD concentration in the leachate decreases significantly while ammoniacal nitrogen concentrations increases. Pilot testwork conducted on leachate from an aged landfill confirmed successful removal of ammoniacal nitrogen by the Anammox® process.

Figure 6: Anammox® pilot plant conducting on-site test work

Start-up

Case 1: Dokhaven Anammox®

The first full-scale granular biomass based Anammox® installation was built at the Dokhaven WWTP (300,000 population equivalent) in Rotterdam, The Netherlands. The Anammox reactor is treating the biosolids dewatering liquor that was pre-treated by an already existing nitritation reactor. The Dokhaven Anammox® reactor conducting the anammox pathway only was started in 2002.

As there was no anammox biomass available at the time of start-up all biomass had to be generated during operation. The overall start-up period took 3 years in which various technological and technical problems were tackled and sufficient granular anammox biomass was produced to achieve a stable operation at a design load of 500 kg/d. Since the start-up of the Dokhaven Anammox® reactor time for starting-up new Anammox reactors has been reduced significantly..

Case 2: Olburgen Anammox®

In 2006 the Anammox® reactor (600 m³) at Olburgen WWTP (The Netherlands) was started up and was achieving full load performance within 180 days. Due to inoculation with active granular biomass from the Dokhaven Anammox® reactor the start-up time was significantly shortened. Figure 7 presents the
ammonium (NH$_4^+$) concentration in the inlet and outlet of the reactor as well as the removal efficiency on ammoniacal nitrogen during the start-up of the Anammox® reactor at Olburgen.

**Case 3: Fermentation industry Anammox®**

Figure 8 presents the start-up in 2009 of an Anammox® reactor (1230 m$^3$) at a fermentation industry in China. This reactor was inoculated with granular biomass from an Anammox reactor in the Netherlands. This reactor could achieve an ammoniacal nitrogen removal efficiency of above 90% in a period of not more than 50 days. The period required for start-up depends on the percentage of active concentrated biomass that is available at start-up as compared to the amount needed for the design load.

![Figure 7: Concentrations and removal of ammonium during start-up of a 600 m$^3$ Anammox® reactor at Olburgen WWTP, The Netherlands](image1)

**Figure 7:** Concentrations and removal of ammonium during start-up of a 600 m$^3$ Anammox® reactor at Olburgen WWTP, The Netherlands

![Figure 8: Concentrations and removal of ammonium during start-up of a 1230 m$^3$ the Anammox® reactor at a fermentation industrial site, China](image2)

**Figure 8:** Concentrations and removal of ammonium during start-up of a 1230 m$^3$ the Anammox® reactor at a fermentation industrial site, China

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With the increasing availability of granular anammox biomass the time required for start-up of Anammox® reactors can be reduced significantly.

**Long term operational experience**

*Case 1: Rotterdam Dokhaven liquor treatment plant*

Treating the effluent from an existing nitritation reactor the Dokhaven Anammox® was designed to perform the anammox conversion of ammonium and nitrite to nitrogen gas only.

![Flow schematic of the sludge liquor treatment plant at Dokhaven WWTP](image)

After the extensive start-up period of 3 years the Dokhaven Anammox® reactor demonstrated removal on ammoniacal nitrogen of 95-99% consistently. Although originally designed for a load of 500 kg N/d, more recently the Anammox® reactor at Dokhaven has been loaded with an average of 700 kg NH$_4$-N/d with peaks up to 1200 kg NH$_4$-N/d without compromising the overall performance. The Dokhaven Anammox® reactor has a volume of 70 m$^3$ and is operating at an average volumetric loading rate of 10 kgNH$_4$-N/m$^3$.d with peaks up to 17-20 kg NH$_4$-N/m$^3$.d (anammox reaction only). The reactor produces good quality concentrated granular biomass, which is utilized for start-up of other Anammox® installations.

Figure 10 presents the long term operation of the Anammox® reactor at Dokhaven in 2009-2011. The system demonstrated to be very reliable in handling high variations in loading rates of total kjehldal nitrogen (TKN). The Dokhaven Anammox® reactor was able to recover very rapidly after the performance was compromised by a failure of the pH correction system.

![Long term performance by the Dokhaven Anammox® reactor (2009-2011)](image)
Case 2: Olburgen liquor treatment plant

The sludge liquor treatment plant at Olburgen WWTP (The Netherlands) is financed and operated by the DBFO company Waterstromen, who selected the Anammox process on basis of lowest-cost-of-ownership. The liquor treatment plant at Olburgen WWTP comprises of two Phospaq® struvite reactors of 300 m$^3$ each followed by one Anammox® reactor of 600 m$^3$. The one-step Anammox® reactor at Olburgen WWTP combines nitritation and annamox and has a design capacity of 1,200 kg N/d. The liquor treatment plant treats a blend of sludge dewatering liquors from the sludge treatment plant and industrial effluent from a nearby located food factory. The food factory effluent is pre-treated in an anaerobic UASB reactor.

Figure 11: Flow schematic of the liquor treatment plant at Olburgen WWTP

At the Olburgen WWTP the Anammox® installation is preceded by a Phospaq® struvite reactor to remove and recover phosphorus in the form of magnesium-ammonium-phosphate (MAP). The inlet and outlet concentration of the struvite reactor are 85 and 17 mg PO$_4$-P/l respectively. The struvite is harvested as crystalline particles with an average particle size of around 0.7 mm (figure 12). Analyses showed the produced struvite to be in compliance with EU limits for its use as a slow-release fertilizer (Abma et al, 2010; Driessen et al, 2011).

Figure 12: Struvite powder produced in the Phospaq® reactor at Waterstromen Olburgen WWTP

As the Anammox® process does not require BOD, no bypass of industrial wastewater is needed, allowing full valorization of the complete effluent generating the maximum possible amounts of biogas (Driessen et al, 2010). Earlier operational experience of the Phospaq® struvite reactors and the Anammox® reactors at Olburgen WWTP are extensively described by Abma et al (2010) and Driessen et al (2010).
Figure 10: Photograph and schematic drawing of the Anammox® reactor and the Phospaq® struvite reactors at Waterstromen Olburgen WWTP

Since its start-up in 2006 the Anammox® installation at Olburgen WWTP is achieving removal of total ammoniacal nitrogen well above 90% (Abma, et al, 2010). Figure 13 presents long term operational results of the liquor treatment plant at Olburgen WWTP in the period of 2009-2012 (Driessen et al, 2012). The average ammoniacal nitrogen concentration in the inlet is approximately 325 mg/l while the average outlet concentration was 30 mg N/l. Despite extreme fluctuations in nitrogen loading in the range of 300-1500 kg/d the liquor treatment plant at Olburgen was able to maintain its high level of performance. The Anammox® reactor was capable to handle volumetric loading rates up to 2.5 kg N/m³.d.

Figure 13: Long term performance of the liquor treatment plant at Waterstromen Olburgen
Conclusions

- The Anammox® process has proven to be a reliable and effective method for treating liquors with high ammoniacal nitrogen concentrations like sludge dewatering liquors from sewage plants and anaerobically pre-treated industrial effluents.

- Long term operational experience has proven stable performance of the Anammox® process maintaining removal efficiencies on ammoniacal nitrogen well above 90%.

- Combined treatment with Phospaq™ and Anammox® reactors allows recovery of phosphorus via struvite and effective removal of nitrogen.

References


