Experience from start-ups of the first ANITA Mox Plants
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ABSTRACT

ANITA™ Mox is a new one-stage deammonification Moving-Bed Biofilm Reactor (MBBR) developed for partial nitrification to nitrite and autotrophic N-removal from N-rich effluents. This deammonification process offers many advantages such as dramatically reduced oxygen requirements, no chemical oxygen demand requirement, lower sludge production, no pre-treatment or requirement of chemicals and thereby being an energy and cost efficient nitrogen removal process. An innovative seeding strategy, the ‘BioFarm concept’, has been developed in order to decrease the start-up time of new ANITA Mox installations. New ANITA Mox installations are started with typically 3–15% of the added carriers being from the ‘BioFarm’, with already established anammox biofilm, the rest being new carriers. The first ANITA Mox plant, started up in 2010 at Sjölunda wastewater treatment plant (WWTP) in Malmö, Sweden, proved this seeding concept, reaching an ammonium removal rate of 1.2 kgN/m³ d and approximately 90% ammonia removal within 4 months from start-up. This first ANITA Mox plant is also the BioFarm used for forthcoming installations. Typical features of this first installation were low energy consumption, 1.5 kW/NH₄-N-removed, low N₂O emissions, <1% of the reduced nitrogen and a very stable and robust process towards variations in loads and process conditions. The second ANITA Mox plant, started up at Sundets WWTP in Växjö, Sweden, reached full capacity with more than 90% ammonia removal within 2 months from start-up. By applying a nitrogen loading strategy to the reactor that matches the capacity of the seeding carriers, more than 80% nitrogen removal could be obtained throughout the start-up period.

Key words | anammox, ANITA Mox, deammonification, MBBR, sidestream treatment

INTRODUCTION

With the raising awareness on energy savings, anaerobic sludge digestion is now one of the key processes leading towards energy-neutral or even energy producing wastewater treatment plants (WWTPs). The drawback is the increased ammonium concentration in the sidestream reject water that is recycled to the inlet of the WWTP, which may constitute up to 20–30% of the overall incoming N load. In order to prevent costly extension of the aeration capacity and the size of the aerobic/anoxic tanks, together with increased consumption of expensive external carbon sources, dedicated sidestream treatment processes using autotrophic N-removal through anaerobic ammonium oxidation (anammox) have gained increased popularity and are seen as a long-term solution, especially when considering energy- and cost-effectiveness. Compared to conventional nitrification/denitrification processes, autotrophic N-removal processes (i.e. anammox-type processes) offer many advantages such as (i) 60% reduction of O₂ demand, (ii) no chemical oxygen demand (COD) requirement and (iii) lower sludge production.

Due to the very slow growth rate of anammox bacteria, different biofilm N-removal processes, with or without support material, have been developed as two-stage systems, such as combined SHARON/Anammox-granular processes (Abma et al. 2007) and one-stage systems, also referred to as ‘Deammonification’ processes, such as granular Sequencing Batch Reactors (SBRs) (Wett 2007; Vlaeminck et al. 2008; Vazquez-Padin et al. 2009) or Moving-Bed Biofilm Reactors (MBBRs) (Rosenwinkel & Cornelius 2005; Cema 2009).

The ANITA Mox process is a one-stage MBBR deammonification process where partial nitrification to nitrite by ammonia oxidizing bacteria (AOB) and autotrophic N-removal by anammox bacteria occur simultaneously within the aerobic and anoxic zones of the biofilm, resulting

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from oxygen mass transfer limitation under limited dissolved oxygen (DO) conditions. The biological processes taking place inside the biofilm developed on the plastic carriers are illustrated in Figure 1.

The very slow growth of anammox bacteria and sensitivity towards high concentrations of oxygen, nitrite/free nitrous acid and free ammonia during the start-up phase have been widely reported and therefore limit a widespread application of anammox type processes. To shorten the start-up phase, new ANITA Mox processes are seeded with a small fraction of colonized carriers, which reduce the time required for the development of a mature deammonification biofilm on the brand new carriers. The concept of seeding has proven to dramatically decrease the start-up time from up to a year down to 2–3 months depending on the amount of seeding (Christensson et al. 2011; Lemaire et al. 2011) and are in contradiction with studies by Schneider et al. (2009) reporting that seeding with fully functional deammonification biofilm was not an efficient start-up strategy for MBBR deammonification systems. To meet the request for seeding carriers, the first ANITA Mox full-scale plant at Sjölanda WWTP is used as a nursery for anammox bacteria growing on suspended carriers, referred to as the ‘BioFarm’.

An add-on feature to the ANITA Mox is the real-time DO control strategy, where nitrite production is maximized without nitrite being further oxidized to nitrate. A control loop continuously calculates the amount of NO3-Nprod/without nitrite being further oxidized to nitrate. A control DO control strategy, where nitrite production is maximized growing on suspended carriers, referred to as the lunda WWTP is used as a nursery for anammox bacteria seeding carriers, the

are in contradiction with studies by Schneider et al. (2009). Approximately 60% of the reject water is treated by an existing SBR (1,920 m³) operated in nitritation mode only and the remaining 40% representing around 200 kgN/d is today treated by a full-scale ANITA Mox plant (200 m³).

The Sundet WWTP (80,000 PE) has a total capacity of 5.5 tBOD7/d and a maximum hydraulic capacity of 0.8 m³/s to the biological treatment. Today, only primary sludge and biological sludge are digested in two mesophilic anaerobic digesters, but in the near future, external substrates (food residuals) will be co-digested, hygienized and digested a second time in a newly built digester. After dewatering, all reject water is treated in the ANITA Mox process.

METHODS

Design parameters of full-scale ANITA Mox plants at Sjölanda WWTP and Sundet WWTP

The full-scale plant at Sjölanda WWTP consists of four MBBRs with a total volume of 200 m³. The individual 50 m³ reactors are 6 m high, made of fibre glass, fully covered and insulated and can be operated independently or in series. Biofilm-Chip™ M3 and Anox™ K3 carriers (AnoxKaldnes, Sweden) have so far been used in these MBBRs. NH4, NO3, pH and total suspended solids (TSS) are measured on-line (WTW, Germany) in the reject water feed and inside each reactor. Airflow and DO are also measured and controlled in each reactor. An off-gas online analyser (Horiba, Japan) was used for oxygen transfer trials and determination of potential N2O emission.

The main design and operating parameters of the ANITA Mox reactors are presented in Table 1 and the reject water composition and sludge dewatering operation are detailed in Table 2.

The full-scale plant at Sundet consists of a single 350 m³ covered reactor. It is a refurbished SBR, using the existing fine-bubble aeration system and with two 4 kW STAMO mixers. 45% Anox™ K5 carriers were added to meet the first design phase. NH4 and pH were measured on-line.
(WTW, Germany) in the inlet reject water feed and NH₄⁺, NO₃⁻, pH, DO inside the reactor.

**Analysis**

Mixed liquor samples were filtered at 1.6 μm before analysis for NH₄⁺, NO₃⁻, NO₂⁻ and soluble COD using Dr Lange kits (Hach Lange, Germany). TSS were analysed according to *Standard Methods* (APHA 1995).

**RESULTS AND DISCUSSION**

Due to limitations of seeding media available and in order to optimize the start-up procedure, the four ANITA Mox reactors at Sjölunda WWTP were started up at different times. In 2010 the first 50 m³ ANITA Mox full-scale reactor (MBBR1) was filled with 40% BiofilmChip M (BCM) carriers and seeded with 0.9 m³ pre-colonized carriers with anammox activity corresponding to 3% of the overall volume. After 3 months of operation, effluent NH₄⁺ was typically below 100 mgN-NH₄/L except after occasional incidents of power failure (e.g. day 280), see Figure 2. The nitrate level in the outlet was also on average below 100 mgN-NO₃/L and the ratio NO₃⁻-produced:NH₄-removed was in the range of 8–22% (Figure 2(c)), which is close to the stoichiometric ratio (i.e. 11%) if nitrate was only produced by anammox bacteria with no further oxidation of nitrite into nitrate by the NOB and no reduction of nitrate by heterotrophic denitrifiers. The real-time DO control strategy developed for the ANITA Mox process was very successful in limiting the activity of NOB in the system and therefore ensuring that most of the nitrite produced by the AOB is actually used by the anammox bacteria. The nitrite concentration in the outlet was always very low (i.e. <5 mgN-NO₂/L) although transitory accumulations of nitrite up to 120 mgN-NO₂/L were observed during the start-up period with no real impact on the MBBR performances. The fact that nitrite was barely present in the MBBR indicates that the system was likely NO₂ limited and that the anammox activity was limited by the supply of NO₂ from the AOB.

The N-loading and NH₄⁺-removal rate was increased steadily from the start-up, as shown in Figure 2(b). After only 4 months operation and with only 3% of seeding material, NH₄⁺-removal rate reached 1.2 kgN/m³ react.d (Figure 2(b)) with approximately 90% NH₄⁺ removal...
These performances were obtained (i) without any pre-treatment of the reject water, (ii) without any chemical addition of methanol, acid or base solution, (iii) with no need for mechanical mixers in the MBBR (i.e. continuous aeration strategy sufficient for mixing carriers) and (iv) without any heating system even during the winter months in Sweden. Between operation days 280 and 450 the N-loading and removal rate decreased to 0.70–1.1 kgN/m³d and then increased back to its initial capacity of 1.2 kgNH₄-N/m³d, Figure 2(b). The period with lower N-loading and removal rates coincides with issues with reject water supply but also with the warmer summer months where the process temperature increases from around 27–29 °C up to 33 °C. It seems like the better performances that are observed from operation day 450 are also related to the process temperature returning to below 30 °C from mid-November 2011 (operation day 450). In spite of variation in N-load, the NH₄-removal stayed high, typically >90% for the entire operation period.

Long-term operation of the MBBR1 at Sjölunda WWTP has proven the ANITA Mox to be a robust and stable process towards variations in loads of reject water supply, variations in suspended solids, power failure and pump issues typically encountered at treatment plants and still maintained high ammonium removal capacity. High energy efficiency, with a power consumption of 1.45–1.75 kWh/kgNH₄-N, and low carbon footprint, with average N₂O emissions in the range of 0.2–0.9% of the reduced

**Figure 2** | Performances of the first 50 m³ MBBR filled with 40% BCM since start-up: NH₄, NO₂ and NO₃ measured in inlet and outlet (a); NH₄ loading and removal rates (kgN-NH₄/m³reactor.d) and T °C in the MBBR (b); % TN (total nitrogen) and NH₄ removal and ratio NO₃-produced:NH₄-removed in % (c).
nitrogen, were obtained in MBBR1 making the ANITA Mox a sustainable solution (Christensson et al. 2011).

During 2010–2011 the remaining ANITA Mox reactors at Sjölunda were taken into operation using different carriers and seeding percentage. Figure 3 shows the N-loading and removal rate after the second start-up of MBBR 4 on day 308 when 20 m$^3$ of Anox K5 carriers (i.e. corresponding to 80% of the total media amount in the reactor) were taken out in order to seed the reactor at Sundet WWTP for fast start-up. When 20 m$^3$ of new K5 carriers were added to the remaining 5 m$^3$ of pre-colonized anammox carriers left in the reactor, removal rate reached back to 1 kgN/m$^3$d after only 2 months of operation and is still increasing to more than 1.2 kgN/m$^3$d (Figure 3).

**Performance of ANITA Mox full-scale plant at Sundet WWTP**

The ANITA Mox process was started up at Sundet WWTP by seeding with 20 m$^3$ K5 carriers from the BioFarm on 6th December 2011. The seeding media corresponded to 13% of total carrier filling degree. Since the process was started up during the coldest winter months, the temperature was kept around 28°C by batch wise heating of water when needed during the first month of operation. To promote growth of anammox bacteria the reactor was fed with an amount of reject water corresponding to an ammonium load slightly higher than the capacity of the seeding media. The influent flow was continuously increased and the total amount of reject water was treated in the ANITA Mox process after only 2 months of operation. Influent ammonium concentration to the ANITA Mox reactor varied between 820 and 1,100 mgNH$_4$-N/L. From the first day of operation the effluent NH$_4$-N concentration has always been below 220 mgNH$_4$-N/L with an average NH$_4$-N removal of 88% (Figure 4(a) and (c)). Nitrate concentrations in the MBBR outlet have been in the range of 16–88 mgNO$_3$-N/L which corresponds to a ratio 2–8.2% of produced NO$_3$-N to NH$_4$-N removed (Figure 4(a) and (c)). One nitrite peak, corresponding to 60 mgNO$_2$-N/L has been observed during the operation period, otherwise the effluent NO$_2$-N have an average concentration of 2.9 mgNO$_2$-N/L (Figure 4(a)).

The nitrogen load on the process has increased from 0.01 to 0.83 kgN/m$^3$d, which corresponds to an increasing nitrogen removal from 0 to 0.63 kgN/m$^3$d (Figure 4(b)). An overall nitrogen removal of over 84% has been maintained since the process start-up (Figure 4(c)). Relatively low loading and removal rates in kgN/m$^3$d at Sundet WWTP are explained by the present shortage of reject water supply at the WWTP compared to the design load and are not due to poor process performance as could be seen at the restart of MBBR4 where the seeded carriers originally came from (Figure 3).

N$_2$O measurements performed during 10 d in May 2012 show that the N$_2$O emissions from the ANITA Mox unit at Sundet WWTP correspond to an average of 0.75% of nitrogen removed. The highest N$_2$O emission recorded during the period equals 3.1% of nitrogen removed and N$_2$O in the off gas varied between 0 and 163 ppm. The study shows that the process tends to emit the least N$_2$O during stable operation without any...
disturbances and a DO concentration >1 mgO₂/L. Daily averages show that operation at a DO concentration <1 mgO₂/L can give rise to N₂O emissions corresponding up to 2.15% of nitrogen removed while stable operation with a DO concentration >1 mgO₂/L can allow low daily averages of N₂O emissions down to 0.06% of reduced nitrogen. Figure 5 illustrates emitted N₂O in percentage of nitrogen removed together with effluent NH₄-N, NO₂-N and DO concentrations in mg/L during two 24 h periods from the 23rd to 24th and from the 29th to 30th of May. The graphs of DO and emitted N₂O from the first 24 h period indicate that the aeration of the process is disturbed and that the disturbance occurs more frequently between midnight on the 23rd and noon on the 24th (four times) where N₂O emissions above 1% of reduced nitrogen are measured directly after the unaerated period. The disturbance in aeration occurs less frequently after noon until midnight of the 24th (two times) and Figure 5(a) shows that the N₂O emissions tend to decrease as the process is operated during
longer periods without disturbances; the N$_2$O emissions measured after noon on the 24th have peaks corresponding to 0.8% of nitrogen removed and low concentrations of less than 0.1% are recorded through longer periods. Figure 5(b) shows a 24 h period where aeration of the process is undisturbed and the N$_2$O emissions are low, in the range of 0.04–0.16% of nitrogen removed.

**CONCLUSION**

- The ANITA Mox process is a very robust MBBR deammonification technology to address issues of increasing N-load on WWTP coming from advanced sludge treatment processes while reducing the overall carbon footprint and tending towards energy-sufficiency.
- The specific start-up strategy, where carriers with already colonized anammox biofilm were seeded to the ANITA Mox process, shortened start-up time to 2 months at Sundet WWTP and 4 months at Sjölunda WWTP, reaching a N-removal rate of 1.2 kgN-NH$_4$/m$^3$reactor.d with 90% NH$_4$ removal efficiency.
- Carriers with a very large protected surface area, such as BiofilmChip M and Anox K5, are well suited for deammonification processes as they create a dense and compact biofilm with high anammox activity allowing for smaller reactor design.
- The average N$_2$O-emissions from the ANITA Mox process (i.e. 0.2–0.9% of N-removed) are in the low range of what has been previously reported from different full-scale sidestream anammox processes.

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