AMMONIACAL NITROGEN REMOVAL FROM SLUDGE LIQUORS – OPERATIONAL EXPERIENCE WITH THE DEMON PROCESS

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Abstract

Digestion of organic waste and enhanced treatment of municipal sewage sludge are increasingly popular methods for energy recovery. A side effect of sludge digestion is the release of ammonia from digested organic materials. Sludge liquors produced in the dewatering of digested sludge typically contain high concentrations of ammonia, requiring dedicated systems for sludge liquor treatment. This paper provides operational experience of the DEMON process at the Apeldoorn wastewater treatment plant in the Netherlands. The DEMON process is a nitrification/deammonification process whereby ammonia and nitrite are simultaneously converted to nitrogen gas, without the use of organic carbon. An autotrophic process using anammox bacteria is used for deammonification. Process control is based on minute variations in pH, resulting in a very simple and stable process operation. An explanation of the process, plus the results of startup and one year operation of the DEMON process at WWTP Apeldoorn are presented.

Keywords

Ammonia removal, nitrogen, anammox, deammonification, DEMON

Liquor strength development

With the increased attention for sustainability the energy content of sewage sludge has become a major issue and sewage sludge is no longer regarded as a waste product, but as a source of energy. Advanced methods for recovery of energy from biosolids or biowaste are being developed. Also the co-digestion of sewage sludge with other waste products has become a potential source of income for operators of wastewater treatment plants.

Digestion of biosolids aims at conversion of organic substances into methane gas and inorganic compounds. A side effect of the conversion of organic material is the release of inorganic nitrogen compounds, mainly in the form of ammonium. There is a direct relation between the efficiency of the digestion process and the release of ammonia. This effect is visible in the ammonia concentrations of liquors produced in the dewatering of digested biosolids (Table 1).

Table 1: Digester loading vs. ammonia concentration in dewatered sludge liquors.

Material entering digester	Digester feed sludge dry solids	Ammonia concentration in dewatered sludge liquors
• Primary and secondary sludge, gravity thickener	3% -4%	500 – 800 mg/l
• Primary and secondary sludge, belt thickener	6% – 8%	900 – 1400 mg/l
• THP treated primary and secondary sludge	16%	2200 – 3000 mg/l
• Primary and secondary sludge, co-mixed with industrial biowaste.	6% – 8%	1000 – 3500 mg/l

Return liquors from sludge dewatering plants contribute significantly to the ammonia load to the main wastewater treatment plant. In cases where imported municipal wastewater sludge or biosolids are digested on site the ammonia load from sludge liquors may be upto 40% of total plant load. Separate treatment of return liquors may then be an alternative to costly expansion of the main treatment plant.

The Apeldoorn Project

The Apeldoorn wastewater treatment plant is operated by the public utility Waterschap Veluwe. The plant has a capacity of 300,000 population equivalent. Sludge is imported from other treatment plants in the Veluwe area for digestion or dewatering on site. Two existing digester tanks were augmented by a third digester to allow co-digestion of biosolids from industrial sources (Figure 1).

Figure 1: Apeldoorn WWTP, digester tanks

Prior to the Construction of the third digester the main treatment plant was struggling to meet the final effluent standard of 10 mg/l N-total. Molasses were dosed as an external carbon source to the main plant to support the denitrification process. This resulted in additional production of activated sludge, which caused problems in maintaining the optimum mixed liquor suspended solids concentration in the activated sludge system. Stable operation of the main treatment plant proved difficult and discharge standards were frequently not met. Obviously the import of biosolids would further increase the ammonia load to the main plant, thus creating the necessity of return liquor treatment. Construction of a return liquor treatment plant would allow import of third party biosolids, would eliminate the need of costly dosing of molasses in the main plant, and furthermore would improve process stability of the main plant enabling it to meet the discharge standards.

Waterschap Veluwe bravely decided to start three separate projects simultaneously: i) refurbishment of the existing sludge dewatering facility, ii) construction of a third digester to receive third party biosolids and iii) construction of a liquor treatment plant for removal of ammonia from return liquors.

DEMON was selected as the preferred method for liquor treatment through a competitive tender procedure, with lowest total cost of ownership as the only selection criterion. The flow and load data as presented in Table 2 were used as a basis for the design.

Table 2: Return liquor characteristics

Parameter	Unit	Average	Maximum	Minimum
Flow	m^3/d	1,020	1,270	760
NKj (sol.)	kg/d	1,355	1,690	1,010
NH4-N	kg/d	1,232	1,521	918
COD (tot.)	kg/d	2,522	3,159	1,885
COD (sol.)	kg/d		2,100	
BOD	kg/d	180	210	150
Suspended solids	kg/d	938	1,375	500
Temperature	°C	17	15	17

The DEMON process

General information

DEMON (an acronym for DE-amMONnification) is a cost effective technology for the removal of nitrogen compounds from wastewater with high concentrations of ammonia. The technology is based on a biological process of nitrification and autotrophic denitrification. The process was developed and patented by the University of Innsbruck (Austria) and has evolved into a proven technology.

Deammonification represents a short-cut in the N-metabolism pathway and comprises 2 steps: about half the amount of ammonia is oxidised to nitrite and then residual ammonia and nitrite is anaerobically transformed to elementary nitrogen. Implementation of the pH-controlled DEMON® process for deammonification of return liquors in a single-sludge SBR system at the WWTP Strass (Austria) contributed essentially to energy self-sufficiency of the plant. The specific energy demand of this resource saving sidestream process equals 1.16 kWh per kg ammonia nitrogen removed comparing to about 6.5 kWh for mainstream treatment.

At Strass WWTP deammonification has been in operation in full-scale now for 6 years without interruption, reaching annual ammonia removal rates beyond 90% (Wett, 2006, 2007). Biomass enrichment and DEMON-start-up in Strass took a period of 2.5 years whereas start-up period at the second system at WWTP Glarnerland (Switzerland) was reduced to 50 days due to transfer of substantial amounts of seed sludge.

The DEMON process has been installed at 9 full scale installations; Austria (1), Germany (3), Switzerland (3), Hungary (1) and the Netherlands (1) with 6 more under construction or startup; Austria (2), Serbia (1), Netherlands (1) and Germany (2).

Process description

In a DEMON reactor two separate processes occur: the partial nitification of ammonia and the subsequent anaerobic oxidation of the residual ammonia by nitrite to nitrogen gas (Figure 2).

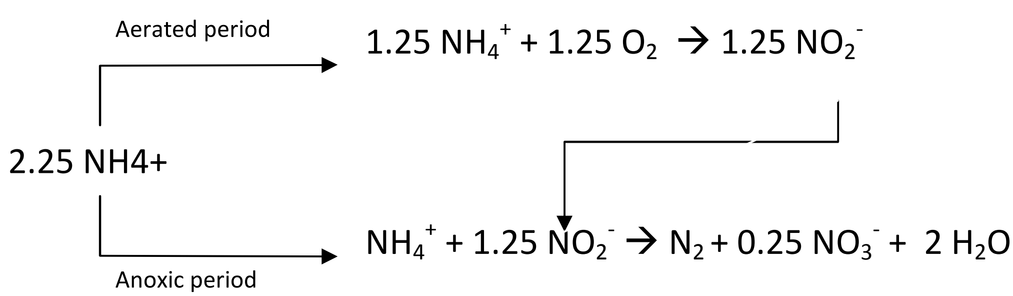

Figure 2: Simplified reaction equation for the DEMON process

Compared to other biological processes for nitrogen removal, the DEMON process is characterised by:

- Low energy requirment, as only 55% of ammonia is oxidised to nitrite;
- No requirement for an external source of carbon (such as methanol), as ammonia is utilised as an electron donor, and not an organic carbon source;
- Low sludge production, due to the low yield of deammonifying bacteria.

In theory the presence of oxygen (required for partial nitrification) inhibits growth of deammonifying bacteria. Nevertheless the DEMON process allows nitrification and deammonification to occur in one single reactor. This is achieved by maintaining a low dissolved oxygen setpoint of approximately 0.3 mg/l. This low DO value has the additional benefit of limiting the growth rate of nitrite oxidising bacteria (such as Nitrobacter) to such values that these bacteria are washed out of the system.

Due to the relatively low growth rate of deammonifying bacteria a DEMON system is operated at a sludge age of approximately 20 days; thus sludge retention is required. A cyclone is used to separate deammonifying bacteria from waste activated sludge. The deammonifying bacteria are subsequently returned to the DEMON reactor, effectively creating longer sludge ages for deammonifying than for ammonia oxidising bacteria and nitrite oxidising bacteria (Wett, 2010). The combination of low DO values and the use of a cyclone ensures that nitrite oxidising bacteria will not be able to accumulate in the DEMON reactor.

To allow for sludge retention the DEMON process is operated as a sequencing batch reactor. The SBR cycle consists of the following steps:

- Fill and aerate (4.5 hours). During this phase the reactor is gradually filled with centrate and the reactor content is alternately aerated and mixed. Nitrification occurs during aerated periods and deammonification occurs during anoxic periods;
- sedimentation (45 min.). At the end of the fill and aerate phase, both aeration and mixing are stopped and the sludge blanket is allowed to settle.
- Discharge (45 min.). The clear supernatant is discharged from the reactor. As the deammonifying bacteria have excellent settling characteristics, the discharge system can be fairly simple. At the end of the discharge phase, the DEMON reactor is ready for the next cycle.

DEMON Apeldoorn design

The DEMON process for Apeldoorn WWTP is designed on the basis of the design parameters as indicated in **Table 3**. As the DEMON process operates as a sequencing batch reactor an influent buffer tank is required to buffer centrate during the sedimentation phase and the discharge phase. This two hour period leads to a required buffer tank volume of 110 m³. The maximum suspended solids concentration in the centrate is rather high. With a sludge age of 20 days this would lead to a large reactor volume to maintain a MLSS of 5 g/l. However, at Apeldoorn WWTP an obsolete tank with a volume of 1500 m³ was available. It was decided to use this tank as a combined buffer tank and sedimentation tank. The aim of the sedimentation step prior to the DEMON reactor is to reduce TSS in the feed liquor to a concentration below 300 mg/l. Effectively 500 m³ of the combined tank is used for sedimentation and 1,000 m³ is used as a buffer.

Table 3: Design parameters

Parameter	Unit	Value
Volume	m^3	2,900
Effective height	m	6.5
Mixed liquor suspended solids	g/l	5.0
Sludge age	Days	20
Sludge production	kg/d	725
Aeration system (SOTR)	kg O_2/d	3,100
Caustic dosing		None
Carbon source dosing		None
Heat addition	kW	550

Figure 3: DEMON system at Apeldoorn WWTP

Centrate typically has an alkalinity to ammonia ratio of 1:1 (mol/mol). With this ratio sufficient alkalinity is available for nitrification of 50% of available ammonium at stable pH. For this reason no dosing of caustic soda is required.

Due to the low predicted temperature of centrate heating of influent is required to maintain the required reactor temperature of 30 °C.

Effluent from the DEMON is discharged in batches of 330 m^3 (at average load), three times a day. DEMON effluent is discharged to the aeration tank of the main treatment plant. To avoid rapid changes in hydraulic load an obsolete tank is used as effluent buffer.

pH control

During the fill and aerate phase the reactor is alternately aerated to convert ammonia into nitrite. The conversion rate must be controlled in such a way that sufficient nitrite is produced to allow the deammonification step to occur. However, too high concentrations of nitrite will lead to inhibition of the deammonification step (Dapena-Mora, 2007). Extended aeration may also cause nitrite oxidising bacteria to grow into the system. These nitrite oxidising bacteria will compete with deammonifying bacteria for the available nitrite. pH measurement may be used as a simple method of control. As nitrite and H^+ are produced in a fixed ratio in the nitrification step, changes in pH may be used to monitor nitrite production.

During the fill and aerate phase, the reactor content is alternately aerated and mixed. During the aerated period the pH will drop as a result of nitrification. The end of the aerated period is reached when pH in the reactor has dropped over a predefined bandwidth. Aeration is stopped and the anoxic period will start. During the anoxic period pH will rise again due to the deammonification process and due to the feed of centrate alkalinity. As soon as pH has fully recovered over the predefined bandwidth, aeration is restarted (Figure 4).

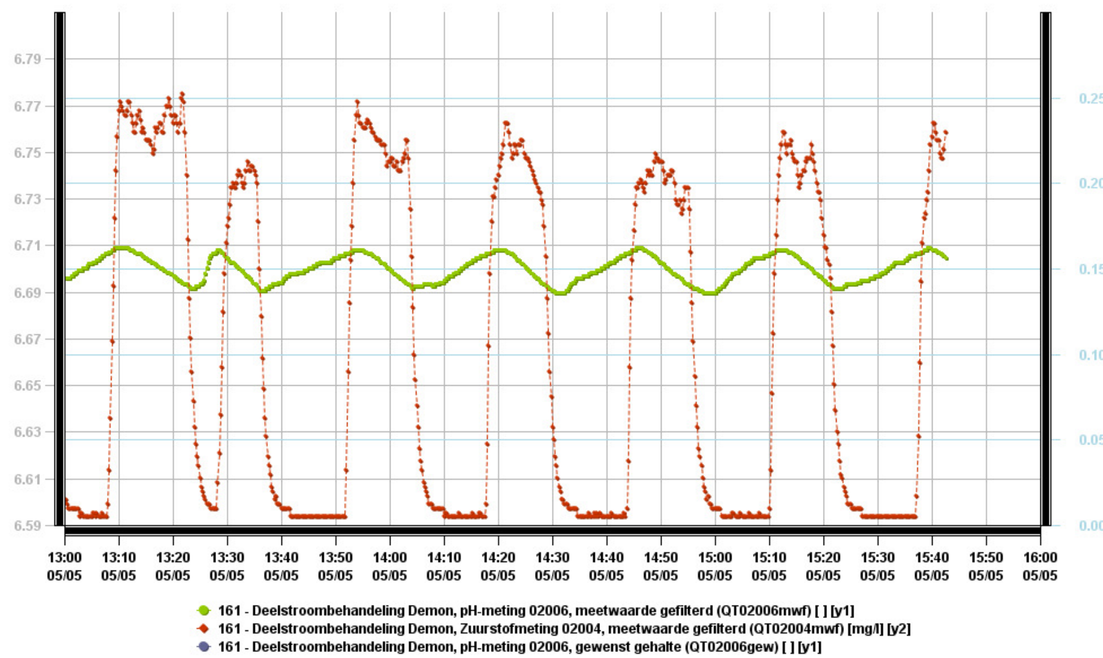

Figure 4: pH control DEMON reactor (green line: pH, red line: oxygen)

The predefined bandwidth for pH fluctuation is approximately 0.02 pH units. It is the relative change in pH value that is important, and not the absolute value. Even though the absolute value of the reading of a pH sensor may drift over time, the measurement of relative changes in pH over a short time period is sufficiently accurate to control the process.

The rise in pH is predominantly caused by the feed of alkalinity to the system. This means that the frequency of aeration is proportional to influent flow. At low flows all available nitrite will be consumed well before the end of the anoxic period, so effectively a waiting period is introduced before the next aeration phase starts (
Figure 5). When flow increases the alkalinity feed will also increase, thus leading to a shorter wait period until the next aeration phase. This allows for a simple control method to absorb rapid changes in flow to the reactor without an effect on treatment efficiency.

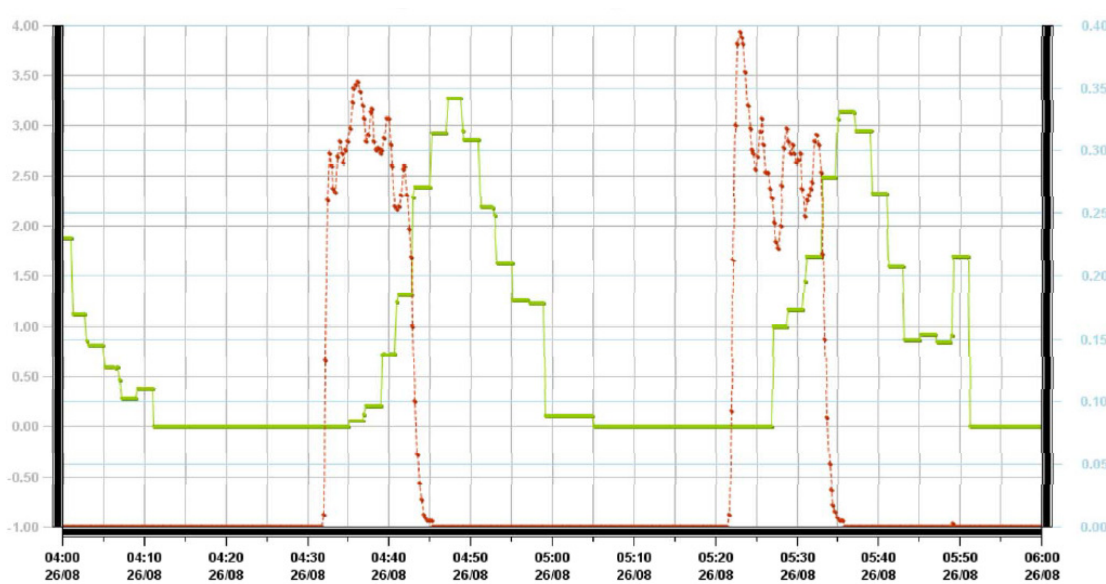

Figure 5: Oxygen (red line) and nitrite (green line) concentrations during oxic and anoxic periods

Cyclone

In the DEMON process three competing processes occur:
1. Nitrification of ammonia to nitrite (oxic conditions)
2. Oxidation of nitrite to nitrate (oxic conditions)
3. Deammonification of nitrite and ammonia to nitrogen gas (anoxic conditions).

Nitrite oxidising bateria (NOBs) compete with deammonifying bacteria for the nitrite available in the reactor. As the deammonification of nitrite is the preferred process, the growth of NOBs should be repressed. For this reason a low oxygen setpoint is maintained in the system. However, growth of NOBs may still occur at low oxygen levels if the sludge retention time is sufficiently long. A second step to repress growth of NOBs is the application of different sludge retention times (SRT) for NOBs and deammonifying bacteria. As deammonifying bacteria are predominantly aggregated in the heavy granular fraction, a cyclone can be applied for the DEMON process, making use of centrifugal forces to select the appropriate SRT separately for ammonia and nitrite oxidising bacteria on the one hand and deammonifying bacteria on the other hand (Wett, 2010). The sludge recycle flow is fed to the cyclone and the overflow is wasted, while the cyclone underflow showing high deammonifying activity is returned to the reactor.

Startup

The DEMON at Apeldoorn WWTP was started in June 2009. Approximately 60 m³ of seed sludge from Strass WWTP was used as inoculums. Startup was severely hampered by work being done at the dewatering plant that was being refurbished simultaneously. As a result of this work the DEMON reactor was loaded with centrate with large variations in total suspended solids. Peak loads upto 7 g/l have occurred. At the same time the third digester on site was being started. Import of industrial biosolids led to large variations in ammonia concentration in the centrate, upto 3000 mg/l.

Because of these large variations in influent quality it proved difficult to operate the DEMON process under stable conditions. Until November 2009 the DEMON process was frequently bypassed due to unacceptably high solids concentrations in the centrate. In November 2009 the problems at the dewatering plant were resolved and a stable feed for DEMON became available. Within weeks the capacity of the DEMON system was high enough to treat all centrate produced on site. As a consequence dosing of molasses in the main treatment plant could be stopped.

Incidents

During the initial startup period a number of incidents occurred that affected the DEMON process.

Continuous aeration

In July 2009 blowers failed to switch off at the end of the aeration phase. As a result aeration continued for 16 hours, resulting in high oxygen concentrations (3 mg/l) and (probably) high nitrite concentrations.

As the incident happened in a weekend (as usual), no nitrite measurements were made. The system was shut down during the rest of the weekend. On Monday centrate feed was gradually resumed. Theoretically high concentrations of nitrite and oxygen are toxic for deammonifying bacteria (Dapena-Mora, 2007), however no significant decrease in capacity was observed.

Loss of nitrification

In December 2009 a loss of nitrification capacity was observed in the main treatment plant of Apeldoorn, possibly due to a toxic event. In January 2010 a reduction in nitrification capacity was observed in the DEMON process. Extended aeration subsequently led to accumulation of nitrite oxidising bacteria in the reactor, causing a drop in pH and decrease in ammonia removal efficiency. It was decided to waste a significant volume of sludge from the reactor, which temporarily led to a decrease in capacity of the system. Under controlled conditions the nitrification and deammonification capacity was restored within two weeks, effectively repressing nitrite oxidising bacteria.

Phosphate

In 2009 phosphate concentrations in the centrate were very high, upto 300 mg/l. Literature suggests that high concentrations of phosphate will cause inhibition of the deammonification step (Dapena-Mora, 2007)However, no detrimental effect on the performance of the DEMON process was observed. In 2010 chemical precipitation of phosphate in the main treatment plant was applied to mitigate struvite problems. As a result the phosphate concentration in centrate was reduced to 150 mg/l.

Struvite

Due to the formation of struvite the capacity of pumps and pipelines have deteriorated. As a mitigating measure the heat exchanger located in the centrate feed line is now being bypassed, resulting in a significant reduction in pressure loss. Bypassing the heat exchanger has no consequences for the process as the centrate temperature is significantly higher than predicted. The actual centrate temperature is 27 °C, against a predicted temperature range of 15 – 17 °C. As a result of the higher centrate temperature the DEMON operates at a stable temperature of 32 °C without the addition of heat.

Operational experience

The DEMON process at Apeldoorn is designed as a fully automated process. Feed rate to the DEMON reactor is automatically determined on the basis of the level in the centrate buffer tank. Operator intervention is limited to adjustment of setpoints for oxygen, pH and daily volume of waste sludge. No chemicals are being dosed and only three sensors are required to run the process: pH, oxygen and ammonia. As a result only a limited effort is required to operate the system, on average 0.5 – 1 day per week.

However, it is important to regularly monitor the trends of the process and the correct interpretation of these trends requires the expertise of a qualified process engineer. If a process engineer spends 5 minutes on monitoring trends two to three times per week, then process disturbances can de detected and remedied in an early stage, without consequences. Failure to detect process disturbances in an early stage may lead to significant loss in capacity in a later stage, which will then take one to two weeks to recover.

During startup of the DEMON process at Apeldoorn a number of incidents have occurred. Early detection has prevented these incidents from developing into serious problems. No additional seeding with DEMON sludge has been required after the initial startup in June 2009.

Ammonia removal efficiency

Centrate shows large variations in ammonia concentration, which are mainly caused by different batches of third party biosolids being digested. Notwithstanding these variations the DEMON process operates consistently with an ammonia removal efficiency of 88 – 92%. The removal efficiency on the sum of ammonium, nitrite and nitrate is approximately 85 – 86%, mainly due to the presence of nitrate in the effluent. The volume of centrate produced at Apeldoorn WWTP is slightly lower than predicted (800 m³/day against a predicted 1200 m³/day). Due to slightly higher ammonia concentrations than predicted, the average load to the DEMON process is 1200 kg/day $NH_{4,}$ as predicted.

Conclusions

- The DEMON process can be successfully applied for the removal of ammonia from sludge liquors, without the need for an external carbon source or any other chemical.
- The use of a cyclone in the DEMON process allows for different SRTs for different types of bacteria, thus greatly enhancing process stability.
- The DEMON process at Apeldoorn is significantly less vulnerable for high concentrations of nitrite, oxygen or phosphate than generally described in literature.
- Operation of the DEMON process requires limited but regular monitoring by a process engineer, rather than a process operator.

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