Aerobic granular sludge technology: an alternative to activated sludge?

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Abstract Laboratory experiments have shown that it is possible to cultivate aerobic granular sludge in sequencing batch reactors. In order to direct future research needs and the critical points for successful implementation at large scale, a full detailed design of a potential application was made. The design was based on the laboratory results, and two variants of a full-scale sewage treatment plant based on Granular sludge Sequencing Batch Reactors (GSBRs) were evaluated. As a reference a conventional treatment plant based on activated sludge technology was designed for the same case.

Based on total annual costs both GSBR variants proved to be more attractive than the reference alternative (7–17% lower costs). From a sensitivity analysis it appeared that the GSBR technology was less sensitive to the land price and more sensitive to a rain weather flow (RWF). This means that the GSBR technology becomes more attractive at lower permissible RWF/DWF ratios and higher land prices. The footprint of the GSBR variants was only 25% compared to the reference. However, the GSBR with primary treatment only cannot meet the present effluent standards for municipal wastewater in The Netherlands, mainly because of a too high suspended solids concentration in the effluent.

A growing number of sewage treatment plants in the Netherlands are going to be faced with more stringent effluent standards. In general, activated sludge plants will have to be extended with a post treatment step (e.g. sand filtration) or be transformed into Membrane Bioreactors. In this case a GSBR variant with primary treatment as well as post treatment can be an attractive alternative.

Keywords Aerobic granular sludge; nitrogen removal; phosphate removal; potential; process economy

Introduction

Conventional Sewage Treatment Plants (STPs) based on activated sludge technology require a large footprint. This is caused by the relatively poor settling characteristics of activated sludge, resulting in low permissible dry solids (DS) concentrations in aeration tanks and in a low maximum hydraulic load of secondary sedimentation tanks. In the 1990s, compact attached growth technologies in several configurations were developed (immobilised bed, fluidised bed and airlift reactors). The main feature of these, continuously operated technologies is a high volumetric load, occasionally without a separate sludge/water separation step. The process conditions in airlift reactors are simple and the area requirement is limited. Because of the large specific biofilm area, the volumetric conversion capacities can be high (Heijnen et al., 1993). The main disadvantage of these systems is the relatively high investment costs. Recent research showed that it is possible to grow granular sludge in a batch-wise operated system without a carrier at high dissolved oxygen (DO) concentrations (>80%) resulting in high biomass concentrations and high volumetric loads (7.5 kgCOD/(m².d)) (Beun et al., 2000; Etterer and Wilderer, 2001). Because of the outstanding settling properties and sequential operation the use of a traditional or integrated settler is not necessary. Separation of sludge and effluent occurs within the reactor during.
a short settling phase. No long idle times due to sludge settling are required in these Granulated Sequencing Batch Reactors (GSBRs).

Presently, research is focussing on the mechanism of granulation and although the precise mechanism is not known (yet) the following process conditions are assumed to play an important role:

- A short settling time results in the selection of well-settling biomass, because biomass particles with low settling velocities are washed out with the effluent. At laboratory scale, granules with settling velocities higher than 12 m/h were maintained in the reactor.
- Applying high substrate gradients, for example by means of a pulse feed or a plug flow feed through the settled bed, is essential for granulation and for simultaneous conversion processes within the granule. The substrate diffuses into the core of the granules and a fraction is converted into a storage product as poly-β-hydroxybutyrate (PHB). As a result substrate is equally distributed in the granule and the actual growth rate of the organisms will be lower, because of the growth on storage polymers. This growth rate combined with a non-transport-limited system, results in the formation of smooth and dense granules (Picireanu et al., 1998). Another aspect of substrate diffusion throughout the granules is that shortages and decay of bacteria are minimised, which reduces disintegration of granules and which enables simultaneous COD and N-removal.
- Formation of smooth and dense granules is, as is shown in biofilm research (Gjaltema et al., 1997; Tay et al., 2001; Kwok et al., 1998), stimulated when granules are exposed to large shear forces caused by intensive (non-mechanical) mixing in the reactor. Because of the requirement of sufficient shear forces laboratory research up to now has been carried out in an airlift reactor.

Laboratory research has shown good results concerning simultaneous COD-, N- and P-removal, when an anaerobic feeding phase was combined with low DO (10–20% saturation) in the aerated period. In a 3-litre laboratory scale reactor synthetic wastewater was fed as a plug-flow through the settled bed of granules, during an anaerobic period of one hour (total cycle time three hours). The composition of the synthetic wastewater based on COD (with acetate as carbon source), N$_{kj}$ and P$_{total}$ corresponds with sewage. The aforementioned feeding pattern proved to generate more stable granules than with a pulse feed of three minutes. This was due to the selection of relatively slow growing phosphate-accumulating organisms (PAOs). These organisms store acetate as PHB during the anaerobic feeding period while releasing phosphate, while during the aerated period PAOs use the stored PHB as a carbon source and take up the released phosphate again. During aeration, ammonia is converted to nitrate, which can serve as an electron acceptor for PAOs in the core of the granules where oxygen is depleted. To enlarge the anoxic zone volume within granules, a low DO was applied (20%). At these conditions high COD-, N- and P-removal efficiencies were reached and amounted respectively to 100%, 98% and 99%.

The effect of different hydrodynamic conditions (shear stress) was tested by comparing granulation in an airlift reactor and in a bubble column. The disadvantage of a bubble column is a lower effective shear force compared with an airlift reactor, which may influence granulation negatively. Except for a longer start-up phase, granulation occurred in the bubble column with a similar performance compared to the airlift reactor.

An experiment with presettled sewage showed good results towards granulation. Granular sludge with a sludge volume index (SVI) of 36 ml/g and an average diameter of 1.1 mm was formed in a laboratory reactor.

The complete laboratory research, the results of which are summarised above, will be further outlined in other publications. In this paper the feasibility of a full-scale STP based on aerobic granular sludge technology was evaluated by means of a comparison with a conventional STP based on activated sludge technology.
**General assumptions**

A standard Dutch wastewater composition was used, as defined by the Dutch foundation for applied research for water management (STOWA): 600 mg/l COD (216 mg/l dissolved; 384 mg/l suspended); 55 mg/l N\text{\textsubscript{kj}} (45.7 mg/l dissolved; 9.3 mg/l suspended), 9 mg/l P\text{\textsubscript{total}} and 250 mg/l suspended solids. The average wastewater flow 160 l/(pe.d) was taken with a peak Rain Weather Flow (RWF) of 34 l/(pe.h). The effluent requirements are based on the discharge regulations for municipal wastewater in The Netherlands, meaning extensive total nitrogen and phosphate removal (N\text{\textsubscript{total}} = 10 mg/l and P\text{\textsubscript{total}} = 1 mg/l). Primary treatment consists of conventional sedimentation and the removal of suspended solids depends on the dosing of flocculants. Removal efficiencies for suspended solids of 50% (no flocculants) and 80% (dosing of flocculants) were taken. Metal salts were not dosed in the GSBR variants because of the need for the selection of PAOs.

For the calculation of the capital costs, depreciation periods for civil parts and mechanical/electrical parts of respectively 30 and 15 years were used. Capital costs were calculated based on annuities with an interest rate of 6%. Operational costs were based on main cost factors such as sludge disposal costs, power use of aerators, chemical use and maintenance costs. The power use was corrected for power production generated from biogas. In Table 1 the starting points for the calculation of the operating costs are given.

**Treatment alternatives and technological starting points**

Two alternatives of aerobic granular sludge technology were compared to a conventional STP based on activated sludge technology. The following GSBR variants were taken into account:

- GSBR with primary treatment including chemical dosing with extensive removal of suspended solids. Post treatment was assumed not to be required.
- GSBR with post treatment only. The post treatment consists of removal of suspended solids from the effluent from the GSBR (see Figure 1).

Figure 2 gives a global process flow diagram (PFD) of the reference variant. The calculations of the reference alternative were based on a process temperature of 10°C, a design sludge load of the aeration tanks of 0.14 kgCOD/(kgDS.d) and a SVI of 150 ml/g for the design of secondary sedimentation tanks.

The design of the GSBR alternatives was based on biological phosphate removal, which was assumed to be possible in a full-scale GSBR applying alternating anaerobic feeding periods and aerobic reaction periods. Preliminary calculations showed that chemical phosphate removal is too costly because of a higher sludge production resulting in increased sludge disposal costs and also because of a higher chemical use.

In order to be assured of plug flow conditions while feeding from the bottom of the GSBR through the settled granules bed, the maximum hydraulic surface load during the feeding period was chosen at 7.5 m/h. This leads to a construction height of the GSBRs.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Starting points for costs calculations</th>
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<tbody>
<tr>
<td><strong>Cost factor</strong></td>
<td><strong>Unit</strong></td>
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<tr>
<td>Electricity</td>
<td>€/kWh</td>
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<tr>
<td>Sludge disposal</td>
<td>€/tonDrySolids</td>
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<tr>
<td>Iron chloride (41%)</td>
<td>€/ton</td>
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<tr>
<td>Land price</td>
<td>€/m\textsuperscript{2}</td>
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<td>Polyelectrolyte (liquid, 50%)</td>
<td>€/kg active</td>
</tr>
<tr>
<td>Maintenance civil parts</td>
<td>% of investments</td>
</tr>
<tr>
<td>Maintenance mechanical parts</td>
<td>% of investments</td>
</tr>
<tr>
<td>Maintenance electrotechnical parts</td>
<td>% of investments</td>
</tr>
</tbody>
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which were assumed to be built as bubble columns, of 5–6 m. The granule sedimentation velocity was estimated at 15 m/h. The total cycle time amounts to 60 minutes, which is formed by 20 minutes anaerobic feeding period, 27 minutes aeration or reaction phase, 5 minutes sedimentation followed by 7.5 minutes decantation. The COD design load of the GSBR was chosen at 0.3 kgCOD/(kgDS.d), which corresponds with pilot research for the application of an airlift reactor treating municipal wastewater (STOWA, 1997). In this research the net sludge production was almost zero, meaning an equal sludge content in influent and effluent.

The number of parallel treatment lines was determined by the length of feeding time compared to the total cycle time. It was assumed that at most one GSBR can be fed with wastewater which leads to three treatment lines if the filling time is a third part of the total cycle time. In the case of post treatment, the overflow from the GSBR is buffered. Because effluent from the GSBR is discharged by gravity, the initial flow is high. In order to reduce the dimensions of the post treatment step, the effluent of the GSBR has to be buffered.

Sludge treatment for the reference and GSBR alternatives consists of gravitational thickening of primary sludge, mechanical thickening of surplus sludge, digestion and dewatering.

**Results**

Table 2 shows the effluent qualities for both GSBR alternatives. Based on the influent characteristics and technological starting points the GSBR with post treatment can meet the
The effluent requirements. The GSBR alternative with primary treatment does not meet the required effluent quality with respect to suspended solids. This is caused by an insufficient removal of suspended solids in the primary treatment and the assumption that suspended solids in a GSBR cannot be removed. A high suspended solids effluent concentration results also in increased $N_{kj}$- and $P_{total}$-concentrations.

The effluent requirements for the alternative with only primary treatment can only be met if the suspended solids concentration in the wastewater fed to the GSBR is less than 10–30 mg/l. However, this does not mean that a GSBR with primary treatment is not an attractive concept. If a more stringent effluent quality is required (e.g. $N_{total} = 2.2$ mg/l, $P_{total} = 0.15$ mg/l), which is the case in The Netherlands for a growing number of STPs discharging to sensitive surface waters, conventional activated sludge systems have to be extended with a post treatment step (e.g. with sand filtration) or can be transformed into Membrane Bioreactors. In this case a GSBR with primary treatment as well as post treatment can be an attractive alternative.

The footprint of the total treatment plant was calculated by the sum of the net surfaces of all process units and buildings, multiplied by a factor of 1.3. The calculations show that the footprints of the GSBR alternatives were only around 25% of the footprint of the reference alternative. It can be concluded that the GSBR technology is very compact, which is an important advantage in relation to activated sludge technology, especially in densely populated areas.

Figures 3 and 4 show respectively the investment costs and the total specific annual costs (sum of capital and operational costs). Despite the fact that a GSBR with primary treatment cannot comply with the effluent standards, the costs for this variant are also depicted in Figures 3 and 4. As can be seen from Figure 3 the investments for the GSBR alternatives are lower compared to the reference alternative (15–30% on average). As can be expected, the investment costs for the GSBR alternative with primary treatment appear

<table>
<thead>
<tr>
<th>Parameter</th>
<th>GSBR with primary treatment</th>
<th>GSBR with post treatment</th>
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<tbody>
<tr>
<td>COD (mg/l)</td>
<td>80</td>
<td>40</td>
</tr>
<tr>
<td>Suspended solids (mg/l)</td>
<td>50</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>$N_{kj}$ (mgN/l)</td>
<td>4.1</td>
<td>2.0</td>
</tr>
<tr>
<td>$NO_3$ (mgN/l)</td>
<td>5.9</td>
<td>8.0</td>
</tr>
<tr>
<td>$P_{total}$ (mg/l)</td>
<td>1.5</td>
<td>1.0</td>
</tr>
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to be lower than the GSBR alternative with post treatment. The lower hydraulic design load for secondary treatment in comparison with primary treatment mainly causes this.

On the basis of the total specific annual costs the picture does not change (Figure 4). Again the GSBR alternatives prove to be the most attractive. The total annual costs of the GSBR alternatives with primary and post treatment respectively are on average 17% and 7% lower compared to the reference alternative. The capital costs of the GSBR alternatives are relatively high because of the high share of the mechanical/electrical works in the investments (40–45%). In general the part of the mechanical/electrical works for conventional activated sludge systems amounts to 25–30%.

**Sensitivity analysis**

The influence of the RWF/DWF ratio and the land price on the total annual costs was calculated for a GSBR with post treatment as well for the reference, both for a capacity of 120,000 p.e. The results of the calculations are given in Figure 5. The GSBR concept appears to be less sensitive to the land price than the reference, which is logical because of the compactness of the technology. On the other hand the GSBR technology is more sensitive to an increasing RWF compared to activated sludge technology. The reason for this higher sensitivity was because of the large impact of the maximum batch volume on the design of the GSBR. At higher RWF the maximum batch to be treated increases and as a result of this the volume of the GSBR also increases.

**Conclusion**

Aerobic granular sludge is a very promising technology from an engineering as well as economic point of view, and should therefore be further developed. Essentially this will
involve the demonstration of combined N, P and COD removal at field conditions with municipal wastewater.

Based on total annual costs both GSBR variants prove to be more attractive than the reference alternative (7–17%). Additional calculations showed a low sensitivity to the land price and a high sensitivity to rain weather flow. The footprint of the GSBR variants is only 25% of a conventional activated sludge design.

A growing number of sewage treatment plants in The Netherlands are going to be faced with more stringent effluent standards. In general, activated sludge plants will have to be extended with a post treatment step (e.g. sand filtration) or will have to be transformed into a Membrane Bioreactor. In this case a GSBR variant with primary treatment as well as post treatment can be an attractive alternative.

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