### Guideline for granular sludge reactor design

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Abstract

The partial nitritation-anammox pathway is an innovative alternative for nitrogen removal from wastewater compared with conventional nitrification-denitrification over nitrate. Granular sludge reactors are suitable systems to develop partial nitritation-anammox that present several advantages compared with floc-based systems such as lower footprint and higher settleability. A review on granular sludge technology is given to provide a guide for reactor design, focusing on aerobic granular sludge systems to carry out the partial nitritation-anammox pathway. Microbial kinetic factors as well as hydrodynamic and operational parameters involved in aerobic granular sludge systems are described. Fundamentals of sequencing batch reactor design for aerobic granular systems are provided and modelling is put forward as a useful tool for biofilm system design. The outcome of the review shows that an appropriate selection pressure is essential to develop proper granules, mainly short sludge settling times and relatively high shear stress. Sequencing batch reactors are appropriate systems to develop granules since their operational flexibility allows establishing suitable selection pressures. Modelling granular sludge has to take into account physical-chemical and biological aspects. Modelling granular sludge partial nitritation-anammox systems allows the assessment of important parameters that influence the reactor design and operation. Granule size and oxygen concentration are key factors for granular sludge partial nitritation-anammox reactor design.

**Keywords:** anammox, control, granular sludge, modelling, partial nitritation, reactor design
1. INTRODUCTION

1.1. Biological nitrogen removal from wastewater

Due to the potential problems that nitrogen compounds can cause in natural resources, effective nitrogen removal in wastewater treatment plants is required. High concentrations of ammonium, nitrite and nitrate are toxic for life. Free ammonia can cause severe problems in aquatic life such as fish mortality or impacts on reproduction. Moreover, an excess of nitrogen and phosphorus enhances the eutrophication in water bodies. These nutrients stimulate an excessive algae growth and these algal blooms impede the penetration of sunlight with the subsequent death of the aquatic flora. The death plants promote a depletion of oxygen, which is highly necessary for aquatic life and its lack can hamper the development of the ecosystem and also cause bad odours.

Nitrogen in wastewater is present mostly in the form of ammonium. Its biological removal implies a series of reactions performed by different bacteria to obtain nitrogen gas, which is innocuous to the environment. The conventional strategy to remove ammonium from wastewater is based on the nitrification-denitrification over nitrate pathway. In the last decade, an innovative method that allows important savings in energy and carbon source was and is being developed and implemented: the coupling of a partial nitrification and the anammox reaction.

An overview of these biological nitrogen removal pathways is given below.

- Nitrification-denitrification

The most common strategy to remove ammonium from wastewater is nitrification-denitrification over nitrate. Nitrification concerns the oxidation of ammonium to nitrite (nitritation) and then to nitrate (nitratation) under aerobic conditions. First, ammonium is aerobically converted to nitrite by ammonium oxidizing bacteria (AOB) (Eq. 1) and further, nitrite is oxidized to nitrate by nitrite oxidizing bacteria (NOB) (Eq. 2).

\[
\text{NH}_4^+ + 1.5 \text{O}_2 \rightarrow \text{NO}_2^- + \text{H}_2\text{O} + 2\text{H}^+ \quad [1]
\]

\[
\text{NO}_2^- + 0.5 \text{O}_2 \rightarrow \text{NO}_3^- \quad [2]
\]

Both AOB and NOB are chemolithoautotrophic microorganisms. These bacteria use inorganic compounds as electron donor and their carbon source is carbon dioxide, or in practice, bicarbonate.

During denitrification, nitrate and/or nitrite is reduced to nitrogen gas by heterotrophic microorganisms under anoxic conditions. This transformation implies several subsequent reduction steps (Eq. 3).
The electron donor in these reactions is a carbon source, that normally has to be added to the wastewater (usually methanol or ethanol), while the nitrogen compounds act as electron acceptors.

- **Partial nitritation-anammox**

The partial nitritation-anammox pathway constitutes a more sustainable alternative for nitrogen removal from wastewater than the conventional nitrification-denitrification over nitrate.

Partial nitrification is the oxidation of ammonium only to nitrite (nitritation) (Eq. 1). Further oxidation to nitrate can be avoided by imposing limited oxygen concentrations, taking advantage of the higher oxygen affinity of ammonium oxidizers compared to nitrite oxidizers (Garrido et al., 1997). Temperature and sludge retention time (SRT) can also be used to promote the partial nitrification. Ammonium oxidation has higher activation energy than the oxidation of nitrite. Therefore, working at relative higher temperatures (above 25 °C) would allow the removal of NOB, which would grow slower than AOB (Hellinga et al., 1998).

The anammox process is a shortcut in the nitrogen cycle where ammonium is combined with nitrite to yield nitrogen gas in the absence of carbon source (Strous et al., 1998). Anammox bacteria are autotrophic microorganisms belong to the genus *Planomycetes*. They have a slow growth rate and productivity and their optimal temperature of operation is 35 °C and pH 8. The research on anammox technology started two decades ago. Enrichments at lab-scale were realized by Strous et al. (1999) and Van de Graaf et al. (1996). About 10 years later, the technology would be successfully implemented at full-scale in the wastewater treatment plant of Rotterdam, The Netherlands (van der Star et al., 2007).

During partial nitrification half of the ammonium in wastewater is oxidized to nitrite. This reaction can be followed by the anammox conversion under anoxic conditions, in which about equimolar amounts of ammonium and nitrite are converted to nitrogen gas (Eq. 4). This is the reaction between the nitrite formed during the partial nitritation and the remaining ammonium that was not converted.

\[
\text{NH}_4^+ + \text{NO}_2^- \rightarrow \text{N}_2 + 2\text{H}_2\text{O} \quad [4]
\]

Compared with conventional nitrification-denitrification for nitrogen removal, the partial nitritation-anammox pathway, also termed completely autotrophic nitrogen removal, requires up to 62.5% less oxygen. This implies important saving in aeration, one of the main costs in wastewater treatment plants. Moreover, since the whole process is autotrophic, organic carbon is not required, which means 100% savings in carbon source addition. Also, due to the
autotrophic reactions CO₂ emissions are minimal. Furthermore, owing to slow anammox growth rate, the sludge production is expected to be lower.

Biofilm reactors are suitable systems to carry out partial nitritation-anammox pathway. Granular sludge can be used to develop partial nitritation-anammox systems. The following section will have a look to granular sludge technology and also will go with more detail into the application of granular sludge to perform partial nitritation-anammox process.

1.2. Granular sludge

Granular sludge is a special type of biofilm in which biomass grows in compact aggregates (granules) without any carrier material. Granular sludge technology started to be developed about 40 years ago at Wageningen University. At that time, granules were implemented for anaerobic treatment in upflow anaerobic sludge bed (UASB) reactors (Lettinga et al., 1983).

- Why granular sludge technology?

Compared to biomass growing in flocs, granular biomass presents several advantages that make it very attractive for wastewater treatment purposes. Granules are denser and have a stronger microbial structure than flocs. Thus, granular biomass has very high settling velocity, while the typical settling velocity for flocs is at least three times lower. These excellent settling properties allow the use of high hydraulic loads to the reactors without the wash out of the biomass. Besides, more compact clarifiers can be used or in some cases, an extra unit is not required to separate the biomass. This implies a lower footprint and important savings in construction. The high biomass retention also enables to enhance the performance of the reactor and a faster removal of the different contaminants.

From a microbiological point of view, granules consist of different layers where diverse microorganisms can be present as well as different reactions can take place. In conventional wastewater treatment plants with biomass growing in flocs, different units and recycling are required to perform the aerobic and anaerobic conversions. However, in granular sludge, anaerobic and aerobic reactions can occur at the same granule, since the stratification allows different conditions along the biomass. For instance, in an aerobic system, the outer part of the granule, where oxygen is available, nitrifiers can grow, while in the inner part, denitrifiers, anammox bacteria or phosphate accumulating organisms (PAOs) can develop themselves under anaerobic and anoxic conditions. Figure 1 shows the differences in the structure of a floc and an aerobic granule.
Taking advantage of the stratification of the biomass in granular sludge, completely nitrogen removal is feasible in one unit as for example in the CANON reactor operated at the Olburgen sewage treatment plant in The Netherlands (Abma et al., 2010) or more ambitious, the simultaneous removal of organic matter and nutrients in one unit, as it was demonstrated with the Nereda technology applied in a full-scale plant in The Netherlands (van der Roest et al., 2011).

By applying granular sludge technology, important savings in space and energy can be achieved, leading to a more cost-effective wastewater treatment plant.

- **Anaerobic and aerobic granular sludge**

  Anaerobic granular sludge technology has been extensively studied and is widely applied in wastewater treatment plants to remove biodegradable organic matter. The aggregation and interaction of many microorganisms such as methanogenic bacteria and acetogens growing in anaerobic granules allow the conversion of organic matter to CO$_2$, CH$_4$, fatty acids and H$_2$. UASB reactor has been and is the most usual reactor configuration to grow anaerobic granules for COD removal. Many modifications and improvements have been developed in UASB reactor to enhance their efficiency.

  Disadvantages of anaerobic granulation include the long start-up time and the relative high operation temperature needed. Moreover, this technology only established for COD removal – no nutrient removal – and is not suitable for the treatment of low-strength organic wastewater and cannot remove nutrients.

  These drawbacks are overcome through aerobic granulation technology. Mishima and Nakamura (1991) established aerobic granules in an upflow sludge blanket reactor. The technology was further developed in sequencing batch reactors (SBRs) (van Loosdrecht and Heijnen, 1993; Morgenroth et al. 1997; Beun et al., 1999; Tay et al., 2002a).
- **Heterotrophic granules**

The application of aerobic granular technology to wastewater treatment allows removing organic matter, nutrients and toxic substances. The so-called Nereda technology is based on aerobic heterotrophic granules that are able to remove simultaneously COD, nitrogen and phosphorus in one unit (de Kreuk et al., 2005). This technology was implemented successfully at full-scale in Epe, The Netherlands in 2011 (van der Roest et al., 2011). The technology is based on SBR mode operation with cycles of feeding under anaerobic conditions followed by two aeration periods, a settling period and an effluent discharge. The influent is fed from the bottom of the reactor in a plug-flow regime with the subsequent effluent withdrawal. Anaerobic feeding is used to obtain high concentrations of organic carbon and to grow PAOs. During the aeration period heterotrophs grow and PAOs take up phosphate. Regarding ammonium, this is oxidized to nitrite and nitrate in the aerobic outer layer of the granules, while denitrification takes place in the anoxic inner zone of the granules by PAOs, which use stored PHB as electron donor to reduce the nitrate.

- **Autotrophic granules**

Complete autotrophic nitrogen removal can be carried out in granules using anammox bacteria. The process can be developed in two reactor units, one to oxidize part of the ammonium to nitrite in aerobic conditions and a subsequent reactor where anammox bacteria grow in anaerobic granules, as in the SHARON-anammox configuration (Van Dongen et al., 2001). Alternatively, complete autotrophic nitrogen removal can be developed in a single reactor unit containing aerobic granules. In this case, limited oxygen conditions have to be established to enable the coexistence of ammonium oxidizing bacteria (AOB) and anammox bacteria at the same granule. More specifically, AOB grow in the outer part of the granules, while anammox bacteria develop inside of the granules, where anoxic conditions are present, since anammox reaction is inhibited by oxygen (Strous et al., 1997). Figure 2 shows a representation of a granule that develop partial nitritation-anammox pathway.

![Figure 2. Partial nitritation-anammox in a granule](image)

Nowadays, the anammox process developed in granules is already implemented at full-scale to treat reject water with high ammonium concentrations, both in two-reactor configurations (Van der Star et al., 2007) and in a single reactor (Abma et al., 2010). This
process further fits in innovative process schemes for energy-efficient treatment of municipal wastewater (Kartal et al., 2010).

2. DEVELOPING AEROBIC GRANULES

Several factors influence the formation, structure and developing of aerobic granular sludge. Aerobic granule formation depends on microbial aspects as well as hydraulic and operational conditions. As it was proposed by van Loosdrecht et al. (1995), the biofilm structure is the result of a balance between the biomass surface production rate (growth) and detachment. In general, aerobic granulation is a complex reaction process that has not been well established yet and that requires more research to overcome the limitations for industrial and wastewater treatment application.

This section shows an approximation of the mechanisms and factors involved in the formation of aerobic granular sludge as well as the different parameters that affect the development and structure of aerobic granules.

2.1. How to start granulation?

Microbial aspects have to be taken into account to answer this question. Many microorganisms are present in the aerobic sludge of a wastewater. Filamentous bacteria can hinder the compaction of the sludge, decrease the settleability of this and promote the bulking of the biomass. To develop a granular sludge system, filamentous bacteria need to be avoided. The kinetic selection theory (Chudoba et al., 1973) proposes a selective method for biomass based on the substrate uptake rate of the microorganisms in aerated systems. High macro-gradients of substrate along the system would prevent the growth of filamentous bacteria while improving the development of floc-forming microorganisms, with good settling properties and which would be the precursors in the formation of granules (Figure 3). Systems that provide low substrate concentrations such as continuously fed completely mixed reactors enhance the dominance of filamentous microorganisms. However, plug-flow reactors or SBR allow having high substrate concentrations, which improves the growth of good settling sludge.

The alternation of feast and famine conditions presents competitive advantages for the selection of bacteria that form granules capable of combined COD, N- and P-removal. Recall that these bacteria are favoured by high substrate concentrations, being able to accumulate polyhydroxyalkanoate (PHA) during these “feast” periods and to consume the storage material during the periods without substrate. The filamentous bacteria can only be competitive during low substrate concentrations and therefore the feast and famine cycle benefits the selection of granule-former organisms.
For the stability and cohesion of the aggregates, extracellular polymer substances (EPS) play an important role. EPS can be polysaccharides, proteins, nucleic acids, phospholipids or humic substances. They participate in the stability of granules through London forces (hydrophobic character of proteins), electrostatic interactions (Ca$^{2+}$ ions) and hydrogen bonds (hydroxyl groups -hydrophilic polysaccharides- and water). Hydrophobic bacteria in the seed sludge also contribute to the faster growth of aerobic granules providing stability (Wilen et al., 2008).

2.2. Hydraulic and operational factors during granulation

Apart from the abovementioned microbial factors and chemical aspects in the stability of granule formation, the selection of appropriate hydraulic and operational pressures on different parameters such as shear stress, organic loading rate (OLR) or sludge settling time are highly important for the development and formation of good aerobic granular sludge. The most important influencing factors are detailed in the next subsections.

- **Substrate composition and organic loading rate (OLR)**

Aerobic granular sludge can be developed on various organic substrates such as glucose and acetate (Tay et al., 2002b) as well as on real wastewater (Arrojo et al., 2004). Low organic loading rates promote the formation of small and compact granules. In contrast, high organic loading rates enhance the formation of large but flyaway granules. Very high organic loading rate can lead the disintegration and breakdown of the granules (Tay et al., 2004; Adav et al., 2010).

- **Hydraulic shear stress**

The shear stress exerted on the granules is an important factor in the formation and structure of the granules. The shear forces depend on the surficial gas velocity in the reactor and influence the sludge settling velocity and the diameter of the granules. The higher the surficial gas velocity, the higher the stress forces on the granules, yielding denser and more compact...
granules, resulting in an improved sludge settling velocity. However, when the shear stress is too high, the granules are subject to disintegration. At low surface gas velocities, small granules could be formed, but microscopic observation showed the growth of filamentous bacteria and the appearance of flocs (Zhu et al., 2013). Shear stress due to collisions with the mechanical parts of the reactor and between particles may be considered as well.

In general, the shear forces in an aerobic granular sludge system need to be balanced to avoid the breakdown of the granules (too high shear stress) on the one hand and to allow and enhance the formation and good properties of the granules (above of a threshold shear stress) on the other hand.

- **Sludge settling time**

Various studies have reported the sludge settling time as one of the most important parameters to grow and select aerobic granules (Beun et al., 1999; Beun et al., 2002; Qin et al., 2004). Long sludge settling times allow a lower settling velocity of the sludge, which is reflected in a lower sludge volume index (SVI). Reducing the sludge settling time, more compact granules are formed and the sludge with bad settling properties is washed out. More suspended sludge is left over when applying long settling times. Thus, aerobic sludge granulation is favoured by imposing short settling times.

- **Hydraulic retention time (HRT)**

Short HRTs enhance the wash-out of suspended biomass and decrease its growth, improving the granulation in the system (Beun et al., 1999). The cycle time a SBR can be used as a hydraulic selection pressure. For instance, with short cycle times, nitrifying sludge would be washed out.

### 3. SBR REACTOR DESIGN

Sequencing batch reactor (SBR) is one of the most common reactors to develop aerobic granules. Its flexibility allows the change of parameters and the modification of the operation easily. Regarding granule development, SBRs are suitable to establish the feast and famine cycle, to select the granules by setting short sludge settling times and also to modify other parameters such as the HRT or the substrate loading rate as in other reactor configurations. In general, systems with intermittent operation were found more favourable to develop aerobic granular sludge than continuous reactors (Beun et al., 2002). Moreover, these authors found that the performance of the feeding as pulses allows larger substrate penetrations into the granules compared with systems based on continuous feeding, which also benefits the granulation.
3.1. SBR operation

Figure 4 shows the cycle operation of a SBR. The different steps can vary in function of the function and operation conditions of the reactor. For instance, the feeding can be added in pulses or in continuous at the same time that the reaction takes place. For granular sludge, short feeding times are preferable.

3.2. Fundamental design parameters

A basic guideline is given in this section for the geometric and operational design of an aerobic SBR. Design parameters are selected (Table 1) and then some steps and calculations can be done to obtain a first approach of the SBR design.

Table 1. Parameters for SBR design

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Units</th>
<th>Description</th>
<th>Calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>V_R</td>
<td>m^3</td>
<td>Total volume of the reactor</td>
<td>V_0 + V_f</td>
</tr>
<tr>
<td>V_f</td>
<td>m^3</td>
<td>Volume fed (water)</td>
<td>-</td>
</tr>
<tr>
<td>V_o</td>
<td>m^3</td>
<td>Volume that remains from the previous cycle (water + sludge)</td>
<td>-</td>
</tr>
<tr>
<td>V_m</td>
<td>m^3</td>
<td>Volume purged (sludge)</td>
<td>-</td>
</tr>
<tr>
<td>V_d</td>
<td>m^3</td>
<td>Volume decanted (water)</td>
<td>-</td>
</tr>
<tr>
<td>t_c</td>
<td>min</td>
<td>Total time of the cycle</td>
<td>∑t_i</td>
</tr>
<tr>
<td>t_i</td>
<td>min</td>
<td>Time of each phase</td>
<td>-</td>
</tr>
<tr>
<td>FTR</td>
<td>-</td>
<td>Feeding time ratio</td>
<td>t_f / t_c</td>
</tr>
<tr>
<td>VER</td>
<td>-</td>
<td>Volumetric exchange ratio</td>
<td>V_f / V_R</td>
</tr>
<tr>
<td>HRT</td>
<td>h</td>
<td>Hydraulic retention time</td>
<td>V_d / Q</td>
</tr>
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</table>

* t_i: t_f (feeding time), t_a (active time, for the reaction), t_s (settling time), t_d (decanting time)

The steps in the design of SBR are listed below:

1. Sludge retention time (SRT)

\[
SRT = \frac{X_R}{X_{eff}} \times HRT
\]
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\[ HRT = \frac{V_R}{Q} = \frac{t_c}{VER} \]  

2. Effective fraction of the cycle (EFC)

\[ EFC = \frac{t_c - t_a - t_d - t_a}{t_c} \]  

3. Total sludge mass (\(M_X\))

\[ M_X = Y_{iH} Q \cdot \Delta C_S \cdot HRT \cdot \frac{1}{EFC} \]  

Where \(\Delta C_S\) is the difference between the substrate concentration in the influent and in the effluent. Depending on the purpose, the substrate can be COD, nitrogen, etc.

4. Volume of the settled sludge (\(V_0\))

\[ V_0 = M_X \cdot SVI \cdot SFV \]  

Where SVI is the sludge volume index and SFV is a safe factor for design (around 25%).

5. Select the VER or \(t_c\)

A good starting point is \(VER=0.5\)

6. If VER is chosen, calculate \(t_c\)

\[ t_c = \frac{V_0 \cdot VER}{Q(1 - VER)} \]  

7. Exchange volume of the reactor (VER)

8. Total volume of the reactor

9. Choose the number of reactors required

10. Check the values of \(t_s\) and \(t_d\)

11. Determine the geometry of the reactor

4. MODELLING BIOФILM SYSTEMS

Mathematical modelling is a useful tool to design and optimize systems, to acquire knowledge and predict the behaviour of processes. Biofilm modelling is a complex task that involves a wide number of parameters. When modelling granules, reaction kinetics and physicochemical aspects may be addressed simultaneously.
4.1. Models for biofilm and granular sludge systems

Two different situations can be considered when modelling biofilms: the granulation phase and the mature system (also dynamic scenario). Granulation modelling involves granule size variation, selection of pressures to develop the granules (see section 2) and biological aspects as well. Facing modelling of granular systems implies to consider physicochemical processes, such as mass transfer of substrates, products and oxygen (aerobic systems) or detachment of the biofilm. Also, biological conversions have to be considered, which will depend on the processes occurring in the biofilm. In general, a model should be as simple as possible. It should just try to meet the objective for which was required.

<table>
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<th>Description</th>
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<th>Model information</th>
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<tr>
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<td>Granular</td>
<td>1-d model</td>
<td>Beun et al. (2001)</td>
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<td>Sensitive analysis of CANON process</td>
<td>Biofilm</td>
<td>modification ASM3</td>
<td>Hao et al. (2002a)</td>
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<td>Influence of temperature and inflow variations in partial nitrification-anammox</td>
<td>Biofilm</td>
<td>modification ASM3</td>
<td>Hao et al. (2002b)</td>
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<tr>
<td>COD on partial nitritation-anammox</td>
<td>Biofilm</td>
<td>modification ASM3</td>
<td>Hao et al. (2004)</td>
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<td>Oxygen consumption in partial nitrification-anammox</td>
<td>Biofilm</td>
<td>modification ASM3</td>
<td>Hao et al. (2005)</td>
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<td>Study of bacterial community structure of nitrifying granules</td>
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<td>1-d and 2-d models</td>
<td>Matsumoto et al. (2010)</td>
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<tr>
<td>Heterotrophic and autotrophic granules</td>
<td>Granular</td>
<td>modification ASM3</td>
<td>Ni et al. (2007)</td>
</tr>
<tr>
<td>Anammox reactor</td>
<td>Granular</td>
<td>modification ASM1</td>
<td>Ni et al. (2009a)</td>
</tr>
<tr>
<td>Aerobic granulation of activated sludge with low-strength municipal wastewater</td>
<td>Granular</td>
<td>modification ASM3</td>
<td>Ni et al. (2009b)</td>
</tr>
<tr>
<td>Multi-population biofilm for completely autotrophic nitrogen removal</td>
<td>Biofilm</td>
<td>1-d model</td>
<td>Terada et al. (2006)</td>
</tr>
<tr>
<td>Granule size in partial nitritation-anammox granules</td>
<td>Granular</td>
<td>1-d model</td>
<td>Volcke et al. (2010)</td>
</tr>
<tr>
<td>Granule size distribution in an anammox-based granular sludge reactor</td>
<td>Granular</td>
<td>1-d model</td>
<td>Volcke et al. (2012)</td>
</tr>
</tbody>
</table>

The existing ASM models proposed by the International Water Association (IWA) for floc-based systems can be used as a starting point in granular sludge systems to describe the biological conversions. However, the aggregation in granules creates substantial differences since there is a separation between the bulk liquid and the granules. Concentration gradients of substrates are present in the biological phase, which are influence by diffusion coefficients, conversion rates, granule size, density, porosity, etc. To describe the processes inside the granules, ASM models are not enough. Wang and Zhang (2010) give a review of different mathematical models to face the dynamics of biofilm systems. One-dimensional or multidimensional models can be used, depending on the simplicity of the model. Beun et al.
(2001) describe the simultaneous removal of COD and nitrogen in one dimensional model. Multidimensional modelling of biofilms is showed by Xavier et al (2005). In particular, for granular sludge models, discrete particle models should be used instead of continuous. Table 2 shows some examples of models developed for biofilm systems and some in particular for granular sludge.

Granular sludge models can be implemented in different software. MATLAB allows to develop the whole model by introducing all the equations and parameters. The program AQUASIM simplifies the modelling since it has systems already implemented.

4.2. Controlling partial nitritation-anammox in granular sludge reactors

Partial nitritation-anammox (section 1.1) can be developed in granular sludge by growing granules where AOB and anammox bacteria coexist (section 1.2). This section will describe some aspects related to operation and control of granular systems performing partial-nitritation anammox in one stage.

- Control through low oxygen concentration

Good performance of a partial nitritation-anammox system depends on the suppression of NOB. Partial nitritation-anammox is only achieved when NOB are outcompeted by anammox bacteria. Controlling the oxygen concentration in the bulk liquid can be used to meet this purpose. Ammonium oxidizers have a higher oxygen affinity than nitrite oxidizers, thus limiting the oxygen concentration helps in developing AOB and avoiding the growth of NOB. Modelling studies confirm this fact (Volcke et al., 2010). Also, full-scale implementations of partial nitritation-anammox in one stage were reached by controlling the aeration and keeping low oxygen concentrations inside the reactor, as in the CANON reactor at the Olburgen sewage treatment plant in The Netherlands (Abma et al., 2010).

- Granule size

The granule size is determined by a balance between growth and detachment. Volcke et al. (2010) carried out a modelling study assessing the influence of granule size in reactors performing partial nitritation-anammox with biomass growing in granules. When the particle size increases, higher oxygen concentrations are required to achieve complete ammonium removal. Besides, the larger the granules, the lower the aerobic fraction in the granules, resulting in a relatively higher anammox activity. This outcome was also observed by Volcke et al. (2012). Higher nitrogen gas production is obtained with simulation studies with larger granules due to the improvement of anammox activity, while nitrite or nitrate are accumulated in systems with smaller granules. These results are in agreement with the findings obtained in experimental studies performed by Vlaeminck et al. (2010). Winkler et al. (2011) also found the presence of NOB in smaller granules, while anammox bacteria govern big granules. The increased ammonium surface load owing larger granules is linked with these
results. Higher ammonium surface load results in smaller oxygen penetration depth and as a consequence less aerobic fraction and more anoxic part for anammox bacteria is feasible. Furthermore, the oxygen concentration range in the bulk liquid to obtain good anammox conversion is higher with bigger granules. In general, systems with large granules are less sensitive to changes in the bulk oxygen concentration, giving easier systems for controlling.

5. CONCLUSIONS
- Granular sludge reactors are suitable systems for biological nitrogen removal from wastewater through the innovative partial nitritation-anammox pathway, i.e. completely autotrophic nitrogen removal. This pathway involves important savings in aeration energy, external carbon source addition and sludge handling costs compared to conventional nitrification-denitrification over nitrate, at the same time showing low CO$_2$-emissions.
- The granular sludge technology presents important advantages compared with floc-based systems. It allows a lower plant footprint and thus results in more cost-effective wastewater treatment plants.
- Appropriate operational pressures are required to develop good aerobic granular sludge systems. In general, low organic loading rates, relatively high shear forces, short sludge settling time and hydraulic retention times lead to good granulation.
- Sequencing batch reactors are suitable units to develop aerobic granular sludge, in particular in view of combined COD, N and P removal. Their operational flexibility allows parameter modification easily and the establishment of appropriate selection pressures to develop aerobic granules.
- Modelling is a useful tool for granular sludge reactor design. It allows investigating the combined effect of physicochemical parameters (diffusion coefficients, granule size, among others) and biological reactions, which results in complex systems.
- Controlling the aeration rate and/or the dissolved oxygen concentration is essential to establish partial nitritation and anammox reaction in one unit. The granule size and the granule size distribution also constitute important parameters in the design of granular sludge reactors for partial nitritation - anammox. In general, low dissolved oxygen concentrations need to be imposed to achieve partial nitritation-anammox in a one-stage granular sludge reactor, while the granules should be large enough to allow the growth of anammox bacteria, but not too large to prevent large inactive zones.
REFERENCES


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