Model-based evaluation of oxygen consumption in a partial nitrification–Anammox biofilm process

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Abstract Previous modelling studies indicated that DO was a key factor controlling a partial nitrification–Anammox biofilm process (CANON). As a design parameter, therefore, aeration becomes critical in engineering. Aeration depends on oxygen consumption (OC) taking place in the CANON system which is determined by nitrification, ordinary denitrification, Anammox and even biofilm thickness. Due to the presence of substrate gradients in a biofilm, the amount of OC is difficult to assess with experiments. For that reason, modelling technique was used here to evaluate OC with an expanded CANON model with heterotrophic growth/denitrification involved. Simulations demonstrated that different process/biofilm parameters created different curves of OC, which could help engineers or operators have a better insight into the topic of OC in process design or practical operation.

Keywords Anammox; biofilm; COD oxidation; denitrification; nitrification; oxygen consumption

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Introduction

More and more interests in developing Anammox (anaerobic ammonium oxidation) reactors have emerged in recent years. Because of the decreased oxygen demand, COD requirement and sludge production, Anammox can be considered as a sustainable process for nitrogen removal from wastewater treatment. Potential designs are based on an anoxic Anammox reactor coupled with a partial nitrification process such as Sharon (van Dongen *et al.*, 2001; van Loosdrecht *et al.*, 2004) or Anammox plus partial nitrification simultaneously appearing in a biofilm reactor such as the CANON/OLAND processes (Hao *et al.*, 2002a; Sliekers *et al.*, 2002; Kuai and Verstraete, 1998) or aerobic deammonification (Hippen *et al.*, 1997; Siegrist *et al.*, 1998; Helmer and Kunst, 1998). Implementation of Anammox in urban wastewater treatment would lead to a significantly increased sustainability of these systems (van Loosdrecht *et al.*, 2004). The problem for the introduction of the Anammox process is their very slow growth rate (making running pilot plants time consuming) and the complex interactions in Anammox-nitrifying biofilms.

In order to evaluate the operation conditions and to speed up the scale-up process, especially for biofilm-based Anammox processes (e.g. the CANON process), simulations are a very helpful tool (Hao *et al.*, 2002a; Hao *et al.*, 2002b). The COD influence on the CANON process has also been fully evaluated with an expanded CANON model (Hao and van Loosdrecht, 2004) supplemented with heterotrophic conversions based on ASM3 (Gujer *et al.*, 1999). In contrast to general belief, the simulations demonstrated that COD had almost no influence on the CANON process at stable states. This implies that the Anammox activity could be expected in stable operating nitrifying biofilm reactors (Hao and van Loosdrecht, 2004), with a well controlled aeration level. Bearing in mind the need of well-controlled aeration, one more question about oxygen consumption (OC) remains to be ascertained as engineers and operators really feel concern about this practical question.

For optimal design and control of the aeration capacity of a CANON process operating on a COD containing wastewater, the OC of the different processes needs to be known. From ordinary experiments and operation, only the actual dissolved oxygen is generally known. When the mass transfer coefficient is also known, this can be used to estimate the total OC. However, the contribution of heterotrophic and nitrifying OC and the compensating reactions of denitrification and Anammox in the net oxygen uptake remain obscure. Here, modelling can be a powerful tool to evaluate the contribution of these processes.

In this study, the expanded model (CANON + ASM3) was used to demonstrate the net OC of a biofilm system involving simultaneous Anammox, nitrification, carbonaceous oxidation and denitrification. Different process and biofilm parameters were applied to acquire the scenarios of OC under different working conditions, which are intended to be helpful for process design and practical operation.

Simulation approach

Reaction model and mathematical model

A biofilm reaction model involving simultaneous Anammox, nitrification, carbonaceous oxidation and denitrification has been developed to evaluate the COD influence on the CANON process (Hao and van Loosdrecht, 2004). The CANON model supplemented with the parts of ASM3 describing denitrification and carbonaceous oxidation created the biofilm reaction model (Hao and van Loosdrecht, 2004).

Simulation of OC

According to the proposed biofilm reaction model, there are three main oxygen consuming processes: ammonium oxidation, nitrite oxidation and COD oxidation. Anammox and denitrification have major influences on OC since prevailing Anammox and denitrification both mean less OC for ammonium, nitrite and COD oxidation. Although there should be a balance of the net OC, this depends on many factors such as process parameters, biofilm parameters and even kinetic parameters, and thus is very difficult and complex to establish by observation/measurement in experiments/operation.

In simulations, an extra oxygen term was added in the expanded model, parallel to the original oxygen term (a normally controlled DO level in bulk). The new added oxygen term had no control of DO and thus could theoretically calculate the net/overall OC during simulations. In this way, the complexity of OC in the interactions was simplified and the net OC could be output from simulations.

Simulation method

The expanded model was incorporated into a biofilm compartment of a software package AQUASIM (Reichert, 1998; Hao and van Loosdrecht, 2004). An extra oxygen term representing OC was added to the model, which was the only modification to the originally incorporated model.

In order to be comparable to earlier simulation studies, the simulations in this article were all with the same parameters or data used in the previous studies (Hao *et al.*, 2002a; Hao *et al.*, 2002b; Hao and van Loosdrecht, 2004). Both COD and ammonium biofilm surface loads (COD SL and ASL) were used as process parameters and OC was also expressed as biofilm surface consumption (g $O_2/m^2 \cdot d$). In this study, COD and ammonium surface loads varied in the ranges of 1–12 g COD/$m^2 \cdot d$ and 0.6–1.6 g N/$m^2 \cdot d$. Temperature and biofilm thickness (BT) varied in the ranges of 10–30°C and 0.4–2 mm. The oxygen level in the bulk liquid was kept at 0–4 g O_2/m^3. The simulated OC was a model output and then transformed into biofilm surface load (g $O_2/m^2 \cdot d$) according to the biofilm surface area (3,240 m^2) and the inflow (50 m^3/d) used in the study.

Corresponding to the previous studies (Hao *et al.*, 2002a; Hao *et al.*, 2002b; Hao and van Loosdrecht, 2004), five cases were simulated in this study:

(1) Influence of ASL on OC (I): for the CANON process (T = 30°C, BT = 0.7 mm and COD SL = 0);
(2) Influence of ASL on OC (II): for the expanded model (T = 30°C; BT = 0.7 mm; COD SL = 8 g COD/m^2·d)
(3) Influence of COD SL on OC (T = 30°C; BT = 0.7 mm; ASL = 1.23 g N/m^2·d);
(4) Influence of temperature on OC (BT = 2 mm, COD SL = 8 g COD/m^2·d, ASL = 1.23 g N/m^2·d);
(5) Influence of biofilm thickness on OC (T = 30°C; COD SL = 8 g COD/m^2·d, ASL = 1.23 g N/m^2·d).

Results and discussions

Influence of ASL on OC in the CANON process

Figure 1 shows the net OCs at different ammonium surface loads. At each given ASL, increasing the DO level in bulk liquid results in more OC since both ammonium and nitrite need more oxygen for their oxidation at a higher DO level. When the DO level increases up to an extent, the net OCs tend to become flat as most of the ammonium and nitrite have been fully oxidized into nitrate. At this state, the net OCs are proportional to full nitrification of the influent ammonium (4.57 g O_2/g N, excluding assimilation of nitrogen), and clearly there is no Anammox activity under this state. The slope lines represent a net result of complex interactions between ammonium oxidation, nitrite oxidation and Anammox.

In the CANON process, there are mainly three types of autotrophic organisms due to no COD involvement: Anammox bacteria, ammonium oxidizers and nitrite oxidizers. Accumulation of nitrite is a key process for the Anammox reaction to occur (Hao *et al.*, 2002a). Around the optimal DO level, nitrite either accumulates and is anammoxed or is further oxidized into nitrate. Therefore, the net OC of the CANON process is determined by the state of the nitrite in the biofilm.

Influence of ASL on OC in the expanded CANON model

Figure 2 shows the simulation results with COD involved in the inflow. Different from Figure 1, there are no plateaus of the OCs. In this case, the curves represent a sum of the

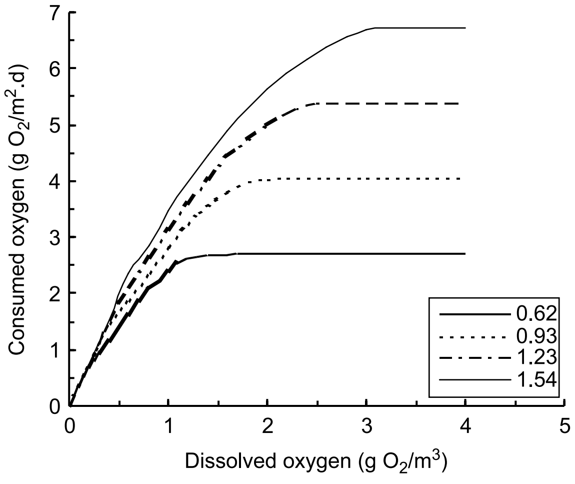

Figure 1 Relation between DO, ASL and OC in the CANON process ($T = 30$°C, BT = 0.7mm, COD SL = 0; Legend: ASL (g N/m^2d))

amount of oxygen consumed in both nitrification and COD oxidation. COD involvement in the inflow certainly increases the net OCs. On the other hand, COD involvement in the inflow delays the processes of both nitrification and Anammox, making the optimal DO level for the maximal dinitrogen gas production shift to a higher level (Hao and van Loosdrecht, 2004). Figure 2 shows that there are no differences between the OCs with different ammonium surface loads under lower DO levels (<1 g O_2/m^3) even though effluent COD values have become low ($<10\,g/m^3$) at DO $= 0.5-1.0$ g O_2/m^3. The removed COD seems contradictive with the consumed oxygen at this DO range as 8 g COD/m^2·d of COD SL should need at least 2.9 g O_2/m^2·d of OC during aerobic dissimilation (yield rate $=$ 0.63 g COD/g COD). However, the simulations indicated that COD storage played a main role in COD removal at this DO range. This is because ASM3 involves the concept of COD storage.

At higher DO levels, aerobic COD oxidation and nitrification become prevalent and so the OCs created differences. Full aerobic oxidation and nitrification (or creating a plateau of the OCs) needs a higher DO level. E.g. 1.54 g N/m^2·d of ASL is expected to have a plateau of OC (8.4 g O_2/m^2·d) around DO $=$ 9 g O_2/m^3, which is clearly beyond reality.

Influence of COD SL on OC in the expanded CANON model

The COD influence on the Anammox and nitrification activities is characterized by a higher DO level needed for the maximal dinitrogen gas produced by Anammox (Hao and van Loosdrecht, 2004). The higher the COD SL, the higher the optimal DO level. Figure 3 shows almost no differences between the OCs with different COD SLs. However, the simulations demonstrated that both COD oxidation and nitrification were responsible for OC at lower COD surface loads. At higher COD surface loads, COD storage and oxidation play a major role in the OCs. It is expected that major differences of the OCs will appear at even higher DO levels.

The previous study demonstrated that COD oxidation was mainly accomplished under aerobic conditions and that a small part of COD was oxidized via denitrification. Thus, aerobic COD oxidation indeed contributes to a share of the net OCs. Complete nitrification of 1.23 g N/m^2·d should need 5.4 g O_2/m^2·d, according to Figure 1. 1.23–12.35 g COD/m^2·d needs about 0.4–2.6 g O_2/m^2·d during dissimilation. Therefore, the curve of COD SL $=$ 1.23 g N/m^2·d has almost approached to a plateau of the OC (5.8 g O_2/m^2·d at about DO $=$ 5 g O_2/m^3). However, the curve of COD SL $=$ 12.35 g N/

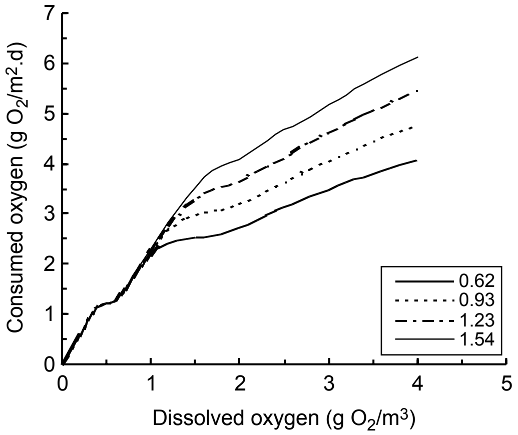

Figure 2 Relation between DO, ASL and OC in the expanded CANON model ($T = 30$°C, BT $=$ 0.7mm, COD SL $=$ 8 g COD/m^2d; Legend: ASL (g N/m^2d))

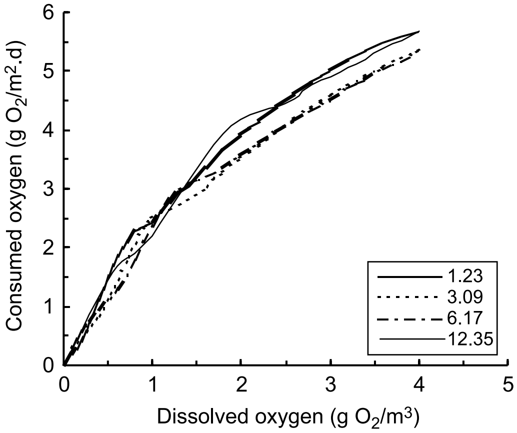

Figure 3 Relation between DO, COD SL and OC in the proposed biofilm reaction model ($T = 30°C$, BT = 0.7 mm, ASL = 1.23 g N/m^2d; Legend: COD SL (g COD/m^2d))

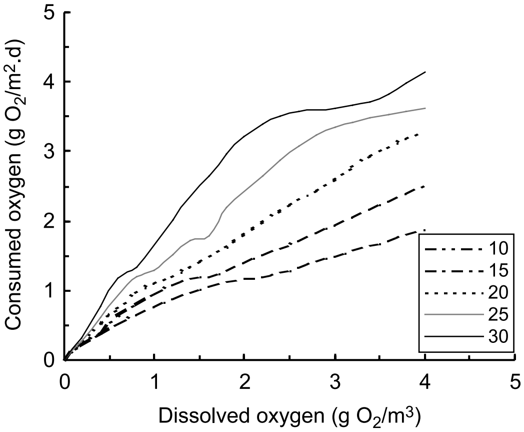

Figure 4 Relation between DO, temperature and OC in the proposed biofilm reaction model (BT = 2 mm, COD SL = 8 g COD/m^2d, ASL = 1.23 g N/m^2d; Legend: temperature (°C))

m^2·d still needs a higher DO level to reach a plateau of the OC (8 g O_2/m^2·d at about DO = 9 g O_2/m^3).

Influence of temperature on OC

Temperature affects bacterial activities. Low temperature means low OCs and high temperature corresponds to high OCs. Figure 4 illustrates such a relation between temperature and OC.

Influence of biofilm thickness on OC

When biofilm thickness increases, mass diffusion into the biofilm becomes difficult. So a thicker biofilm needs a higher DO level for the maximal dinitrogen gas produced during Anammox (Hao *et al.*, 2002a). In other words, a thinner biofilm is beneficial to COD oxidation and nitrification. Figure 5 reflects such a relation between biofilm thickness and OC. Low OC for the thicker biofilms is limited by weak nitrification.

Conclusions

With the help of computer simulations, the influence of COD on aeration requirement for a partial nitrification–Anammox biofilm process (the CANON model + ASM3) was studied.

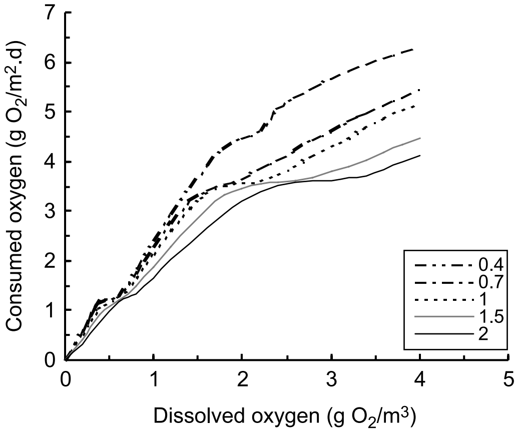

Figure 5 Relation between DO, biofilm thickness and OC in the proposed biofilm reaction model ($T = 30°C$, COD SL = 8 g COD/m^2d, ASL = 1.23 g N/m^2d; Legend: BT (mm))

The simulation results present the net/overall OC for a complex reaction model involving nitrification, Anammox, carbonaceous oxidation and denitrification. Different process/biofilm parameters create different curves of OC. Although the simulation results may not fully reflect reality, the theoretical prediction will help engineers or operators to have a better insight into the interesting topic of OC in process design or practical operation.

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