ADVANCES IN WASTEWATER TREATMENT – REDUCING ENERGY USE WHILE IMPROVING EFFLUENT QUALITY

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ABSTRACT

In recent years there has been significant research into reducing total nitrogen to meet licenced effluent quality from STP's, with tightened limits progressively being applied. Water authorities are also investigating opportunities to reduce costs by reducing aeration and external carbon requirements, and where possible, redirect carbon to energy generating processes. These strategies are inline and/or directly relevant to industry trends in Asia Pacific, and in particular where tight nutrient criteria are applied, such as the east coast of Australia.

This paper outlines conventional and short-cut nitrogen removal processes, demonstrating the potential reductions in energy use, increases in capacity and improvements in effluent quality that can be achieved. The paper provides an overview of the following nitrogen removal pathways:

- Full Nitrification – Denitrification
- Simultaneous Nitrification Denitrification (SND)
- Nitritation – Denitritation "Nitrite Shunt"
- De-ammonification

As Nitrite is an intermediate step for both Nitrification and Denitrification, if the Nitrification process is stopped at the first Nitrite step, and anoxic conditions presented, the nitrite can be reduced to nitrogen gas. This process is known as Nitritation – Denitritation or Nitrite Shunt, and is considered a 'short cut BNR' process. Simultaneous nitrification / denitrification (SND) may be considered as the partial condition between the conventional full pathway and the Nitrite Shunt pathway. The short cut BNR processes can lead to significant savings for both oxygen and carbon requirements. Recent advancement in the improved understanding of Nitrite Shunt control strategies may allow for reduced energy consumption through advanced aeration control and improved carbon utilisation for denitrification over carbonaceous oxidation.

A further short-cut in the nitrogen removal pathway is available with the aid of Anaerobic Ammonia Oxidising Bacteria (Anammox). Anammox reduce Ammonia and Nitrite to Nitrogen gas, without the requirement for carbon. With only the requirement for oxygen to partially oxidize ammonia to nitrite, there are significant reductions in aeration and carbon requirements, with 60% less oxygen and no carbon required. Anammox bacteria are slow growing, limiting their application in mainstream wastewater treatment until recently to side stream processes only.

These short cut BNR processes provide the opportunity to redirect wastewater carbon to the generation of biogas and energy generation, and minimise aeration energy consumption and costs. The overall outcome is a facility energy balance that is moving

toward energy neutrality or surplus. This is possible whilst achieving enhanced nitrogen removal to maintaining high quality effluent. Mainstream de-ammonification is currently under development by several research groups around the world.

An overview of aeration control strategies to promote SND and Nitrite Shunt, and mainstream deammonification processes is provided.

KEYWORDS

Nutrient Removal, BNR, Aeration, Nitrite Shunt, SND, Mainstream Anammox

PRESENTER PROFILE

Aprilia is a Principal Process Engineer with experience in the planning, design, commissioning and optimisation of sewage treatment plant. In particular, Aprilia has specialised interest in advanced biological nitrogen removal, including 'SND', 'Nitrite Shunt' and Anammox / Mainstream Deammonification processes. Aprilia is currently the Lead Process Engineer for the WTP 160S NRP (140ML/day advanced nitrogen removal plant) and Technical Advisor to the WTP Mainstream Deammonification Pilot Plant trial.

1 INTRODUCTION

In recent years there has been significant research into reducing total nitrogen to meet licenced discharge water quality from STP's. Water authorities are also investigating opportunities to reduce costs by reducing aeration and external carbon requirements, and where possible, redirect carbon to energy generating processes. These strategies are inline and/or directly relevant to industry trends in Asia Pacific, and in particular were tight nutrient criteria are applied, such as the east coast of Australia.

Aeration energy can consume 50 to 60% of energy use at a STP (refer **Figure 1** below).

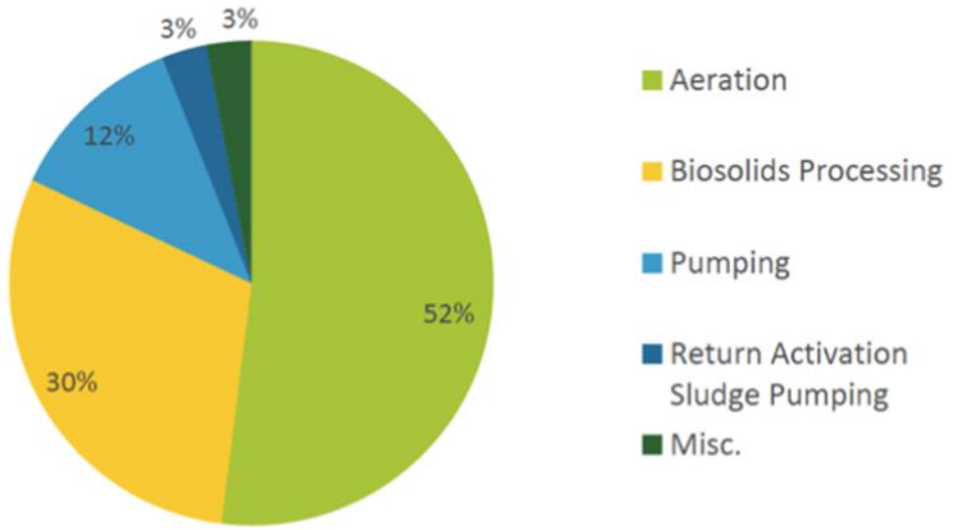


Figure 1 Typical Aeration Use at a Conventional Sewage Treatment Plant

(h 2016)

Wastewater aeration demand is comprised of requirements for:

- Oxidation of carbon

- Nitrification of ammonia
- Mixing requirements

Recent advancement in the improved understanding of Nitrite Shunt processes may allow for reduced energy consumption through more efficient aeration control, and also improved carbon utilisation for denitrification over carbonaceous oxidation.

The paper provides an overview of the following nitrogen removal pathways:

1) Full Nitrification – Denitrification
2) Simultaneous Nitrification Denitrification (SND)
3) Nitritation – Denitritation "Nitrite Shunt"
4) Anammox, Mainstream Deammonification

2 NITROGEN REMOVAL PATHWAYS

2.1 FULL NITRIFICATION – DENITRIFICATION

Nitrogen removal from wastewater in an aerobic/anoxic biological nutrient removal process has historically been undertaken following the full nitrification – denitrification pathway, as shown below in **Figure 2**. This process consumes significant oxygen (and therefore energy to provide the oxygen to the process) and carbon.

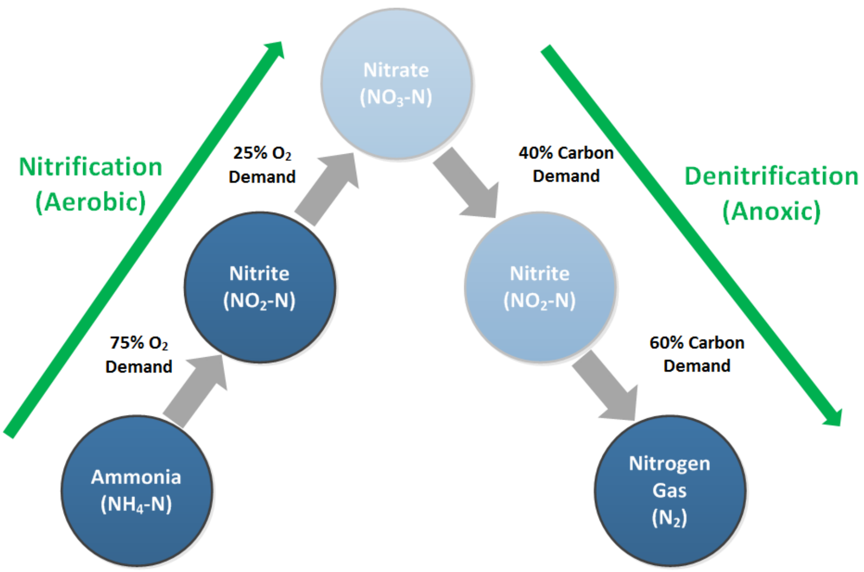


Figure 2: The Nitrification – Denitrification Pathway

Nitrification occurs under aerobic conditions, with autotrophic oxidation of ammonium (NH_4) to nitrate (NO_3), with an intermediate step of nitrite formation (NO_2). Ammonia Oxidising Bacteria (AOB) oxidize Ammonia to Nitrite, and Nitrite Oxidising Bacteria (NOB) oxidise Nitrite to Nitrate. Oxygen is required for both steps.

Denitrification occurs under anoxic conditions, with heterotrophic reduction of Nitrate to Nitrogen gas (N_2) with an organic carbon source. Again, denitrification is a two-step process, where Nitrate is reduced to Nitrite, and then to Nitrogen gas. Carbon is required for both steps.

2.2 SIMULTANEOUS NITRIFICATION DENITRIFICATION (SND)

In STPs where Simultaneous Nitrification Denitrification (SND) activity is promoted, denitrification occurs within the aeration bioreactor (under sequentially varied or low DO conditions), so whilst the full pathway is still followed, there are the following benefits:

a) Reduced TN achieved compared with plants without SND activity (for the same influent C:N ratio) – a greater portion of carbon is utilised for denitrification before it is oxidised
b) Reduced aeration requirements – as carbon is utilised for denitrification rather than oxidised

Prior studies suggest that SND occurs primarily under the following two environmental conditions (Daigger et al.,2007; Littleton et al., 2007):

- Presence of aerobic and anoxic zones within the reactor and,
- Presence of aerobic and anoxic zones within floc particles.

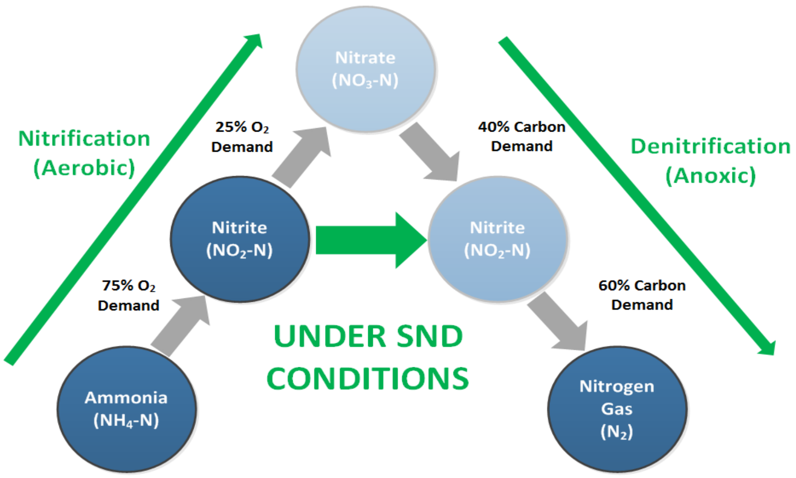


Figure 3 The SND Pathway

While SND provides for improved utilisation of COD and potentially less aeration demand, the conditions may be difficult to control where varying loads and conditions impact the process. SND operation also utilises the full nitrogen removal pathway, hence not providing benefits that may be realised from "Short Cut Nitrogen Removal" processes.

2.3 NITRITATION – DENITRITATION, SND VIA NITRITE, "SHORT CUT NITROGEN REMOVAL", "NITRITE SHUNT"

As Nitrite is an intermediate step for both Nitrification and Denitrification, if the Nitrification process is stopped at the first Nitrite step, and anoxic conditions presented, the nitrite can be reduced to nitrogen gas, as shown in **Figure 3**. This process is known as SND via Nitrite, Nitritation – Denitritation or Nitrite Shunt, and also considered a 'Short Cut nitrogen removal' process. This can lead to significant savings for both oxygen and carbon requirements.

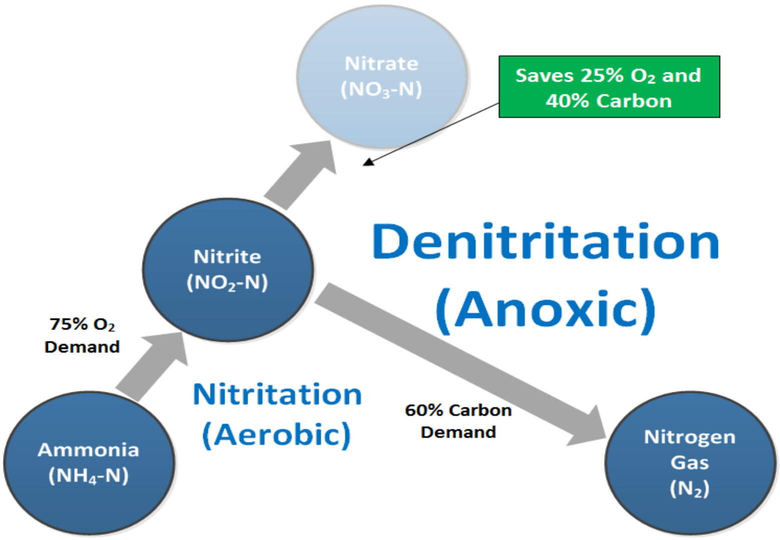


Figure 4 The Nitrite Shunt Pathway

As Nitrite is an intermediate step for both Nitrification and Denitrification, if the Nitrification process is stopped at the first Nitrite step, and anoxic conditions are presented, the nitrite can be reduced to nitrogen gas, as shown in **Figure** *Figure* **4**. This process is known as Nitritation – Denitritation or Nitrite Shunt, and also referred to as "Short Cut Nitrogen Removal". This can lead to significant savings for both oxygen and carbon requirements.

The oxygen and COD demand of conventional and nitrite shunt pathways are shown by the following equations:

- Complete nitrification (NH4+-N => NO3--N) = 4.57 mg O2/mg N
- Partial nitrification or nitritation (NH4+-N => NO2--N) = 3.43 mg O2/mg N
- Denitrification (NO3--N => N2-N) = 2.85 mg O2/mg N
- Denitritation (NO2--N =>N2-N) = 1.71 mg O2/mg N

The oxygen savings associated with partial nitritation are 4.57 to 3.43 = 1.14 mg O2/mg N and COD savings associated with denitritation are 2.85 to 1.71 = 1.14 mg O2/mg N. Subsequently there is no net theoretical oxygen requirement savings with nitrite shunt when sufficient COD is present to convert oxidized N to N2 gas.

However more COD can ultimately be used for denitrification, resulting in less COD oxidation using oxygen that is supplied via aeration, and hence provide a greater N removal potential for the available influent C:N. Further to this, advanced aeration control strategies used to achieve nitrite shunt are intended to reduce over-aeration, increasing oxygen-transfer efficiencies and providing subsequent energy savings. For a specified nitrogen removal requirement where an excess of COD will result, this allows for COD redirection upstream of the reactor, for example by primary settling or high rate carbonaceous A-Stage processes. Reduced COD to the reactor results in less overall aeration demand and the ability to recover a greater percentage of energy via solids digestion, biogas production and cogeneration processes. When the above described benefits are combined in an overall process, it may be possible for some facilities to achieve net energy export.

The carbon requirements for biological nitrogen removal are significantly reduced, as shown above in **Figure 4** (note: saves 40% carbon), with materially lower nitrogen in the treated water being possible for a Nitrite Shunt process compared with conventional (full pathway nitrification-denitrification). This process has a particularly advantage at lower C:N ratios, where denitrification is limited by the availability of carbon.

Nitrite Shunt occurs when Nitrite Oxidising Bacteria (NOB) out selection is achieved, so that the nitrite is not converted to nitrate (as in the full nitrification denitrification pathway), and is therefore available to be converted directly to nitrogen gas.

In a conventional BNR treatment plant, Nitrite is consumed by the NOB as readily as it is produced by the AOB, and typically remainder Ammonia and Nitrate is present in the treated water, not Nitrite. Key to successful implementation of Nitrite Shunt is to provide the required conditions for the out selection of NOBs, and favourable conditions for the preferred growth of Ammonia Oxidising Bacteria (AOB).

The current understanding of factors which affect the out selection of NOBs, and preferential growth of AOBs are as follows:

i. **DO Level:**

'Nitrite Shunt' has been operated successfully in two US plants; at the HRSD pilot plant with high DO levels and where intermittent aeration was key to NOB out-selection, and at the St Petersberg WRF, Florida with continuous operation at low DO levels. At the St Petersberg WRF plant, adaptation of AOB allowed the system to be operated at low DO conditions which allowed heterotrophs to consume nitrite ahead of NOBs, thereby competing for the same substrate for growth. Consequently, NOB out-selection was achieved. Low DO adaptation of AOB might take a longer time but it offers simpler operation and reduced control complexity. There is conflicting literature on the oxygen affinities of AOB and NOB, however it is an important strategy to control NOB out selection in particular.

ii. **Transient Anoxia:**

Transient Anoxia is commonly used to achieve NOB out-selection (Li et al., 2012; Ling, 2009; Pollice et al., 2002; Rosenwinkel et al., 2005; Zekker et al., 2012). Transient anoxia has been a common factor for NOB out selection in mainstream conditions in many recent studies (Regmi et al., 2014). Transient anoxia was one of the key features of the HRSD pilot plants and many others. With intermittent aeration, during the period when air is turned OFF heterotrophs exploit the lag for NOB to consume nitrite, which stalls the NOB growth and aides NOB out selection.

iii. **Residual Ammonia:**

Along with transient ammonia, maintaining residual ammonia has proven effective for NOB out-selection in recent studies in mainstream conditions (Cao et al., 2013; De Clippeleir et al., 2013; Gao et al., 2013; Regmi et al., 2014). The maintenance of residual ammonia allows the AOB growth rate to be close to maximum and therefore AOB grow is at non-limiting substrate conditions. This is key to maintaining high AOB growth rates. Typically, an effluent ammonia of between 1-2 mgNH_4-N/L is considered non-limiting substrate conditions.

iv. Low SRT:

The use of relatively low SRT (close to critical AOB SRT) is a critical step in out-selecting NOB by washing out the NOB population. This provides unfavourable conditions for NOBs but does not adversely affect the AOB population, eliminating NOBs from the system.

v. Inorganic Carbon Limitation Effect on AOB versus NOB:

It has been observed that inorganic carbon limitation appears to provide a selective advantage to the growth of NOB over AOB.

vi. Alkalinity:

When effluent NH_4 and NO_x concentrations are maintained equal, the nitrification and denitrification processes are balanced. This results in alkalinity remaining at a relatively fixed level, thereby avoiding conditions of low alkalinity which could potentially favour NOB growth over AOBs.

vii. FNA Inhibition:

The use of Free Nitrous Acid (FNA) treatment of RAS return streams has been investigated for the ability to assist in out-selection of NOBs, (Wang et al, 2014).

2.4 PARTIAL NITRITATION/ANAMMOX, MAINSTREAM DE-AMMONIFICATION

A further short-cut in the nitrogen removal pathway is available with the aid of Anaerobic Ammonia Oxidising Bacteria (Anammox). Anammox reduce Ammonia and Nitrite to Nitrogen gas, without the requirement for carbon. With only the requirement for oxygen to partially oxidize ammonia to nitrite, there are significant reductions in aeration and carbon requirements, with 60% less oxygen and no carbon required. Anammox bacteria are slow growing, limiting their application in mainstream wastewater treatment until recently to side stream processes only.

This process of partial Nitritation-Anammox is known as De-ammonification, and is shown in **Figure 5**.

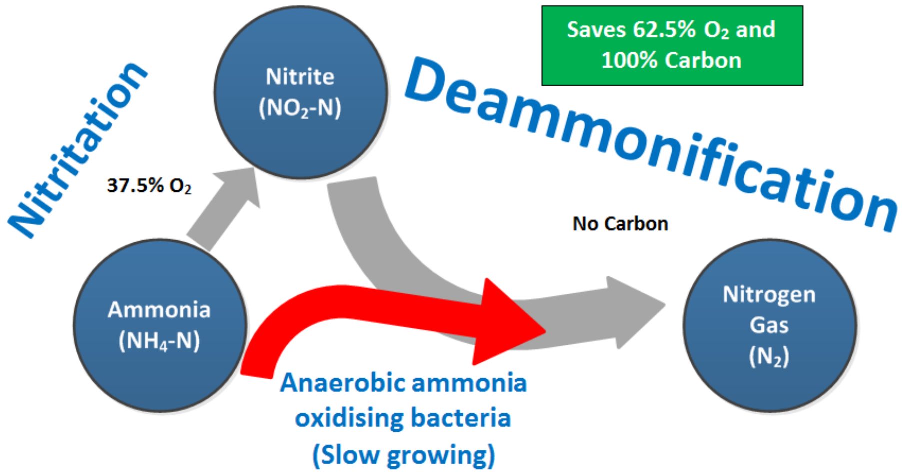


Figure 5: The Partial Nitritation-De-ammonification Pathway

Mainstream de-ammonification provides the opportunity to redirect wastewater carbon to the generation of methane gas, and therefore energy generation, minimising aeration energy consumption and costs. This is possible whilst achieving enhanced TN removal for higher effluent quality. Mainstream de-ammonification is currently under development by several research groups around the world.

A summary of the potential theoretical benefits that apply for the application of Nitrite Shunt and the Partial nitrification – De-ammonification process discussed above are tabulated below:

Table 2.1 Potential Benefits of Ammonia Control Strategies

Pathway	Oxygen[1]	Carbon
Nitrification – Denitrification	100%	100%
Nitrite Shunt	75%	60%
De-ammonification[2]	37.5%	0

Notes:
1) *Oxygen consumption relates to ammonia conversion only, not BOD*
1) *This pathway also has reduced alkalinity requirements.*

(WEF, 2016)

2.5 AERATION CONTROL TO PROMOTE AERATION ENERGY SAVINGS

2.5.1 AMMONIA BASED AERATION CONTROL (ABAC)

For Ammonia Based Aeration Control (ABAC) the DO set points are dependent on the mixed liquor ammonia concentration, allowing for the aeration demand to match the minimum requirements for nitrification.

Depending on the DO set point range selected to achieve the target ammonia concentration, the system can be operated to further reduce aeration requirements through promotion of SND. With minimisation of the aeration DO set points and period of aeration, a maximum anoxic fraction can be achieved, promoting SND.

As acknowledged by Sadowski et al (2015), ABAC is typically applied at STPs to reduce aeration costs, reduce ammonia peaks in the treated water, or both (Rieger et al, 2014). The process involves establishing a target ammonia concentration (usually 1 – 2 mg-N/L) and allowing the control system to vary the dissolved oxygen concentration to meet the ammonia target. As the process operates at lower DO concentrations it increases denitrification performance via simultaneous nitrification and denitrification (SND). This reduces the requirement for external carbon and alkalinity addition (Jimenez et al, 2013).

ABAC has been implemented in full scale process trains, alongside trains operated in conventional DO control at the Nansemond WRF and Henrico WRF in the United States:

- The Nansemond HRSD plant is a 110 ML/d, 7 train, 5-stage Bardenpho process with a large industrial waste contribution. Four of these trains were converted to ABAC control in May 2014 (Uprety et al, 2015). A key objective of the trial was to reduce the supplemental carbon usage, with a 47% average monthly savings achieved. Plant electricity costs decreased 8% during ABAC operational mode. Average kilowatt-hours per month also decreased about 4% during ABAC mode. Aeration savings are based on 4 of the 7 trains being operated in ABAC mode, noting that increased energy savings will occur once blower turndown capability is evaluated and modifications for lower loading conditions are implemented.
- Henrico County WRF is a 285 ML/d plant with a pilot process train in 1 of 8 total trains. The pilot objectives were to reduce supplemental carbon addition and minimise aeration to save energy. During the trial a 40% reduction in carbon was achieved with SND/Ammonia based DO control. (WEF, 2016).

2.5.2 AERATION CONTROL TO PROMOTE PARTIAL NITRITATION IN MAINSTREAM CONDITIONS

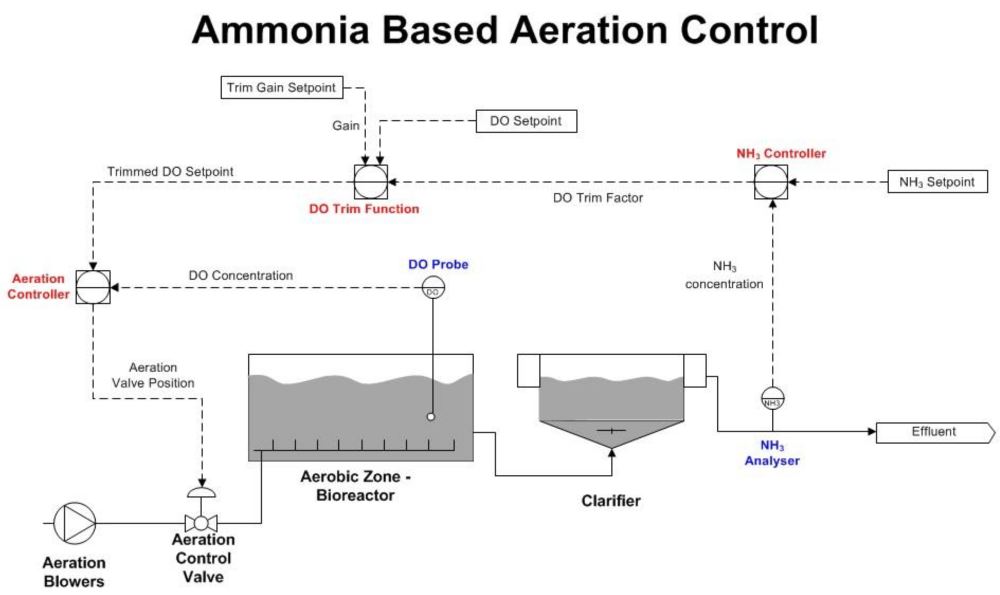
Using DO based control for controlling nitrification extent implies using DO measurement as a surrogate for the ammonia concentration, and proportional nitrification aeration demand. Commonly the DO set point is specified to provide accommodate sufficient airflow under expected reactor conditions, including peak oxygen demand requirements, resulting in over aeration. Alternatively, if the DO set points are reduced to achieve a lesser extent of nitrification, under variable incoming loads this often leads to varied effluent ammonia concentrations and possibly periods of breakthrough. Subsequently, in the case of achieving reliable SND performance or establishing and maintaining nitrite shunt, a more advanced aeration control philosophy is required.

Two such advanced aeration control systems to provide better ammonia removal control, reduced aeration requirements, and enable more efficient COD utilisation for improved TN removal performance are:

- Ammonia Based Aeration Control (ABAC) to promote SND
- Ammonia vs Nitrite (AvN) to promote Nitrite Shunt

Ammonia Based Aeration Control (ABAC) provides for aeration control to the bioreactor to meet a target bioreactor or effluent ammonia concentration. An ammonia analyser measures the ammonia in the target location, of which the online value is compared to an ammonia set point. The aeration system is airflow and distribution is then varied to meet the specific aeration demand to achieve the ammonia set point concentration.

Figure 6 Ammonia Based Aeration Control (ABAC)



Depending on the DO set point range selected to achieve the target ammonia concentration, the system can be operated to further reduce aeration requirements and establish SND conditions. With minimisation of the aeration DO set points and period of aeration, a maximum anoxic fraction can be achieved, promoting SND.

As acknowledged by Sadowski et al (2015), ABAC is typically applied at STPs to reduce aeration costs, reduce ammonia peaks in the treated water, or both (Rieger et al, 2014). Where effluent quality criteria allow higher ammonia residuals, the aeration strategy involves selecting a set point ammonia concentration (usually 1 – 2 mgN/L) and allowing the control system to vary the dissolved oxygen concentration to meet the ammonia target. As the process operates at lower DO concentrations it increases denitrification performance via SND. This also reduces the requirement for external carbon and alkalinity addition (Jimenez et al, 2013).

The Ammonia verses NOx (nitrate + nitrite) AvN aeration controller is regarded as an advanced aeration control specifically developed to enable the promotion of Nitrite Shunt. AvN aeration control promotes conditions for NOB out-selection and therefore Nitrite Shunt, with control of aeration based on specific ammonia, nitrite and nitrate concentrations. The key NOB out-selection factors that the AvN aeration control enables are as follows:

- DO control for transient anoxia, both concentration and/or transient aeration/anoxic periods
- Residual effluent ammonia, providing free ammonia inhibition of NOB

- Residual effluent ammonia, such that AOBs are maintained at maximum growth rate conditions.

With use of the AvN aeration control in combination with an aggressive sludge age to further out select the slower growing NOBs, reliable Nitrite Shunt conditions have been shown to be achievable. Further, the use of Free Nitrous Acid (FNA) treatment of RAS return streams is being investigated as a further means to assist in stronger out-selection of NOBs, (Wang et al, 2014).

Implementation of AvN aeration control has the following significant benefits (Sadowski et al, 2015):

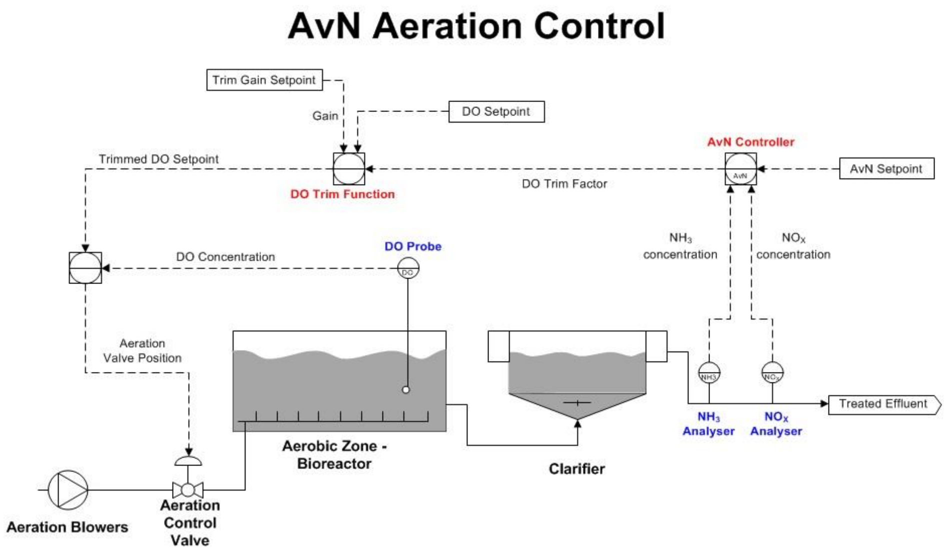
- Reduces energy consumption,

- Achieves the lowest possible effluent TN for a given influent C:N ratio,

- Maximises potential carbon redirection to anaerobic digestion, driving energy neutrality process solutions,

- Conserves alkalinity, reducing the need for supplementary chemical addition.

Figure 7 Ammonia Based Aeration Control



For AvN control, at these equal target ammonia and NOx concentrations, conditions for the out-selection of NOBs occurs, resulting in the development of Nitrite Shunt conditions. There is some evidence in recent application of AvN that indicates the transient anoxia provided by the cycling mode results in better NOB out-selection. At some facilities, aeration cycling may not be practical, requiring continuous aeration AvN strategies. In this case, transient conditions may be provided through anoxic and aerobic sequencing of bioreactors in series.

3 CONCLUSIONS

Advanced aeration operating modes to promote SND through to partial nitritation/Anammox processes to full nitrite shunt provide opportunities to reduce the aeration energy demands for wastewater treatment plants, and reduced supplementary carbon dosing requirements where stringent effluent nitrogen targets are required. Further, when adopted in parallel with carbon redirection strategies, overall facility energy neutrality becomes feasible, whilst maintaining high performance nitrogen removal objectives and also potentially increased biological treatment process capacity.

Further implementation of these nitrogen removal technologies and control strategies are currently being adopted at pilot scale and full scale facilities. Further developments in the understanding and the practical aspects of full scale performance are expected to become available to the community in the future such that the benefits that these technologies bring to wastewater treatment can be fully realised.

ACKNOWLEDGEMENTS

Thank you to my co-author Damien Sharland. We greatly appreciate the support of Jose Jimenez and Pusker Regmi (Brown and Caldwell, USA) for their input and discussion on developing, promoting and modelling SND and short-cut nitrogen processes.

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