# Benchmarking nitrogen removal suspended-carrier biofilm systems using dynamic simulation

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**Abstract** We are witnessing an enormous growth in biological nitrogen removal from wastewater. It presents specific challenges beyond traditional COD (carbon) removal. A possibility for optimised process design is the use of biomass-supporting media. In this paper, attached growth processes (AGP) are evaluated using dynamic simulations. The advantages of these systems that were qualitatively described elsewhere, are validated quantitatively based on a simulation benchmark for activated sludge treatment systems. This simulation benchmark is extended with a biofilm model that allows for fast and accurate simulation of the conversion of different substrates in a biofilm. The economic feasibility of this system is evaluated using the data generated with the benchmark simulations. Capital savings due to volume reduction and reduced sludge production are weighed out against increased aeration costs. In this evaluation, effluent quality is integrated as well.

**Keywords** Biofilm; biological nitrogen removal; dynamic simulation; process design

## Introduction

Compared to the traditional COD removal activated sludge process, biological nitrogen removal systems have the following differences (Yuan *et al.*, 2001). (1) Autotrophs grow slowly and therefore require a long sludge retention time. This causes over-growth of heterotrophs and over-accumulation of inert solids. (2) A nitrogen removal plant has to be operated such that both aerobic and anoxic conditions are present. In a single sludge system, each type of solids goes through all of the existing conditions in the plant. Hence, at any moment only a fraction of nitrifiers and denitrifiers are functional. In terms of SRT design, this implies that an even longer SRT is required than in a fully aerobic nitrification plant. (3) An inherent problem with biological nitrogen removal is that denitrification should be preceded by nitrification. A fraction of the influent COD is carried over to the aerobic zone and is therefore not available for denitrification.

The above complexities make the operation of a biological nitrogen removal plant difficult. However, they have also offered greater possibilities for performance improvement by means of optimised process design. Such a possibility is the use of biomass-supporting media, either fixed or as suspended carriers. Qualitative steady-state analysis of these systems already showed their interesting features (Yuan *et al.*, 2001). (1) More bacteria are maintained in the system, at high solids densities in the biofilm. The system thus can be accommodated in a smaller space and needs a smaller settler. (2) Since a system of screens keeps the carriers in one zone, both nitrifiers and denitrifiers are only present in the zones of the reactor where they are needed. This means the full capacity of the plant in nitrification and denitrification can be used. (3) Most of the COD is kept in the biofilm, the COD leakage in the form of sludge flocs and cell COD is decreased dramatically. This leads to a better availability of influent COD to the denitrifiers.

The main drawback of attached growth processes (AGPs) is that a high bulk DO concentration is needed to drive the diffusion of oxygen into the biofilm. It has been reported that bulk DO concentrations below 3–4 mg/L start limiting the nitrification rate (among others: Hem *et al.*, 1994; Rusten *et al.*, 1994; Aravinthan *et al.*, 1998; Rusten *et al.*, 2000).

## Simulation benchmark

In this paper, the attached growth systems described above are evaluated using dynamic simulations. The advantages of the system are validated quantitatively based on a *"simulation benchmark"* for activated sludge treatment systems (Spanjers *et al.*, 1998; Copp, 2001). The *"simulation benchmark"* plant design is comprised of five reactors in series with a 10-layer secondary settling tank. The IWA's Activated Sludge Model No 1 (ASM1) was chosen as the biological process model (Henze *et al.*, 1987) and the double-exponential settling velocity function of Takács *et al.* (1991) was chosen as a fair representation of the settling process. A number of performance indexes is defined, including an effluent quality measure (EQ), energy terms for pumping (PE) and aeration (AE), and a measure of sludge production ($P_{sludge}$). Also included is a measure of effluent constraint violations. The number of violations is to be reported as well as the percentage of time the constraints are not met. To serve as a reference for the implementation of the above mentioned attached growth systems, the standard benchmark was implemented in the simulator WEST (Hemmis, Kortrijk, Belgium).

A first upgrade of the standard benchmark activated sludge plant could be the integration of dissolved oxygen control into the operating strategy. Especially in the case of AGP, high oxygen concentrations are necessary. This means AGP can more easily be operated cost-effectively when aeration control is implemented. Obviously, a reference benchmark plant with dissolved oxygen control was needed. The intention of the PI-controllers was to keep the dissolved oxygen concentration in the aerated basins at a constant set point. For ASU3 and ASU4, this set point was 2 mg/L. The set point in ASU5 was set to 1 mg/L.

Most of the performance criteria were met by this plant. This was however not the case for the nitrogen removal, since the effluent constraint for ammonia nitrogen was exceeded for more than 30% of the time during dynamic simulation (Table 1) and denitrification was sub-optimal (average effluent $NO_3^-$-N = 10.24 mg/L). This is caused by the relatively low C/N ratio of the influent and the fact that at low influent load, quite a lot of oxygen is recycled to the first anoxic tank.

## Suspended carriers in the aerobic phase

A first attached growth process was implemented with suspended carriers only in the aerobic phase of the plant. The idea behind this implementation is to provide an extra growth

**Table 1** Selected performance criteria for carbon and nitrogen removal during dry weather with constant aeration, controlled aeration and with carriers in the aerobic phase only

| | Controlled aeration | | | Carriers in aerobic phase | | |
|---|---|---|---|---|---|---|
| *Indexes* | | | | | | |
| EQ (PU/d) | 7,099 | | | 8,402 | | |
| AE (kWh/d) | 6,118 | | | 11,133 | | |
| $P_{sludge}$ (kg/d) | 2,630 | | | 2,707 | | |
| *Effluent constraint violations* | | | | | | |
| | G | # | %T | G | # | %T |
| $N_{tot,e}$ | 16.03 | 7 | 14.3 | 18.89 | 14 | 49.14 |
| $S_{NH,e}$ | 3.29 | 12 | 32.9 | 4.14 | 13 | 33.11 |

G = flow-weighted average values (in g/m$^3$); # = number of violations; %T = % time plant in violation platform for the nitrifying biomass and in this way to enhance the nitrogen removal in a plant with a relatively small volume. Münch *et al.* (2000) implemented such an attached growth process in a pilot plant. Based on their loading rates, a total reactor volume of 4,400 m$^3$ was selected. This volume was spread evenly over the five tanks in the benchmark set-up. Carriers were only modelled in the last two aerobic tanks.

For the description of the biodegradation in the tanks with carriers, the ASM1 model was coupled with a simplified mixed culture biofilm model (Rauch *et al.*, 1999). According to Hem *et al.* (1994), however, the strong oxygen dependency of nitrification cannot be modelled using the simple half-order reaction concept used in this model, since the influence of the liquid film diffusional resistance on the biofilm kinetics is quite large. Therefore, the mixed-culture biofilm model was adapted so as to include liquid film diffusional resistance. A value of 1.3 m/d for the liquid film transport coefficient of oxygen was selected (Hem *et al.*, 1994). For the other parameters, the standard parameters proposed in the benchmark description and in Rauch *et al.* (1999) were used.

### Steady-state evaluation

The calculated oxygen dependency of the nitrification rate in the reactors containing carriers is shown in Figure 1. In the first suspended carrier reactor, a linear dependency can be noticed. In the second reactor this is not the case, because at high DO concentration, most of the available ammonia is already nitrified in the first reactor. This makes the second reactor ammonia limited at elevated DO concentrations. The simulated nitrification rates in the first reactor are in line with the values obtained in pilot scale and full-scale investigations (Rusten *et al.*, 1994; Welander *et al.*, 1997). However, the slope of the curve is rather

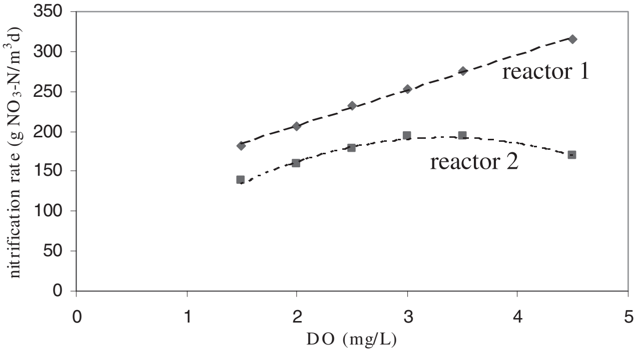

**Figure 1** Nitrification rate versus DO concentration in the suspended carrier reactors

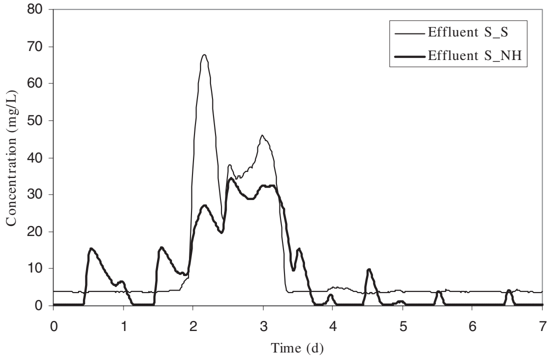

**Figure 2** Effluent ammonia nitrogen concentration compared to the concentration of readily biodegradable substrate in the effluent

small compared to these sources. The slope of the curve is sensitive to the liquid film transport coefficient *h*. The lower this value, the steeper the slope of the curve. Also the amount of aerobic carbon removal in the biofilm is modifying the nitrification capacity of the biofilm. However, because no other literature data was available, the value of 1.3 m/d for *h* was maintained for the rest of the simulations. In order to optimise the nitrification, a set point of 4 mg/L in the first suspended carrier tank was selected. Reflux of oxygen to the anoxic phase could be limited by selecting a set point of 3 mg/L in the second tank with carriers.

Neglecting the sludge on the carriers, a sludge age of 6.4 days was calculated. However, most of the autotrophic biomass was present on the carriers and not in the liquid. Thus, the sludge age of the autotrophic biomass is significantly longer, namely 36 days.

### Dynamic performance evaluation

The results of the dynamic performance evaluation for dry weather are shown in Table 1. The decreased effluent quality has mainly to do with the oxygen-limited nitrification at high ammonia loads and with the high reflux of oxygen to the anoxic zone limiting the denitrification. This also has an effect on the operational costs (Table 2). A higher oxygen concentration in the aerobic tank would further increase the nitrification capacity. On the other hand, this would limit the denitrification in the anoxic tanks even further. Hence, it is of importance to include a deaeration tank. Extra biofilm surface for nitrification should also be able to remedy this problem. A larger surface area can be obtained by increasing the tank volume, or by increasing the specific area of the carriers in the tank. No clear decrease of the sludge production is seen. Indeed, most of the sludge that is produced results from aerobic or anoxic degradation of organic matter. There is however a considerable increase of the required aeration energy. The energy input increased by a factor of about 2, while the necessary volume for treatment only decreased by about 15%.

## Suspended carriers in the complete reactor

The second implementation of the attached growth process uses carriers in all of the tanks. Only a pre-denitrification implementation was studied. Based on volumetric loading rates published by Rusten *et al.* (1994), a reactor volume of 4,000 $m^3$ was chosen. A deaeration tank at the end of the aerobic zone was implemented.

### Steady-state evaluation

In suspended carrier systems, the majority of the influent suspended solids is retained in the anoxic zone. This entails that the leakage of COD is limited and therefore that the COD utilisation efficiency for nitrate reduction is optimised. In the simulation with the DO-controlled benchmark plant, 7,350 kg/d of biodegradable COD is transferred to the oxic

**Table 2** Economic comparison between the DO-controlled benchmark and the suspended carrier plants (Operational costs in €/year, investment costs in €)

| | DO-controlled benchmark | Suspended carrier plant Carriers in aerobic phase | Suspended carrier plant Carriers in complete plant |
|---|---|---|---|
| Operational costs | | | |
| Effluent quality | 397,350 | 462,117 | 365,617 |
| Pumping cost | 10,600 | 10,600 | 7,950 |
| Aeration cost | 151,000 | 277,008 | 565,908 |
| Sludge disposal | 182,000 | 181,175 | 159,300 |
| Investment cost | | | |
| Aeration basin | 653,407 | 563,550 | 575,627 |

**Table 3** Selected performance criteria for the benchmark plant with suspended carriers in the complete reactor

| | | **Dry** | | | **Rain** | | | **Storm** | |
|---|---|---|---|---|---|---|---|---|---|
| *Indexes* | | | | | | | | | |
| EQ (PU/d) | | 6,113 | | | 7,415 | | | 8,409 | |
| AE (kWh/d) | | 23,282 | | | 23,025 | | | 21,602 | |
| $P_{sludge}$ (kg/d) | | 2,119 | | | 2,490 | | | 2,441 | |
| *Effluent constraint violations* | | | | | | | | | |
| | G | # | %T | G | # | %T | G | # | %T |
| $N_{tot,e}$ | 13.77 | 18 | 14.75 | 12.10 | 18 | 7.96 | 16.34 | 5 | 32.94 |
| $S_{NH,e}$ | 3.66 | 7 | 26.70 | 2.55 | 6 | 18.62 | 7.78 | 4 | 42.75 |

G = flow-weighted average values (in g/m$^3$); # = number of violations; %T = % time plant in violation

zone of the plant, while the average nitrate nitrogen concentration in the second anoxic tank is still 4.1 mg/L. In the model description of the suspended carrier plant, only 6,108 kg/d COD leaks to the aerobic zone, while a nitrate nitrogen concentration as low as 1.0 mg/L is reached. This indicates an optimal use of the influent COD for nitrate reduction and the possibility to reach complete denitrification at lower COD to nitrogen ratios.

### Dynamic performance evaluation

Table 2 and Table 3 show that the effluent quality of the system is slightly better than the classical activated sludge system. However, the effluent quality under storm conditions worsens significantly. The first storm event starts with a large load peak. When it enters the plant, the substrate that is not needed for denitrification leaks towards the aerobic phase. There, it is only partly degraded because only a limited amount of heterotrophic biomass is present. Moreover, it hampers the nitrification since the oxygen controllers cannot keep the oxygen concentration above 4 mg/L (their set point is 5 mg/L). Since then fewer nitrates are available to be denitrified, even more COD leaks to the aerobic phase. Due to this situation, the plants need more than a day to recover (Figure 2). This shows that sufficient oxygenation capacity is of extreme importance for a suspended carrier system. This has as a consequence that the energy consumption for aerating this suspended carrier system is quite high as compared to a standard activated sludge nitrogen removal plant (Table 2).

As a last point in this comparison, the decrease of the sludge production should be indicated. This decrease is due to the longer sludge retention times in the biofilm system as compared to the activated sludge implementation. However, the decrease is not spectacular but it still means that the size of the secondary clarifier can be reduced, also because the suspended solids concentrations in the mixed liquor are low.

## Conclusions

The feasibility of attached growth processes for biological nitrogen removal has been evaluated using dynamic simulations. To simulate the bacterial growth on suspended carriers, the Activated Sludge Model No 1 was coupled to a simplified mixed-culture biofilm model. Two types of attached growth processes were studied. In the first, carriers were only added to the aerobic zone of the plant in order to enhance nitrification in a relatively small volume and at low sludge retention times. It was noticed that the longer retention time of the biomass growing on the carriers indeed stimulated nitrification. However, a rather strong dependency on the dissolved oxygen concentration was obvious, causing the required aeration energy to increase significantly. The effluent quality that was achieved was worse than that of the benchmark plant. Mainly the relatively high reflux of oxygen to the anoxic zone limited complete nitrogen removal. Moreover, extra carrier surface area should be available for more nitrifiers to grow in the system. However, this would undo the volume saving that is seen as a major advantage of the suspended carrier plant layout. This plant layout is therefore only considered useful when external factors limit nitrification in an activated sludge treatment plant such as a sludge concentration that has to be limited because of a small settler.

The second plant layout studied included the addition of carriers to all zones of the plant. In this system, the main goal is the physical separation of the heterotrophic and autotrophic biomass. An advantage of the system that could be quantified using simulation is the limited leakage of readily biodegradable material from the anoxic zone to the aerobic zone of the plant. This entails that complete nitrogen removal could be accomplished at low C/N ratios in the influent. However, this plant layout is even more sensitive to the dissolved oxygen concentration in the aerobic zone. If the DO concentration suddenly drops, nitrogen removal can be lost. However, when an attached growth system is operated well, an excellent effluent quality can be obtained.

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