Performance of a CANON and an Anammox biofilm system under different hydrodynamic conditions

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Abstract
The performance of an Anammox and a CANON biofilm system are investigated under different hydrodynamic conditions. The performance of the Anammox biofilm was only little affected by changing hydrodynamic conditions. At steady state, almost all incoming ammonium and nitrite were converted to dinitrogen gas. About 10% nitrate was formed. Hence, the combination of a Sharon (50/50 ammonium conversion to nitrite) and an Anammox reactor does not suffer from mass transfer limitations. The CANON biofilm system on the other hand was very much affected by a change in hydrodynamic conditions. Nitrogen removal dropped drastically when the boundary layer increased, indicating the importance of oxygen mass transfer resistance. Increasing the aeration intensity could circumvent this decrease in nitrogen removal. However, this resistance is an important limitation to the performance of a CANON system and an important consideration in the design of these novel nitrogen removal processes.

Keywords
Anammox, Biofilm, CANON, Modelling, Hydrodynamics

INTRODUCTION

Biological nitrogen removal in wastewater with high nitrogen contents can become a major cost factor, in particular when the wastewater contains only small amounts of biologically degradable carbon compounds (Seyfried *et al.*, 2001). Conventionally nitrogen removal in these wastewaters is achieved using nitrification/denitrification (Sliekers *et al.*, 2002). In such systems, nitrifying bacteria oxidize ammonium to nitrate under oxic conditions, and nitrate is subsequently or simultaneously reduced to dinitrogen gas, under anoxic conditions. Recently however, novel processes for nitrogen removal were developed. These systems hold different advantages over conventional nitrogen removal processes. Benefits are among others the reduction of aeration costs, the omission of the need for external COD addition and the low sludge production. Examples of such novel processes are the CANON process (Hao *et al.*, 2002a&b; Sliekers *et al.*, 2002) and the combined Sharon-Anammox process (van Dongen *et al.*, 2001a&b). In both processes ammonium is first partially oxidized to nitrite by ammonium oxidizers. This nitrite is then used as electron acceptor for the oxidation of the remainder of the ammonium by the recently discovered Anammox organisms. The difference between the two process configurations is that in the CANON process both ammonium oxidisers and Anammox are active in one reactor, while in the

latter process ammonium oxidisers and Anammox are active in two separate reactors. Typically in the CANON biofilm process the ammonium oxidizers are active in the outer layers of the biofilm, while Anammox is active in the inner layers. This way the Anammox organisms are protected from oxygen, which is consumed in the outer layers, because oxygen is inhibiting the Anammox activity. A key factor to the operation of a CANON system is the oxygen transfer to the reactor as in all nitrifying reactors (Zhu & Chen, 2001). This oxygen transfer is limited by two factors: the transfer from air to the bulk phase and the transfer from the bulk phase to the biofilm over a boundary layer. The type of aeration device and the reactor configuration determine the first limitation. The second limitation is determined by hydrodynamic conditions. In this study the behaviour of a CANON biofilm system and an Anammox biofilm system under hydrodynamic process conditions were compared using a one-dimensional biofilm model. The aim of the study was to show the effect of oxygen transfer limitations in the application of the CANON system. This limitation could be the reason why a combined Sharon-Anammox system is to be preferred over a CANON system at higher nitrogen loading rates.

MATERIALS AND METHODS

Biofilm modelling

For the simulation study presented here a one-dimensional multispecies biofilm reactor model was developed in the modelling and simulation environment WEST® (Vanhooren *et al.*, 2003). This biofilm reactor model consists of a completely mixed bulk phase and a layered biofilm. Transport of solubles between the bulk phase and the biofilm is described through diffusion in a laminar boundary layer. The thickness of this boundary layer can be varied, depending on different process conditions. Particulate components can attach and detach to the biofilm. Different empirical equations exist for this attachment. However, in order not to complicate the model, attachment was described as a first order process with respect to the concentration of the particulate component in the bulk phase. Following Horn and Hempel (1997) the rate of biomass detachment is formulated as being dependent on the velocity u_f by which the biofilm surface moves relative to the substratum. If the velocity is negative, then the rate of biomass detachment is zero. If this velocity is positive, then the rate of detachment of a particulate component is set equal to u_f C_I A, with C_i the concentration of a particulate component and A the total biofilm surface area. In the biofilm compartment, diffusion and biological conversion of soluble and particulate components takes place. The diffusion of particulates is of course much smaller than the diffusion of solubles. The governing partial differential equation for both solubles and particulates components in the biofilm thus becomes (Wanner, 2002):

$$\frac{\partial C_i}{\partial t} = D_i \frac{\partial^2 C_i}{\partial z^2} + r_i$$

With C_i the concentration of a component, D_i the diffusion coefficient of a component, r_i the net conversion rate of a component and z the Cartesian co-ordinate perpendicular to the substratum. Solving such a partial differential equation is done in two steps. First the partial differential equation is transformed to a set of ordinary differential equations by using the method of lines (Shiesser, 1991). In this study a 20 layer discretisation is used. For every

time step the thickness L of the biofilm is calculated by the following equation (Rauch *et al.*, 1999):

$$L = \frac{\sum M}{\rho A}$$

With M the mass of a particulate component in the biofilm and ρ the biofilm density.
As a second step the resulting set of ordinary differential equations is integrated by the numerical integrator LSODA (Petzold, 1983).

Extended ASM1 (ASM1.e)

For modelling purposes the Activated Sludge Model nr. 1 (ASM1, Henze *et al*., 2000) was extended with a 2 step nitrification-denitrification model and with the Anammox process (Hao *et al*., 2002a; Sin et al., 2001; Dapena *et al.*, 2003). In previous simulation studies (Hao *et al*., 2002a&b; Koch *et al.*, 2002) endogenous respiration was used to describe decay. However in this study the death-regeneration concept was preferred, because the endogenous respiration of Anammox is not completely clear yet. In the extended ASM1 (ASM1.e) model ammonium is oxidised to nitrite by ammonium oxidisers. This nitrite can be further oxidised to nitrate by nitrite oxidisers. Both nitrite and nitrate as well as oxygen can be used as electron acceptor by heterotrophs for growth, while readily degradable substrate is used as electron donor. This substrate can be supplied in the influent and is also formed through hydrolysis of slowly degradable substrate (X_S). This slowly degradable substrate is formed during decay of biomass, along with inert biomass. The complete stoichiometric matrix in Peterson matrix format (Henze *et al.*, 2000), together with the kinetic expressions are given in Dapena *et al.*, (2003). Parameters characterising heterotrophic and autotrophic activity were taken from literature (Henze *et al.*, 2000; Wiesmann, 1995). Parameters describing Anammox activity were derived from Strous *et al.* (1999).

Process conditions and simulation approach

The reactor configuration and influent conditions in this study are very similar to studies performed earlier by other researchers (Hao *et al.*, 2002 a&b; Koch *et al.*, 2000). Both the CANON and the Anammox reactors were operated at a hydraulic retention time (HRT) of 0.25 days and a temperature of 35°C. Influent concentration for the CANON biofilm reactor was 100 mgN/l. The aeration coefficient ($K_l a$) was set to 110 d^{-1}. This value results from the simple rule that the flux of ammonium that should be oxidised is equal to the flux of oxygen to the reactor. Oxygen transfer limitations are not considered in this expression:

$$K_l a = \frac{3.43\ f\ C^{in}_{NH4+}}{HRT\ \Delta O_2} \approx 110\ d^{-1}$$

With C^{in}_{NH4+} the influent ammonium concentration, f (≈ 0.5) the fraction of ammonium to be oxidised and ΔO_2 (≈ 6 at 35°C) the driving force for air to liquid oxygen transfer. The influent concentrations for the Anammox biofilm reactor were 45 mgN/l ammonium and 55 mgN/l nitrite. The aeration coefficient was of course set to 0 d^{-1}, since Anammox organisms are inhibited by oxygen (Strous *et al.*, 1999).

Diffusion coefficients for soluble components considered in the ASM1.e model (NO_2^-, NO_3^-, NH_4^+, N_2 and readily biodegradable substrate) were derived from Picioreanu *et al.* (1997). The biofilm diffusion coefficient for particulate components considered in the ASM1.e model was set equal to 10^{-10} m²/d and the biofilm density was set to 40 kg/m^3. The biofilm attachment coefficient was set to 10^{-2} d^{-1}. Simulations were performed with boundary layer thickness of 50, 100, 200 and 400 µm. The initial biofilm thickness was set to 700 µm. Simulations with both the CANON and the Anammox reactors were performed over a 250 days period. The first 100 days a boundary layer thickness of 50 µm was imposed. Then every 50 days the boundary layer thickness was increased up to the final value of 400 µm.

RESULTS AND DISCUSSION

Simulation of the Anammox biofilm system

As discussed before simulations for the Anammox biofilm system were performed at boundary layer thickness 50, 100, 200 and 400 µm. The increasing boundary layer thickness had only little influence on the behaviour of the biofilm system. In all cases about 85 mgN/l dinitrogen gas and 11mgN/l nitrate is formed. Only small amounts of ammonium and nitrite were still present. A representative Anammox biomass concentration profile is depicted in Figure 1.

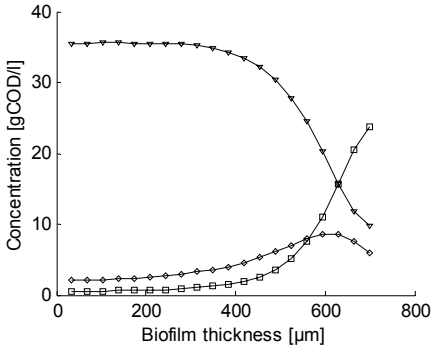

Figure 1 Biomass concentration profile in the biofilm with a boundary layer of 50 µm

Simulation of the CANON biofilm system

An increasing boundary layer thickness has an important influence on the performance of the CANON system, in contrast to the Anammox biofilm system. Conversion of nitrogen dropped from 85 mgN/l to 50 mgN/l when the boundary layer thickness was increased from 50 µm to 400 µm. Bulk ammonium concentration increased simultaneously from 3 to 46 mg/l. Also the oxygen concentration in the bulk phase increased from 1.0 to 3.5 mg/l, as can be seen in Figure 2. Typical Anammox, ammonium oxidisers and oxygen concentration profile in the biofilm are depicted in Figure 3. From these Figures it can be concluded that oxygen transfer resistance to the biofilm is a major factor influencing operation of the CANON system. This should be taken into consideration in the design stage of such a process. Increasing the bulk oxygen concentration by increasing the aeration intensity to the

reactor or biofilm surface area can of course circumvent the problem at hand, but this solution has a significant cost associated with it. Also, since both hydrodynamic conditions and reactor loading may vary considerably during dynamic operation, careful control of the aeration intensity will be necessary in order to obtain high nitrogen removal efficiency in a CANON system. Finally it can be noted that imposing low oxygen conditions is essential for the operation of the CANON reactor because otherwise nitrite oxidisers will be able to persist. In all the simulations performed in this study these nitrite oxidisers were competed out by the ammonium oxidisers and Anammox. So, the aeration intensity has to be high enough to ensure adequate oxidation of ammonium, but can also not be to high. Control of a CANON biofilm system can therefore be a difficult task and might complicate the application of the process. Obviously, this will be a point of future research.

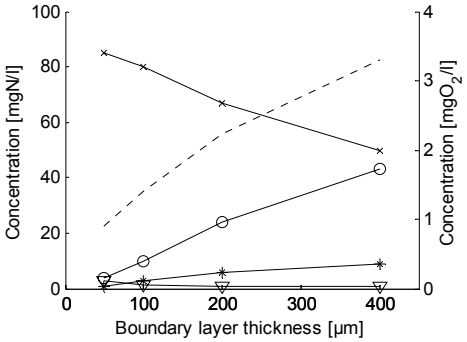

Figure 2 Bulk concentration profiles of NO_2^- (∇), NO_3^- (*), NH_4^+ (x) and N_2 (o) and oxygen (--) as function of the boundary layer thickness

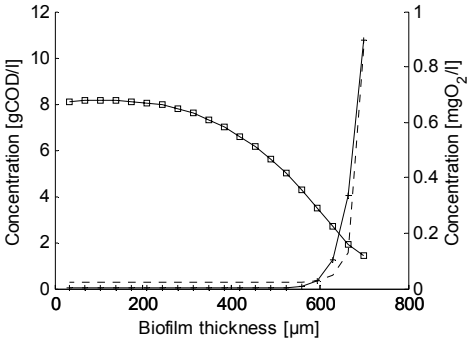

Figure 3 Anammox biomass (□), ammonium oxidisers (+) and oxygen (--) concentration profile in the CANON biofilm with a boundary layer of 50 µm

CONCLUSIONS

This study revealed that the performance of an Anammox biofilm system is only little affected by changing hydrodynamic conditions. At steady state, almost all incoming ammonium and nitrite were converted to dinitrogen gas. About 10% nitrate was formed. Hence, the combination of a Sharon and an Anammox reactor does not suffer from mass transfer limitations. The CANON biofilm system at the other hand was very much affected by a change in hydrodynamic conditions. In the case of a small boundary layer (50 µm) 85% of the incoming ammonium was converted to dinitrogen gas at steady state. When the boundary layer thickness was increased stepwisely to 400 µm, the ammonium conversion dropped to 50%, indicating the importance of oxygen mass transfer resistance. This resistance is an important limitation to the performance of a CANON system and an important consideration in the design of these novel nitrogen removal process. Increasing the aeration intensity could circumvent this decrease in nitrogen removal and careful control of the CANON system will therefor be essential.

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