Controlling the nitrite:ammonium ratio in a SHARON reactor in view of its coupling with an Anammox process

E.I.P. Volcke*, M.C.M. van Loosdrecht and P.A. Vanrolleghem***

*BIOMATH, Department of Applied Mathematics, Biometrics and Process Control, Ghent University, Coupure Links 653, B-9000 Gent, Belgium (E-mail: *eveline.volcke@biomath.ugent.be*)

**Department of Biochemical Engineering, Delft University of Technology, Julianalaan 67, NL-2628 BC Delft, The Netherlands

Abstract The combined SHARON–Anammox process for treating wastewater streams with high ammonia load is the focus of this paper. In particular, partial nitritation in the SHARON reactor should be performed to such an extent that a nitrite:ammonium ratio is generated which is optimal for full conversion in an Anammox process. In the simulation studies performed in this contribution, the nitrite:ammonium ratio produced in a SHARON process with fixed volume, as well as its effect on the subsequent Anammox process, is examined for realistic influent conditions and considering both direct and indirect pH effects on the SHARON process. Several possible operating modes for the SHARON reactor, differing in control strategies for O_2, pH and the produced nitrite:ammonium ratio and based on regulating the air flow rate and/or acid/base addition, are systematically evaluated. The results are quantified through an operating cost index. Best results are obtained by means of cascade feedback control of the SHARON effluent nitrite:ammonium ratio through setting an O_2 set-point that is tracked by adjusting the air flow rate, combined with single loop pH control through acid/base addition.

Keywords Anammox; operating cost index (OCI); partial nitritation; process control; SHARON; simulation

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Introduction

The combined SHARON–Anammox process for treating wastewater streams with high ammonia load is discussed. In the SHARON process, nitrification of ammonium to nitrite (nitritation) without nitrate formation is achieved by working at high temperature (30–40 °C), neutral pH (approximately 7.5) and maintaining an appropriate sludge retention time (SRT). In the last few years, the coupling of the SHARON process with a so-called Anammox process, in which ammonium and nitrite are converted to nitrogen gas, has gained a lot of interest (van Dongen *et al.*, 2001). Compared with conventional nitrification/denitrification, the combined SHARON–Anammox process allows large savings on aeration energy (up to 63%) and carbon source addition costs (up to 100%), while sludge production is low. One application of the SHARON–Anammox process is to treat sludge digestion reject water in order to relieve the main wastewater treatment plant (WWTP) with limited aeration capacity. For normal sludge digestion reject water, it can be reasonably assumed that the SHARON influent contains approximately equimolar amounts of ammonium and bicarbonate. Owing to alkalinity destruction only partial nitritation will occur: typically approximately half of the ammonium will be converted to nitrite (van Dongen *et al.*, 2001). Hence, the SHARON effluent will contain approximately the required nitrite:ammonium ratio of 1:1 that is needed to feed the Anammox reactor (Figure 1). In practice, the actual nitrite:ammonium ratio *needed* for full conversion by the Anammox process will depend on the biomass yield and is typically

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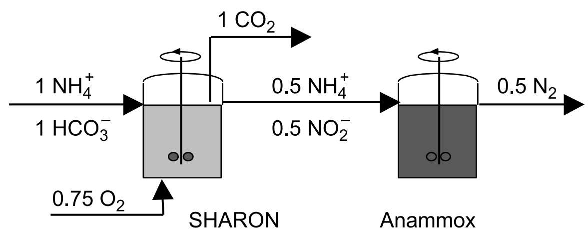

Figure 1 Simplified scheme of the SHARON–Anammox process

somewhat higher. Also, the nitrite:ammonium ratio *produced* by the SHARON process depends upon a number of factors, e.g. influent alkalinity.

Previous work (Volcke *et al.*, 2005) used a simulation study of the SHARON process with realistic influent conditions to compare an operating mode with fixed air flow rate with an operating mode with cascade pH control and one with cascade O_2 control. However, this study did not consider direct pH dependency of the SHARON biomass growth rate, that is expected to have an important effect in this process with varying pH. Also, the performance of stand-alone O_2 control and pH control was not evaluated. This contribution considers both direct and indirect pH effects on the SHARON process. Possible control handles of the SHARON process with fixed reactor volume are identified and several operating modes are evaluated in a systematic way and quantified by means of an operating cost index (OCI). The operating modes under study differ in the applied control strategies for O_2 and pH, in a single loop configuration or combined with cascade control of the produced nitrite:ammonium ratio.

Simulation study of a SHARON–Anammox system

Influent conditions

In order to obtain a realistic influent file, daily averaged on-line measurements for flow rate and ammonium concentrations, as well as weekly laboratory analyses for bicarbonate alkalinity and pH from the full-scale SHARON process in Rotterdam were used. Figure 2 gives the resulting load profiles for ammonium and bicarbonate. The influent flow rate varies between 0 and 921 m^3/day (mean 422), the influent bicarbonate:ammonium molar ratio varies between 0.16 and 3.59 (mean 1.1) and the influent pH varies between 7.6 and 8.3 (mean 8.0).

The SHARON and Anammox reactor models

The SHARON reactor model, implemented in Matlab-Simulink, was developed by Volcke *et al.* (2002) on the basis of the model of Hellinga *et al.* (1999). It consists of both liquid and gas phase mass balances and takes into account the effect of varying air flow rate in the SHARON model on the transport coefficients for O_2, CO_2 and N_2 between the two phases. The model further considers the pH effects that occur during nitrification of highly concentrated streams. The SHARON reactor is a continuously stirred tank reactor (CSTR), operated without sludge retention. Hence, the hydraulic retention time (HRT) equals the

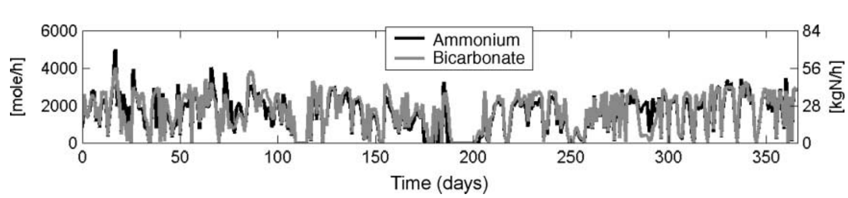

Figure 2 Typical yearly SHARON influent characteristics: ammonium and bicarbonate loads

sludge retention time (SRT). In steady state the SRT (=HRT) equals the inverse of the growth rate of the microorganisms:

$$\frac{1}{\mathrm{SRT}} = \mu^{\mathrm{amm}} = \mu_{\max}^{\mathrm{amm}} \frac{C_{\mathrm{NH_3}}}{K_{\mathrm{NH_3}}^{\mathrm{amm}} + C_{\mathrm{NH_3}}} \frac{C_{\mathrm{O_2}}}{K_{\mathrm{O_2}}^{\mathrm{amm}} + C_{\mathrm{O_2}}} \frac{K_{\mathrm{I,HNO_2}}^{\mathrm{amm}}}{K_{\mathrm{I,HNO_2}}^{\mathrm{amm}} + C_{\mathrm{HNO_2}}} \tag{1}$$

The actual growth rate (μ^{amm}) is determined by the SRT. The corresponding ammonia (NH_3) concentration (and in this way also the total ammonium conversion) is determined by the concentrations of oxygen and nitrous acid (HNO_2) (also related to the total ammonium conversion) and by temperature and pH. Temperature determines the value of $\mu_{\max}^{\mathrm{amm}}$ and the equilibrium constants of NO_2^-/HNO_2 and NH_3/NH_4^+. μ^{amm} comprises direct and indirect effects of the reactor pH. The direct effect is described in the model through the pH dependency of the growth rate of ammonium oxidisers as determined by Van Hulle *et al.* (2004) and shown in Figure 3:

$$\mu_{\mathrm{amm}}^{\max} = \mu_{\mathrm{amm}}^{\max^*} \frac{\mathrm{K_{pH}}}{\mathrm{K_{pH}} - 1 + 10^{|\mathrm{pH_{opt}} - \mathrm{pH}|}}; \quad \mathrm{K_{pH}} = 8.21; \quad \mathrm{pH_{opt}} = 7.23. \tag{2}$$

The pH also plays an indirect role through the fractions of total ammonium and total nitrite that are in the uncharged state (NH_3, HNO_2). The pH itself decreases due to ammonia conversion and increases by bicarbonate stripping in the form of CO_2. The resulting model is well suited for scenario analysis, as performed in this study.

The SHARON reactor volume is set constant at 528 m^3, corresponding with a mean retention time of 1.25 days for the given influent conditions. A constant reactor temperature of 35 °C is assumed.

The Anammox reactor model, implemented in Matlab-Simulink as well, describes a CSTR of 75 m^3 with almost complete (99.5%) biomass retention, operated at 35 °C. Anammox kinetics are based on the model proposed by Dapena-Mora *et al.* (2004). Inhibition of Anammox growth by nitrite is incorporated by Haldane kinetics, with an inhibition coefficient of 15 gN/m^3, in accordance with Strous *et al.* (1999).

SHARON reactor operating modes under study

In this study, a SHARON reactor with fixed and constant volume, operated without sludge retention, is considered. Consequently, the SRT (= HRT) varies with varying influent flow rate (no buffer tank is considered). The influent ammonium and bicarbonate

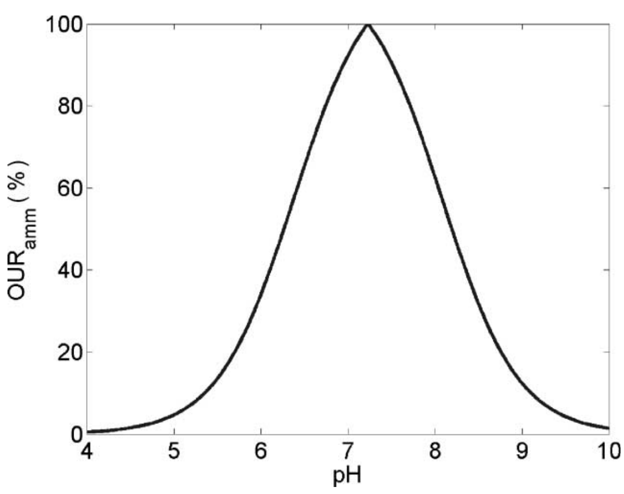

Figure 3 pH dependency of the oxygen uptake rate (OUR) of ammonium oxidizers (Van Hulle *et al.*, 2004)

concentrations vary as well (see Figure 2). In order to control the ammonium conversion and in this way the produced nitrite:ammonium ratio, the following control handles are identified from Eq. 1:

- Acid/base addition: This directly influences the pH. As the pH increases, the substrate (NH_3) concentration increases and the inhibitor (HNO_2) concentration decreases, enhancing ammonia conversion. However, the pH should stay in a range that guarantees acceptably high values of μ_{max}^{amm} (see Figure 3).
- Adjusting the air flow rate: An increasing air flow rate results in a higher O_2 level in the reactor, increasing the ammonium conversion as long as the Monod term is not approaching one. If the (aerobic) SRT is too high, the air flow rate can be turned off periodically in order to prevent nitrate formation. The air flow rate not only effects the O_2 concentration but also the pH; as the air flow rate increases, more CO_2 is stripped from the reactor, resulting in a pH increase.

In this contribution, several control strategies, based on acid/base addition and/or regulating the air flow rate, are systematically evaluated. Table 1 summarises the different operating modes of the SHARON reactor that have been studied. O_2 is controlled by adjusting the air flow rate between almost zero (3.6×10^{-7}) and 20,000 m^3/h. The O_2 set-point is either fixed (O_2 control), or set between zero and the prevailing saturation concentration (8.96 mg/L) by a master controller that aims at reaching the set-point R^{sp} for the nitrite:ammonium ratio (cascade O_2 control). The pH is controlled by addition of acid (96% H_2SO_4) or base (50% NaOH) at a flow rate of maximum 50 L/h. The pH set-point is either fixed (pH control), or set between 6.23 and 8.23 (around pH^{opt} according to Eq. 2) by a master controller in order to reach the set-point R^{sp} for the nitrite:ammonium ratio (cascade pH control). For both cascade O_2 control and cascade pH control, the set-point for the nitrite:ammonium ratio is set at $R^{sp} = 1.23$, corresponding to the ratio of their stoichiometric coefficients in the Anammox reactor model. Finally, the different O_2 and pH control strategies can be combined, resulting in eight different operating modes.

All controllers are proportional controllers, tuned under short-term conditions for a constant influent, using the ISE and ITAE criteria and preventing saturation of the actuators. Oxygen and pH sensors are described as first-order systems with a time constant of 20 s. The on-line measurements of ammonium and nitrite are modelled as being ideal, but with a delay of 0.5 h. Ideal valves for acid and base addition are assumed.

Economic evaluation of control strategies

The optimal design and operating mode of a process is a trade-off between effluent quality and the associated investment and operating associated costs. An operating cost index (OCI) is a useful tool in simplifying this cost analysis. Vanrolleghem and Gillot (2002) have previously demonstrated the use of an OCI to compare control strategies through

Table 1 SHARON reactor operating modes under study (for details, see text)

Control variables Control handle	O_2 Air flow rate $\Phi_{G,in}$	pH Acid/base addition	$(TNO_2/TNH)^{sp} = R^{sp}$ (master) O_2^{sp} (slave) pH^{sp}(slave)
1. No control	Constant $\Phi_{G,in}$	–	–
2. O_2 control	Constant O_2^{sp}	–	–
3. Cascade O_2 control	O_2^{sp} set by master	–	Constant R^{sp}
4. pH control	Constant $\Phi_{G,in}$	Constant pH^{sp}	–
5. Cascade pH control	Constant $\Phi_{G,in}$	pH^{sp} set by master	Constant R^{sp}
6. O_2 control + pH control	Constant O_2^{sp}	Constant pH^{sp}	–
7. Cascade O_2 control + pH control	O_2^{sp} set by master	Constant pH^{sp}	Constant R^{sp}
8. Cascade pH control + O_2 control	Constant O_2^{sp}	pH^{sp} set by master	Constant R^{sp}

the COST benchmark (Copp, 2002). In this study, the OCI is defined as in Volcke *et al.* (2005):

$$\mathrm{OCI} = \gamma_1 \cdot EQ + \gamma_2 \times AE + \alpha_{\mathrm{acid}} \times \Phi_{\mathrm{acid}} + \alpha_{\mathrm{base}} \times \Phi_{\mathrm{base}} \quad [€/\mathrm{year}] \tag{3}$$

The effluent quality term EQ only covers ammonium in the Anammox effluent, as this is recycled to the main wastewater treatment plant and ends up in the effluent stream for plants with a lack of aeration capacity. The differences in the SHARON reactor air flow rates for the different scenarios are accounted for through the aeration energy term AE. The costs for acid and base addition are taken into account as well. The values for the cost coefficients γ_1, γ_2, α_{acid} and α_{base} are summarised in Volcke *et al.* (2005). Note that the OCI only includes those operating costs that differ between the scenarios under study. Savings in operating costs between operating modes thus equal the investment costs that can be supported for extra control equipment.

Simulation results and discussion

The behaviour of the SHARON reactor under the operating modes corresponding with the different control strategies of Table 1, and their effect on the subsequent Anammox process have been simulated. The results are summarised in Table 2 and discussed in the following paragraphs.

SHARON operating mode 1: no control

In case the SHARON reactor is operated with a fixed air flow rate, periods of high influent flow rates (lowered SRT) cause a pH increase because of decreasing ammonium conversion, again lowering the growth rate of ammonium oxidisers and causing their wash-out. Air flow rates from 1000 up to 8000 $\mathrm{m^3/h}$ all resulted in complete wash-out of the ammonium oxidisers after less than 30 days. Consequently, hardly any ammonium conversion occurs in the Anammox reactor and the OCI term for effluent quality is very high. Note that we even disregard the fact that the permit of the wastewater treatment plant may be in jeopardy when the maximum discharge limit is not reached.

SHARON operating mode 2: O_2 control

Figure 4 shows the different OCI contributions for the different O_2 set-points examined. The best results (smallest OCI) are obtained for $O_2^{sp} = 3$ mg/l, but under these conditions hardly any Anammox conversion is realised due to nitrite inhibition of the Anammox process. A fixed oxygen set-point does not guarantee the realisation of a fixed nitrite:ammonium ratio (and certainly not the optimal one). The effluent quality term makes up the largest fraction of the costs. The mean air flow rate corresponding with $O_2^{sp} = 3$ mg/L is about $\Phi_{G,in} = 3000\ \mathrm{m^3/h}$. For this reason, this value is used in the operating modes with constant air flow rate (4, 5 and 8).

SHARON operating mode 3: cascade O_2 control

This strategy consists of increasing the oxygen set-point (to increase ammonium conversion) when the produced nitrite:ammonium ratio is too low. However, under this operation, all ammonium oxidisers are washed out within 20 days. This is caused by the fact that during a period of high influent flow rates (short SRT), the resulting decrease in ammonium conversion causes an increase in the oxygen set-point, that is met by increasing the air flow rate. As a result however, also more CO_2 is stripped from the reactor, increasing the pH to such an extent that the growth rate of the ammonium oxidisers decreases even further and the biomass is eventually washed out. For this reason, it seems advisable to combine cascade O_2 control with pH control (operating mode 7).

Table 2 Simulation results for the different SHARON reactor operating modes under study

Operating mode			OCI [€/year]				
			EQ	**AE**	**Acid**	**Base**	**Total**
1. No control	$\Phi_{G,in} = 3000\,m^3/h$	–	492,420	34,270	0	0	526,690
2. O_2 control	$O_2^{sp,optimal} = 3\,mg/L$	–	248,010	40,400	0	0	288,410
3. Cascade O_2 control	O_2^{sp} set by master $R^{sp} = 1.23$	–	478,630	121,310	0	0	608,930
4. pH control	$\Phi_{G,in} = 3000\,m^3/h$	$pH^{sp,optimal} = 6.25$	227,150	34,270	17,840	2,190	281,450
5. Cascade pH control	$\Phi_{G,in} = 3000\,m^3/h$	pH^{sp} set by master $R^{sp} = 1.23$	443,580	34,270	12,120	2,640	492,610
6. O_2 control + pH control	$O_2^{sp,optimal} = 3\,mg/L$	$pH^{sp,optimal} = 7.23$	140,830	65,080	540	31,030	237,480
7. Cascade O_2 control + pH control	O_2^{sp} set by master $R^{sp} = 1.23$	$pH^{sp,optimal} = 7.23$	56,300	59,330	5,200	4,740	125,570
8. O_2 control + cascade pH control	$O_2^{sp,optimal} = 4\,mg/L$	pH^{sp} set by master $R^{sp} = 1.23$	231,760	48,430	7,110	9,180	296,480

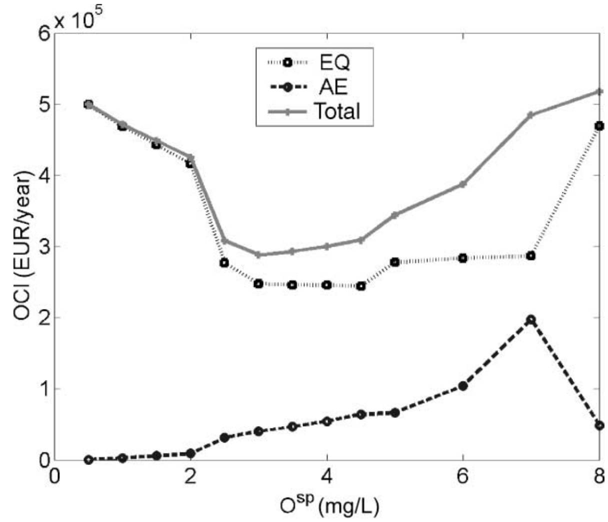

Figure 4 OCI in terms of O_2^{sp} for O_2 control

SHARON operating mode 4: pH control

Figure 5 shows the value of the different OCI components for the different values of the pH set-point examined. The best results (smallest OCI) are obtained for $pH^{sp} = 6.25$ mg/L, although this set-point is not well tracked because of insufficient control authority (limitation on amount of acid/base added). The nitrite:ammonium ratio produced in the SHARON reactor is not constant and most of the time is lower than the optimal ratio, so a large quantity of ammonium remains unconverted in the Anammox reactor.

SHARON operating mode 5: cascade pH control

Cascade pH control is based on increasing the pH^{sp} when the produced nitrite:ammonium ratio is too low, in order to increase the conversion due to higher NH_3 and lower HNO_2 equilibrium concentrations. However, the strategy does not perform well because the maximum growth rate of the ammonium oxidisers decreases at higher pH levels. As a result, very little nitrite is produced in the SHARON reactor and only little Anammox

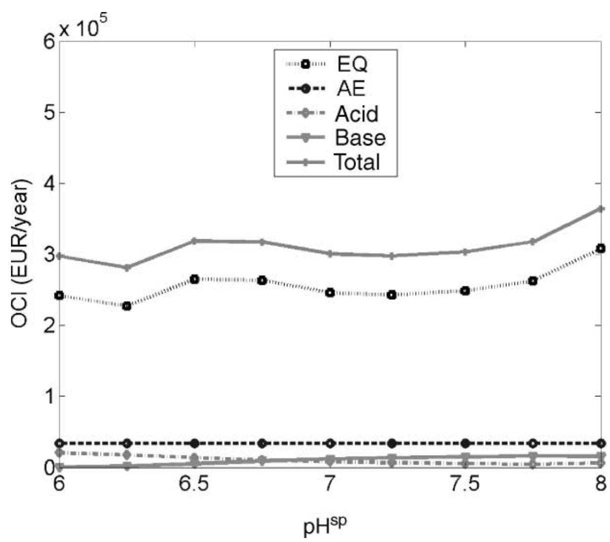

Figure 5 OCI in terms of pH^{sp} for pH control

conversion takes place in the subsequent Anammox reactor, resulting in a very bad effluent quality.

SHARON operating mode 6: O_2 control = pH control

Numerous combinations of fixed oxygen set-points (ranging from 1 to 7 mg/L) and fixed pH set-points (from 6.5 to 7.5) have been examined. The best results (minimum OCI) were obtained for $O_2^{sp} = 3$ mg/L and $pH^{sp} = 7.23$. However, even in this case, sometimes too much ammonium is converted in the SHARON reactor, leading to complete inhibition of the Anammox conversion by nitrite. Consequently, no ammonium conversion occurs in the Anammox reactor.

SHARON operating mode 7: cascade O_2 control + pH control

In order to avoid an unacceptable pH increase due to CO_2 stripping at high air flow rates (see operating mode 3), cascade O_2 control is combined with pH control to a fixed set-point. The optimum value of the pH set-point, giving rise to the minimum OCI value (Figure 6) is found as 7.23. Note that this value corresponds with the maximum growth rate of ammonium oxidisers (Figure 3, Equation 2). Figure 7 shows the corresponding reactor performance. Although the individual nitrite and ammonium concentrations in the SHARON reactor still vary, the produced nitrite:ammonium ratio remains quite constant, without nitrite excess produced. As a result, the Anammox reactor performs very well and a very good effluent quality is obtained, reflected in an OCI value as low as 125,570 €/year. From the operating cost savings compared with other operating modes, it should be possible to support the investment costs for online ammonium and nitrite analysers (assumed to cost about 2 × 25,000 €). Also, it must be stressed that this is the only operating mode so far, for which a good Anammox conversion takes place. In previous work where explicit pH dependency of the SHARON biomass growth rate was not considered (Volcke *et al.*, 2005), stand-alone cascade O_2 control appeared to perform well. However, in reality, biomass will only grow between certain pH limits, resulting in the necessity of pH control on top of cascade O_2 control.

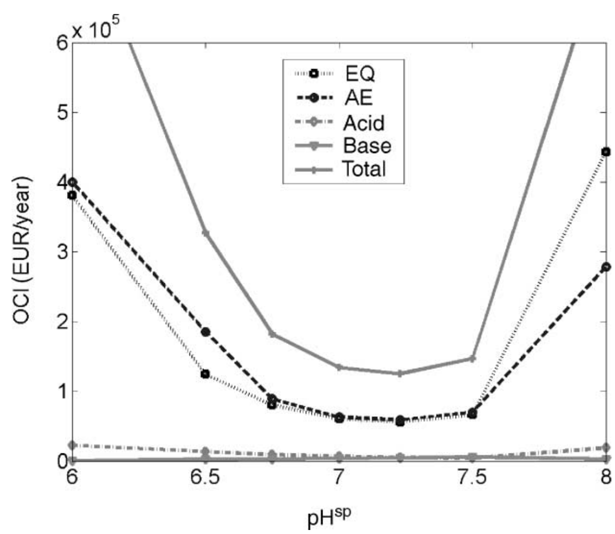

Figure 6 OCI in terms of pH^{sp} for cascade O_2 control + pH control

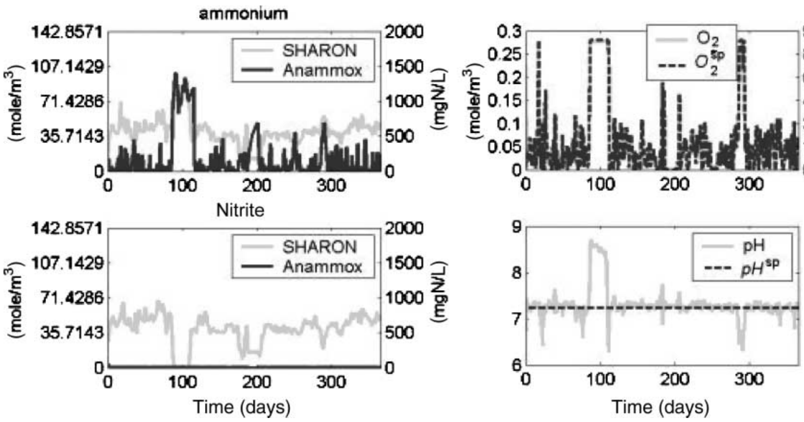

Figure 7 Reactor performance for cascade O_2 control + pH control (at $pH^{sp} = 7.23$)

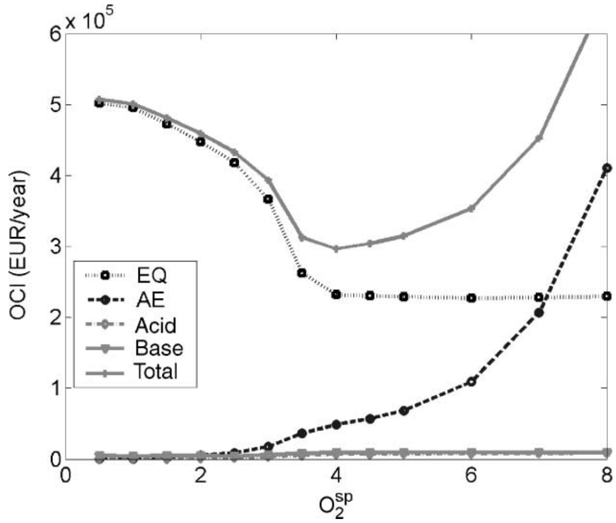

Figure 8 OCI in terms of O_2^{sp} for O_2 control + cascade pH control

SHARON operating mode 8: O_2 control + cascade pH control

Figure 8 summarises the simulation results in terms of costs for this operating mode. The best results are obtained for a fixed set-point $O_2^{sp} = 4$ mg/L. However, even for this best case scenario the nitrite:ammonium set-point is not well tracked, resulting in nitrite inhibition in the Anammox reactor, thus no consistent Anammox conversion takes place.

Conclusions and perspectives

By means of a simulation study different operating modes for a SHARON reactor were evaluated in view of their effect on a subsequent Anammox process. The operating modes differ in the applied control strategies for the produced nitrite:ammonium ratio, the O_2 concentration and the pH in the SHARON reactor in order to cope with varying influent conditions. Control of the nitrite:ammonium ratio produced by the SHARON reactor is essential to avoid toxic nitrite concentrations, which inhibit the Anammox conversion.

Control of O_2 and/or pH in the SHARON reactor is in the first place necessary to avoid wash-out of ammonium oxidisers from the SHARON reactor, due to retention time and process condition changes. Satisfying results were obtained only with cascade O_2 control, in which the O_2 set-point is set by a master controller tracking a fixed nitrite:amonium ratio, combined with pH control that avoids excessive pH increase under high oxygen supply conditions due to concomitant CO_2 stripping. At all times the Anammox process remained active under this operating mode.

All results have been quantified in an economic way by means of an operating cost index (OCI) for a wastewater plant with limited aeration capacity. The operating cost savings realised with the cascade O_2 control combined with pH control warrant the investment costs for the necessary on-line ammonium and nitrite sensors (payback time less than 1 year).

It must be noted that the chosen volume for the SHARON reactor will probably influence the usefulness of control. The relationship between reactor design and control will be the topic of future study.

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