Aerobic granular sludge

In recent years, a significant part of research on wastewater treatment has focussed on development of compact systems. Wastewater treatment plants (WWTP) can be designed compact when biomass is maintained in the system without the use of conventional settling tanks as in flocculated activated sludge systems. Examples are developments in the field of Membrane Bio-Reactors, Biological Aerated Filters and other biofilm systems. For conventional biofilm technology the surface area of the biofilms, needed for mass transfer and therefore the conversion processes, is limited by the reactor surface the biomass can attach to. When biofilms are grown in a granular shape, the maximum surface area per volume of reactor can be obtained. Most compact systems for the treatment of municipal sewage are based on continuously operated reactors.

In this kind of continuously operated systems, it was possible to grow granular sludge with slowly biodegradable substrates (e.g. methanol or ammonia). In the case of easily biodegradable substrates, these systems can only be used when enough basalt was added to the system (as carrier material and for shear reasons, Kwok et al., 1998).

Research concerning the formation of storage polymers (Van Loosdrecht *et al.*, 1997; Krishna and van Loosdrecht, 1999) finally resulted in the idea of growing aerobic granules without carrier material on readily biodegradable substrates in a Sequencing Batch Reactor (Morgenroth *et al.*, 1997; Beun *et al.*, 1999; Dangcong *et al.*, 1999). The conversion of readily biodegradable COD into a substrate yielding a lower maximal growth rate facilitated granule formation. In 1998, an international patent was submitted and granted (Heijnen and Van Loosdrecht, 1998). An extension of this first patent was submitted in 2004, including the description of anaerobic feeding (Van Loosdrecht and De Kreuk, 2004).

This chapter will form a short introduction of aerobic granular sludge and its development from an idea in the lab to a technology that is ready for practical applications. From the first observation of aerobic granules in a sequencing batch reactor (SBR) in 1997 till now, many studies were published. From the year 2000, aerobic granule formation has been excessively studied worldwide (Figure 1). Some of the basic knowledge of aerobic granule formation and the development to full-scale applications within a relatively short period will be described here, as a starting point for further reading.

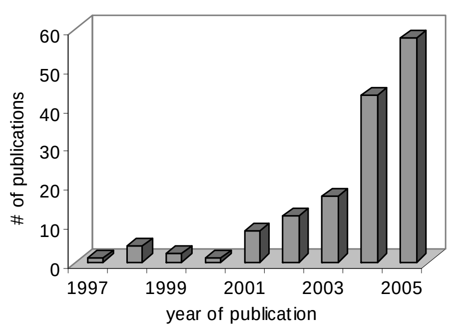

Figure 1 Number of publications about aerobic granular sludge per year

Formation of granular sludge

Granular sludge is well known in anaerobic systems and anaerobic granular sludge reactors (such as UASB, IC and EGSB) proved to perform effectively for several decades. Much research has been carried out on factors concerning granule formation in anaerobic systems. One of the recurring explanations for this granulation is the occurrence of syntrophic juxtapositioned microcolonies. The hydrogen producing acetogens depend on the hydrogen consuming methanogens or sulphate reducing bacteria. Limiting the diffusion distances for hydrogen and other metabolic intermediate metabolites creates a favorable situation for the acetogens. Methanotrix is supposed to play an important role in the actual granule formation. This genus is present throughout all layers of anaerobic granules and has been observed in all types of anaerobic granules independent from the substrate composition. Therefore, it is often suggested that this organism plays an important role in granulation (Guiot *et al.*, 1992; Fang *et al.*, 1994).

In aerobic (but also in denitrifying) biofilms or granules syntrophic mechanisms are not at all or to a much lesser extent involved. This implies that other factors are important for granulation as well (Kosaric and Blaszcyk, 1990).

One of these other process factors is the ***selection of particles by their settling velocities***. In an UASB reactor or other fluid-bed systems, particles are selected by their settling velocity, because only particles with settling velocities higher than the upward velocity of the fluid will stay in the reactor (Lettinga *et al.*, 1980; Kosaric and Blaszcyk, 1990; Alphenaar *et al.*, 1993).

The ***growth rate of the organisms***, however, seems to be one of the main factors responsible for the density of granules or biofilms. Fast growing organisms will produce less dense granules than slow growing organisms (Villaseñor et al., 2000). For example, nitrifiers form a much denser biofilm than heterotrophs under the same circumstances. In anaerobic systems is reported that slow growing methanogens form denser biofilms than fast growing acidifying bacteria. Also, it is reported that an increase of the biomass surface-loading rate (i.e. the growth rate) decreases the biofilm density as well (Van Loosdrecht et al., 1995).

In aerobic biofilm reactors it has been found that ***shear force*** is an important factor for the formation of dense aggregates as well (Kwok et al., 1998). The biofilm density as well as the time to develop a fully covered carrier material decreased with a decreasing shear stress (Van Benthum et al., 1996). This shows that shear effects for obtaining dense biofilms have to be balanced with increased detachment of biofilm fragments from the carrier with increased shear stress. The main shear effect in a biofilm reactor results from particle/particle interaction, especially the collisions of bare carrier with the biofilms (Gjaltema et al., 1997; Kwok et al., 1998). Shear stress has also been recognized as an important factor in anaerobic systems. It has been reported that gas production causes enough movement and shear to decrease the average diameter of the anaerobic granules (Arcand et al., 1994).

Based on a wide range of experimental data a general hypothesis for the structure of biofilms was developed (Van Loosdrecht et al., 1995). This hypothesis states that the formation of dense and smooth biofilms occurs when the detachment rates are high compared to the biomass production. This hypothesis was also verified by mathematical modeling of the structure formation in biofilms (Picioreanu et al., 1998). Biofilms and granular sludge can be considered to be the same from a microbiological point of view, although there are obvious differences from a technical standpoint. The hypothesis stated above might be helpful in explaining the conditions required for the formation of good granular sludge.

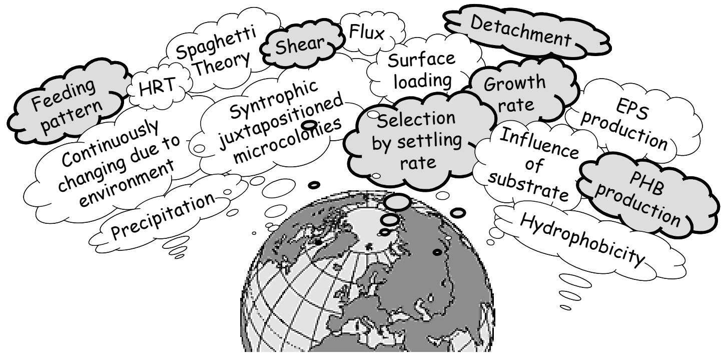

Figure 2 Different ideas about aerobic granule formation exist throughout the world. This research focused on the gray fields in the picture.

Conversion processes in aerobic granular sludge

When aerobic granular sludge technology is to be applied in sewage treatment, nutrient removal (COD, N and P) will be very important. The mechanisms for nutrient removal with aerobic granular sludge are basically the same as used in activated sludge treatment. The main difference is that it does not occur in different tanks, but simultaneously in different zones inside the granules.

As described in the section above, the formation of stable, dense and smooth aerobic granular sludge is based among others on decreasing the actual growth rate of the organisms involved. A method to achieve this in systems that are fed with readily biodegradable substrate is to convert these substrates into cell-internally stored polymers as polyhydroxy-alkanoates (PHA, specifically the poly-β-hydroxybutyrate or PHB). During the preliminary experiments and in most other studies (from which an overview is given in de Kreuk *et al.* (2004)), the conversion of external substrates into cell-internally stored polymers was obtained by applying a feast-famine regime. With such regime, about 60% of the dosed COD is first converted into PHB before it is used for growth (Beun *et al.*, 2002). This feeding regime allowed formation of stable granular sludge at specific process conditions (high DO, high shear stress), but it was not sufficient to maintain stable aerobic granules at low oxygen concentrations (Mosquera-Corral *et al.*, 2005).

Phosphate or glycogen accumulating organisms (respectively PAO or GAO) perform the conversion step from readily biodegradable substrate to PHA most efficiently. By applying an anaerobic feeding period, PAO or GAO were able to proliferate, because of their ability to store the substrate cell-internally during an anaerobic period and grow during the subsequent aerobic period. Readily biodegradable substrate will be taken from the influent during the anaerobic period, leaving no substrate for solely aerobic fast growing heterotrophic organisms during the aeration period. Therefore, PAO or GAO will dominate, resulting in stable and smooth aerobic granular sludge (De Kreuk and Van Loosdrecht, 2004), even under low oxygen concentrations and decreased shear stress (in a bubble column).

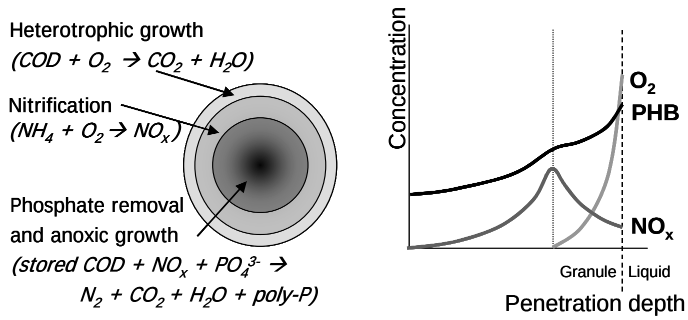

Figure 3 Schematic representation of the layered structure of aerobic granules and of the substrate and electron acceptor concentrations inside the granules during the famine phase.

Simultaneous nitrification/denitrification (SND) is an important mechanism in aerobic granular sludge. Distribution of heterotrophic and autotrophic organisms in granular sludge plays and important role in SND. During the feast period, the concentration of external carbon is high. This substrate will diffuse into the granules completely and will anaerobically (PAO), aerobically or anoxically (other heterotrophs) be stored. During the famine period, cell-internally stored substrate is available throughout the granule (schematically shown in Figure 3). Since autotrophic organisms need oxygen, they will exist in the aerobic layers of the granule. In this layer, ammonium will be converted to nitrate. The nitrate can penetrate to the interior of the granule were the stored substrate can serve as carbon source for denitrification. Optimal nitrogen removal in the system will occur when the aerobic and anoxic volume are well balanced throughout the aeration period (Beun et al., 2001, De Kreuk *et al.*, 2005a; De Kreuk *et al.*, In Preparation).

Designing a new wastewater treatment system

At the start of the research to aerobic granular sludge, aerobic granular sludge formation was shown as a side effect of PHB formation, in a well-controlled 3-liter laboratory set-up with pulse feeding. Because of the great possibilities for wastewater treatment that this well settling aerobic granules could offer, first lab results had to be translated to a robust full-scale concept. Because of the specific circumstances needed for aerobic granular sludge formation, scaling-up an aerobic granular sludge reactor is not only a matter of economical reasoning but moreover a balance between economics and conventional scaling laws. In the scale-up procedure as applied in the scope of the development of aerobic granular sludge technology, practical solutions and economical advantages were coupled to conventional scale-up strategies.

Scaling procedures – an overview

When a new process, micro-organism or product is developed, the process often has to be scaled-up from a laboratory experiment to a full-scale installation. There are different procedures to come to a full-scale design that represents the laboratory circumstances in which the process is developed and optimised.

Before the method of scaling can be determined, the category in which the development is situated has to be clear. Luyben/van der Lans (this course) formulated a possible subdivision of scale-up problems along the dimensions of process & equipment and product & operation (Figure 4). When a new product has to be produced with new equipment, increase can only be achieved by step-by-step enlargement of the production volume (in reality or by modelling). Scale-up of a known product in an already known process can be done by optimisation and a new product with a know process can be done by analogy, since there is already a lot of information on that specific process. The most common situation is the development of a new product with known equipment. In that circumstance, a scale down approach can be used according to the strategy as is given in Figure 4, without the pilot step. The known equipment is scaled-down to a laboratory test-rig in which the process can be simulated and optimised. Finally the optimal process is scaled-up to a full-scale application (Oosterhuis, 1984).

Different methods for a scale-down/scale-up approach have been described in literature with a basic difference in know-how and know-why scaling (Deckwer and Schumpe, 1993). The first group covers the rules of thumb that are often used, like keeping the value of a typical operation or equipment variable constant (for example constant k_la, constant Power/Volume ratio). Know-why methods study the process and take more aspects into account. The fundamental scale method implies solving all micro-balances for momentum, mass and heat-transfer of the system. Since this method is impossible to use for complete microbial processes, a simplified semi-fundamental method is often used, based on flow models in the reactor (Oosterhuis, 1984).

Besides the use of a know-how method, the most used know-why approach for scale-up is derived from dimensional and regime analysis. This method is based on the analysis of the total system and determining a set of dimensionless numbers from the dimensionless balance equations or from similarity principles.
Similarity in wastewater treatment systems can be found in: geometric; kinematic (similarity in time, velocities); dynamic (forces of the same kind act upon corresponding particles at corresponding times in geometrically similar systems); chemical; biological and/or thermal similarity (a fixed relation between concentration at corresponding points in small and large scale). It can be easily stated that complete similarity in wastewater treatment plants on small and large scale is impossible (Horvath and Schmidtke, 1983). Complete similarity can be mathematical contradictory, technological impossible or economical unfeasible. To make a choice which dimensionless groups can be similar and which not, without affecting the process excessively, the field of regime analysis is entered. This analysis compares characteristic times of subprocesses, to identify the rate-limiting step at production scale. These rate-limiting steps are translated to laboratory scale, thereby ensuring that the rate-limiting step is established. The production on laboratory scale can be optimised or the process can be further developed in the regime of the rate-limiting step, after which the optimised process is scaled up to the full scale application (Groen, 1994).

Development of the aerobic granule technology
A said before, aerobic granule formation was initiated and developed at laboratory scale. The large-scale experience is limited to comparable processes as large scale SBRs for wastewater treatment (Wilderer et al., 2000) and continuously fed biofilm airlift reactors (Nicollela *et al.*, 2000; Mulder *et al.*, 2001). Because of the required process conditions for selecting and growing granules, this process equipment could not be applied one-to-one.
The scale-up problem of the aerobic granular sludge technology can be situated between the two upper quadrants of Figure 4. The first aerobic granules were observed in a biofilm suspension airlift reactor (BASR), formed from biofilm fragments that originated from broken biofilm particles (Tijhuis et al., 1994). Hereafter, research to the new aerobic granulation process without a carrier was started in a laboratory scale reactor. At the beginning, knowledge about the most favourable

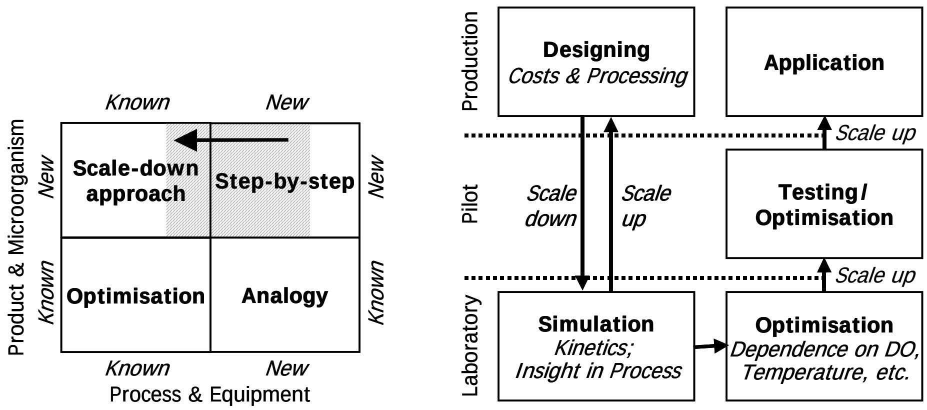

Figure 4 Different approach of scale up approach to scale-up conditions (Luyben, 1992) and the scale down approach for new processes or equipment as used in the development of aerobic granular sludge technology

reactor type or configuration for granule formation was not available, since the desirable process conditions had to be found. The laboratory scale reactor was not scaled down from a typical large-scale installation, but the dimensions were chosen to be practical. E.g., the laboratory-scale reactor height was one meter to have a good gas-liquid mass transfer, mixing and stratification during settling. To be able to work with a limited reactor volume, the diameter was chosen small, which resulted in a height/diameter ratio of 15 (Beun et al., 1999). It is clear that this is not in line with full-scale plants, and that geometrical similarity is not possible.

Since the scaling problem was situated between two variants, a combined step-by-step and scale-up/scale-down approach has been executed as is schematically shown in Figure 4. The scale-up/scale-down is a translation from laboratory experiments into a design of the full-scale plant and visa versa. In other words, the design of a full-scale operational installation occurred at the same time as the laboratory experiments and was done in close cooperation of the engineers of DHV Water (Amersfoort, The Netherlands). The morphology of the granules and the conversion processes at different process conditions were studied at 3-litre scale. The experimental results were translated to a full-scale design and the bottlenecks for the technical design were translated back to experiments.

Bottlenecks and solutions found in the scale-up/scale-down approach

The design strategy of the innovative aerobic granular sludge technology was to translate laboratory scale observations of aerobic granule formation to a robust and economically feasible full-scale process. Therefore, a good understanding of granule morphology, structure and stability was needed. Furthermore the conversion processes in aerobic granular sludge were studied experimentally and by modelling, in order to be able to optimise the nutrient removal efficiency and to obtain an economically feasible technology, having the ability to fulfil effluent demands.

A short summary of the research performed in the scope of the technology development at the TU Delft in cooperation with DHV (Amersfoort, The Netherlands), originating from bottlenecks and sensitivities that were studied and/or solved in the scale-up/scale-down process, are given below.

- The dissolved oxygen (DO) concentration, and thus the aeration, highly influences the energy requirement and the nitrogen removal efficiency. Beun (2001) showed an optimum in nitrogen removal at 40% dissolved oxygen (DO) by modelling, but experiments (low DO and pulse feed;

Mosquera-Corral *et al.*, 2005) shows granule instability at this low oxygen concentrations. This was not the case when a long anaerobic feeding period was applied. An anaerobic feeding period selected for phosphate accumulating organisms or glycogen accumulating organisms, resulting in stable, dense and smooth granules (De Kreuk and Van Loosdrecht, 2004).

- Besides the granule instability at low oxygen concentrations, pulse feeding at large scale is also undesired, because it would imply the need for large buffer tanks. Furthermore a pulse feed is economically and technically unrealistic when 800 m^3 h^{-1} (dry weather flow) needs to be treated in an average WWTP. Increasing the feeding time from a pulse feed, as described by Beun (1999), to an anaerobic feeding period with a duration of 1/n·total cycle time (n = amount of SBR lines applied at full scale) would solve several bottlenecks; a long feeding period is technical simpler, less expensive and less space consuming, since buffer tanks are not needed. This feeding regime also has advantages for the nutrient removal, leading to high simultaneous COD, N and P removal (De Kreuk *et al.*, 2005a);
- The temperature during the laboratory scale experiments was well controlled at 20°C. However, this temperature is high for moderate to cold climates as in The Netherlands, were sewage temperature in winter can cool down to 8°C. Therefore, the effects of temperature on reactor start-up, nutrient removal and granule morphology were studied and described in de Kreuk et al. (2005b);
- Biological processes in the granules are determined by concentration gradients of oxygen and diverse substrates. The concentration profiles are the result of many factors, e.g., diffusion coefficients, conversions rates, granule size, biomass spatial distribution and density. All of these factors strongly influence each other, thus the effect of separate factors cannot be studied experimentally. Moreover, due to the long sludge age in granule systems, lengthy experiments should be carried out before we can speak of a steady state reaching system. Therefore, a good computational model for the granular sludge process provides significant insight in the most important factors that affect the nutrient removal rates and in the distribution of different microbial populations in the granules. Moreover, a model could be used as tool to optimise the design of a full-scale system. De Kreuk et al. (In Preparation) presents a model for aerobic granule sludge reactors and the influence of oxygen concentration, temperature, granule diameter, sludge loading rate and cycle configuration are analysed in this publication.
- The actual full-scale design and description of the bottlenecks and cost optimisation was performed by the engineers of DHV, showing that a system based on aerobic granular sludge could reduce annual and specific costs, save up to 80% of land and uses 30% less energy than a comparable sewage treatment plant based on activated sludge with bio-P (De Bruin *et al.*, 2004).
- The final step-by-step approach of the development of this new technology comprised experiments with sewage. This was done first at laboratory scale (De Kreuk and Van Loosdrecht, 2006). Hereafter, the economical and technical feasible full-scale design was translated to a pilot plant reactor, in which tests with sewage were performed at WWTP Ede, The Netherlands, of which a summary of the results is presented below.

The step-by-step approach at laboratory scale in combination with scale-up/scale-down of the technical design, led to insight in process conditions vital for aerobic granulation and optimisation. This will hopefully lead to full-scale applications in the near future.

Results of the pilot scale installation based on aerobic granular sludge at WWTP Ede, The Netherlands

Because of the promising results of laboratory scale studies with synthetic influent, with pre-settled sewage and the feasibility of the full-scale design, as described shortly above, a pilot plant research was started by DHV, The Netherlands, in cooperation with TU Delft and founded by STOWA. This study was performed at wastewater treatment plant Ede, The Netherlands. In this section, the results of this study are summarized.

Aims of the pilot-plant study

The first aim of the pilot plant study was the investigation of possibilities of, and which circumstances were preferable for granule formation. Aspects taken into account were pre-treatment, biological phosphate removal and the influence of shear stress. The latter was studied by using two types of reactors: an airlift reactor (high local shear forces) and a bubble column (stratification). Average shear stress in both reactors was more or less equal, depending on aeration rate.

The second part of the research aimed at the optimisation of the process. The conditions for high nitrogen and phosphate removal efficiencies were investigated. This included the stability of the granules, the effects of a dynamic feeding pattern and the need for post- or pre-treatment.

Figure 5 The two reactors of the pilot plant at WWTP Ede, with other equipment in the container and the tank to pre-settle incoming sewage

Methodology

The Pilot-plant (figure 5 and 6) was build by Logisticon Water Treatment (Groot Ammers, The Netherlands). Equipment for measurement and control was supplied by Hach Lange (Tiel, The Netherlands) and Siemens (Den Haag, The Netherlands). The pilot installation existed of two parallel reactors (height 6 m; diameter 0.6 m; effective volume 1.5m^3). The reactors could be used as airlift reactor or bubble column and could be fed with pre-treated (pre-setteled) or raw sewage.
To improve the pre-treatment, a sand-filter could be placed after the settler. In the first period, both reactors were fed with pre-treated (pre-settling and sand-filter) sewage. When granule formation was complete, reactor 1 was fed with pre-settled sewage, while reactor 2 was fed with raw sewage (January to July 2005).
The reactors were aerated by using a fine bubble aerator (bubble column, reactor 1) or a coarse bubble aerator (airlift, reactor 2). Oxygen concentrations were measured on-line and the aeration was controlled around 2 mg L^{-1} with a proportional integral derivative (PID) control connected to the compressors.

Two methods of effluent withdrawal could be used. The effluent could be withdrawn from an extraction point at 4 meters. This method was closest to the laboratory scale experiments and effluent withdrawal and feeding occurred separately. The second method was effluent withdrawal via an overflow at the top of the reactor. Effluent withdrawal and influent feeding could occur simultaneously; the incoming influent pushed the effluent out of the reactor. After the feeding, the upper 30 centimetres of the reactor content was drained to compensate for the gas hold-up. This method was used when granule formation was completed.
The total cycle consisted of the following steps: simultaneous feeding and effluent withdrawal 60-70 minutes, drain 5 minutes, aeration 100-165 minutes, denitrification 0-10 minutes (no aeration), settling 10-25 minutes.

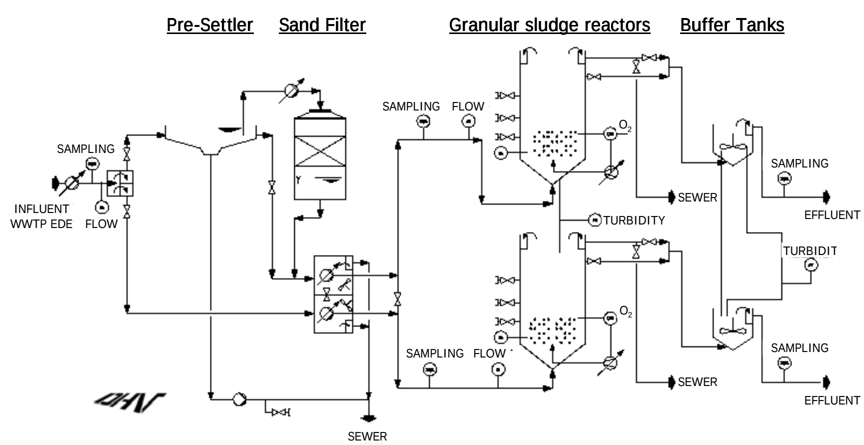

Figure 6 Process scheme of the pilot plant set-up

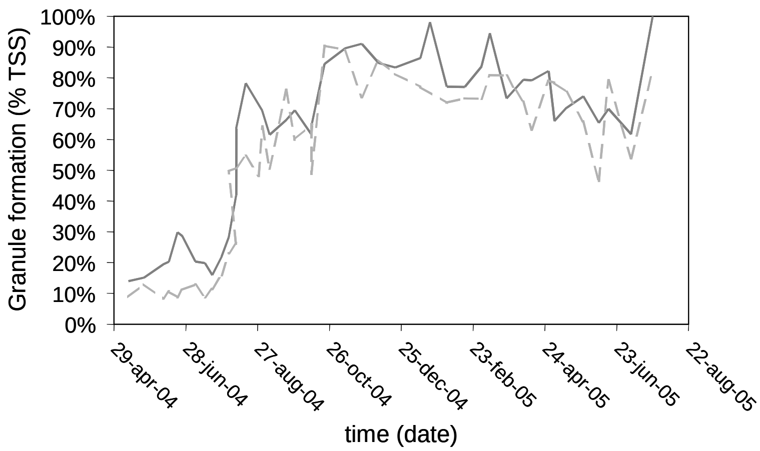

Figure 7 Development of the amount of granules (>0.212 mm) in the pilot reactors as percentage of the total dry weight (reactor 1 solid line, reactor 2 dotted line).

Granule formation was monitored by SVI measurements and by determination of the granule size distribution. The latter was done by sieving a sample through a 0.212 mm, 0.425 mm and 0.6 mm sieve and measuring the total dry weight of the biomass on the sieves. Biomass larger than 0.212 mm was considered granular sludge and the amount of granules was expressed as percentage of total dry weight in the sample. Dry weight (total suspended solids or TSS) and ash content were measured as in the laboratory scale experiments. NH_4^+, NO_2^-, NO_3^-, total N (organically and inorganically bound nitrogen), ortho- and total PO_4^{3-} and COD concentrations in influent and effluent were measured using test kits (Dr. Lange type LCK, Manufacturer: Hach Lange, Düsseldorf, Germany). The SVI_5 and SVI_{30} were determined by reading the volume of biomass in a 1 L sample, after a settling period of 5 and 30 minutes respectively and calculated with the biomass dry weight in this sample.

Results and Discussion

<u>Granule formation</u>

During the start-up period, nitrification was suppressed, in order to obtain fully anaerobic conditions during feeding and to create optimal conditions for the growth of phosphate accumulating organisms (PAO). The influent during the start-up was pre-treated with pre-settling and sand filtration, in order to limit the growth of protozoa during this period. When the first aerobic granular sludge appeared (around 50% granules) the selection pressure was increased, by decreasing the settling time. This led to more than 95% of granular sludge, which did not change significantly when this selection pressure was lowered again. The different shear stress in the airlift reactor and bubble column did not lead to different granule formation rates. Because of the full-scale advantages of bubble columns, the riser from reactor 2 was removed for the second part of the research, resulting in two parallel bubble columns.

From October 2004 the feeding and effluent withdrawal was changed to a simultaneous feeding and withdrawal regime. This resulted in a decreased settling pressure from 6.5 m h^{-1} to 2-3 m h^{-1}. The maximum hydraulic load during feeding was limited to 3 m h^{-1} to avoid wash-out of suspended solids with the effluent. This change did not result in changed granule stability or morphology.

The TSS concentration in the bubble columns was 9 to 10 g L^{-1} and consisted of more than 80% granular sludge, during the whole steady-state operation (in total 10 months, figure 7). The largest fraction of the granules was bigger than 0.6 mm. The average SVI_5 and SVI_{30} were 77 mL g^{-1} and 60 mL g^{-1} respectively.

Proces optimisation

After granule formation was completed, the nitrification process was stimulated. After approximately 5 weeks, complete nitrification could be observed. The N-removal efficiency based on soluble nitrogen compounds was high, independent of the nitrogen load that was applied (highest load applied 2.9 mgN kgTSS^{-1} d^{-1}). This means that the nitrification capacity of the granular sludge could be considered robust and resistant against changes in sludge loading.

Total nitrogen removal (nitrification and denitrification) was sufficient (figure 8). From January 2005 till July 2005, the average value of the sum of ammonium and nitrate in reactor 1 and 2 was 9.2 and 8.9 mg L^{-1} respectively.

The biological phosphate removal was continuously high during the total period of N-removal (January to July 2005). Average orthophosphate concentrations in the effluent of reactor 1 and 2 were respectively 0.9 and 0.8 mg P L^{-1} (Table 1).

The total-N, and to a lesser extent the total P, removal highly depends on the presence of suspended solids in the effluent. When the reactor is fed with a constant flow, the concentration of suspended solids in the effluent stayed low (10-20 mgTSS L^{-1}). Pretreatment did not influence this concentration, while surplus sludge was removed during the drain period. Applying a simple post-treatment could easily reduce the concentration of suspended solids in the effluent.

Preliminary studies were carried out with the use of a drum-filter. With a mesh of 0.01 mm, the average suspended solids concentration decreased to 4 mgTSS L^{-1}.

When the influent flow was varied, more wash-out of the sludge was observed. When the influent flow is kept constant during a certain period, fine material can accumulate in the reactor, which was washed out at as soon as the influent flow is increased.

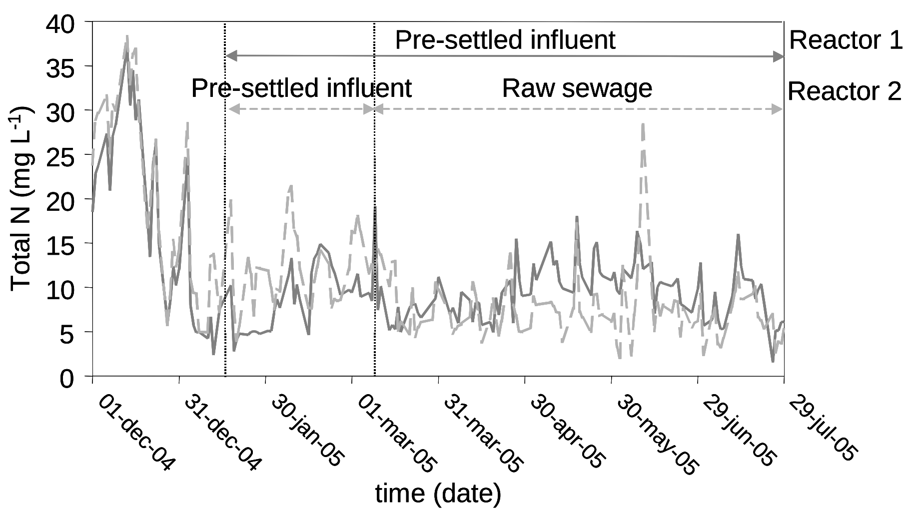

Figure 8 Nitrogen concentrations (sum of NH_4-N and NO_3-N) in the effluent of the two pilot reactors (reactor 1 solid line, reactor 2 dotted line)

Table 1a Average influent and effluent concentrations measured in pilot scale reactor 1 (Januari to July 2005).

Month	Temp	COD load[1]	Influent			Effluent		
			N_{total}	NH_4-N	PO_4-P	NH_4-N	NO_3-N	PO_4-P
	(°C)	(g_{COD} $g_{TSS}^{-1}d^{-1}$)	(mgN L^{-1})		(mgL^{-1})	(mgN L^{-1})		(mgL^{-1})
Jan.	14.1	0.157	48.3	29.6	5.3	2.3	4.1	0.8
Feb.	13.5	0.153	50.0	28.3	5.1	0.6	9.7	1.1
March	12.9	0.143	55.5	32.6	5.6	0.6	8.1	07
April	13.7	0.122	53.5	32.9	5.6	0.3	7.8	0.6
May	15.4	0.149	55.5	37.6	6.5	0.4	11.7	0.9
June	19.5	0.200	63.9	39.4	7.4	1.4	9.3	0.8
July	20.6	0.223	52.2	33.5	6.2	1.1	7.0	1.0

[1] COD load is based on the aeration time

Table 1b Average influent and effluent concentrations measured in pilot scale reactor 2 (Januari to July 2005).

Month	Temp	COD load[1]	Influent			Effluent		
			N_{total}	NH_4-N	PO_4-P	NH_4-N	NO_3-N	PO_4-P
	(°C)	(g_{COD} $g_{TSS}^{-1}d^{-1}$)	(mgN L^{-1})		(mgL^{-1})	(mgN L^{-1})		(mgL^{-1})
Jan.	14.1	0.183	48.4	28.7	5.3	5.5	5.4	0.9
Feb.	13.5	0.188	50.3	28.6	5.1	3.9	7.8	1.0
March	12.9	0.226	62.0	37.1	6.5	2.3	8.3	0.7
April	13.7	0.212	58.3	31.3	6.3	0.8	6.1	0.7
May	15.4	0.214	56.8	36.3	6.6	0.8	6.9	0.8
June	19.5	0.253	63.8	39.4	7.6	3.3	5.1	0.6
July	20.6	0.354	57.2	31.3	6.4	0.8	5.6	1.1

[1] COD load is based on the aeration time

Conclusions

Granule formation in a SBR system is achievable using a complex influent such as domestic sewage. However, a considerably longer start-up time is needed compared with that reported in previous studies using synthetic influent or more concentrated industrial effluents. The granules grown on sewage are more heterogeneous than granules found with synthetic influent. In future installations, it is expected that granules will be formed as long as a high COD load is applied. Therefore, COD-load will be an important process parameter at larger scale operation. The results of the pilot-plant study show that aerobic granular sludge is a promising technology. When granule formation was completed, the granules showed to be robust even at changing temperatures, influent flows and loading rates. Furthermore, the stability of the granules and the effluent quality did not change when the influent was changed to raw sewage. The nitrogen removal even improved because a better COD/N ratio.

A post-treatment for the removal of suspended solids from the effluent is needed to fulfil the required effluent demands. This will also improve the total nitrogen and phosphate concentrations in the effluent.

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