Interaction between control and design of a SHARON reactor: economic considerations in a plant-wide (BSM2) context

Water Science & Technology **Vol 56 No 9 pp 117–125** © IWA Publishing 2007

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Abstract The combined SHARON-Anammox process is a promising technique for nitrogen removal from wastewater streams with high ammonium concentrations. It is typically applied to sludge digestion reject water, in order to relieve the activated sludge tanks, to which this stream is typically recycled. This contribution assesses the impact of the applied control strategy in the SHARON-reactor, both on the effluent quality of the subsequent Anammox reactor as well as on the plant-wide level by means of an operating cost index. Moreover, it is investigated to which extent the usefulness of a certain control strategy depends on the reactor design (volume). A simulation study is carried out using the plant-wide Benchmark Simulation Model no. 2 (BSM2), extended with the SHARON and Anammox processes. The results reveal a discrepancy between optimizing the reject water treatment performance and minimizing plant-wide operating costs.

Keywords Anammox; benchmarking; BSM2; operating cost index (OCI); optimization; plant-wide assessment; reject water treatment; SHARON; simulation; wastewater treatment

Introduction

In wastewater treatment plants (WWTPs) equipped with sludge digestion and dewatering systems, the reject water originating from these facilities contributes significantly to the nitrogen load of the activated sludge tanks, to which it is typically recycled. This is especially problematic in case the latter has a limited aeration/nitrification/denitrification capacity. Reject water treatment before recirculation by means of a SHARON-Anammox process (van Dongen *et al.*, 2001) is a promising option to relieve the activated sludge tanks. In the SHARON process, half of the ammonium in the reject water is nitrified to nitrite. Nitrate formation is suppressed by working at high temperatures combined with maintaining an appropriate sludge retention time, which is equal to the hydraulic retention time as a SHARON reactor is typically operated without sludge retention. In the subsequent Anammox reactor, almost equimolar amounts of ammonium and nitrite are combined to form nitrogen gas. In this way, substantial savings on aeration costs (up to 63%) and external carbon addition costs (up to 100%) are realized in comparison with conventional nitrification-denitrification over nitrate, at the same time minimizing CO_2 and sludge productions.

The impact of reject water streams on the performance of a WWTP has been previously assessed in a simulation study (Volcke *et al.*, 2006c), using the Benchmark Simulation Model no. 2 (BSM2, Jeppsson *et al.*, 2006; Vrecko *et al.*, 2006), that includes the processes describing sludge treatment and in this way allows for plant-wide evaluation. It has been demonstrated that the overall effluent quality of the plant in terms

doi: 10.2166/wst.2007.607

of Kjeldahl-nitrogen and nitrate is improved significantly by treatment of the reject water stream with a SHARON-Anammox process before recirculation. However, in this study of Volcke *et al.* (2006c), the applied control strategy in the SHARON reactor was rather arbitrary, and so was the reactor design. In search of optimizing the control strategy applied to the SHARON reactor, this contribution assesses the interaction between reactor design (volume) and the usefulness of control for the BSM2 case. The results are quantified in terms of conversion efficieny of the SHARON and Anammox reactors, as well as in terms of plant-wide operating costs, which are weighed against investment costs.

Methods

The BSM2, SHARON and Anammox models

The layout of the BSM2, representing a 80 000 PE WWTP (Jeppsson *et al.*, 2006), is given in Figure 1. The predenitrifying activated sludge system and the secondary clarifier are identical to the ones in the Benchmark Simulation Model no. 1 (BSM1, Copp, 2002). The BSM2 plant further contains a primary clarifier, a sludge thickener, an anaerobic digester and a dewatering unit. Plant performance evaluation is based on a one-year simulation, using influent data from Gernaey *et al.* (2005). For the simulation study described here, the BSM2 plant is operated with the default closed-loop strategy, as proposed by Vrecko *et al.* (2006), with some adjustments (Volcke *et al.*, 2006c).

The SHARON reactor model was developed 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 on the transport coefficients for O_2, CO_2 and N_2 between the two phases. The model further considers pH effects that occur during nitrification of highly concentrated streams. More details can be found in Volcke (2006). The Anammox reactor model describes a CSTR of 75 m^3 with almost complete (99.5%) biomass retention. Anammox kinetics are based on the model proposed by Dapena-Mora *et al.* (2004). Inhibition of Anammox growth by nitrite is incorporated using Haldane kinetics, with an inhibition

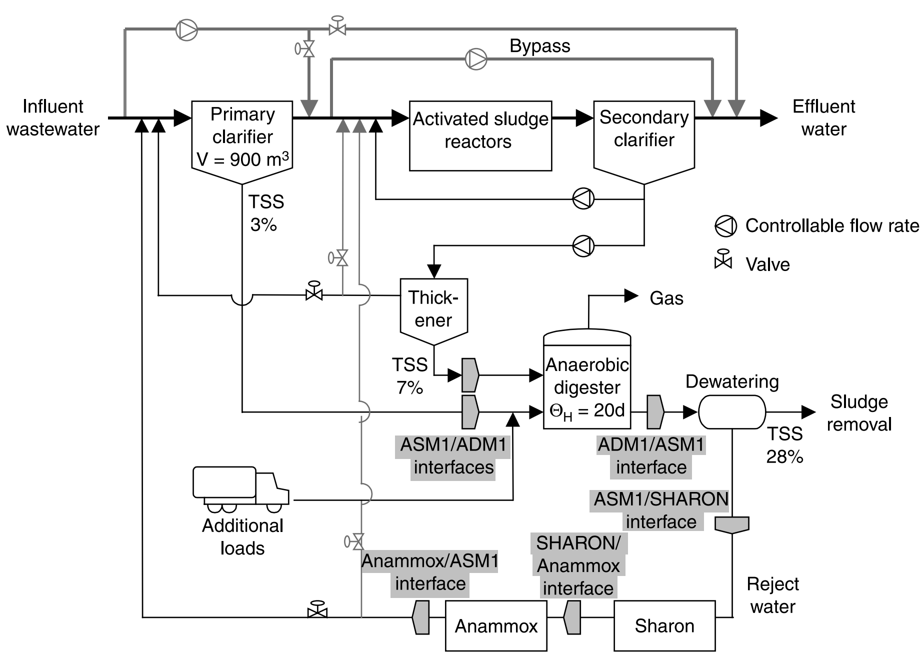

Figure 1 BSM2 plant with anaerobic sludge digestion and reject water recirculation, adapted from Jeppsson *et al.* (2006) for inclusion of the SHARON and Anammox processes

coefficient of 15 gN/m^3. A constant temperature of 35 °C has been assumed for both reactors. As the different submodels are based on different state variables, special attention was devoted to the model interfaces, in the way described by Volcke *et al.* (2006b). All models were implemented in Matlab-Simulink.

BSM2 reject water characteristics

Figure 2 illustrates the characteristics (daily mean values) of the BSM2 reject water, which is fed to the SHARON reactor, in terms of flow rate (mean 172 m^3 d^1), total ammonium concentration (TNH, mean 97 mole m^3) and total inorganic carbon concentration (TIC, mean 102 mole m^3). The TIC:TNH ratio hardly varies (1.02 → 1.11) around a mean value of 1.06, which is typical for reject water. The influent pH remains quite constant at 7.2 ± 0.1.

SHARON reactor operating modes under study

Simulations have been performed for different values of the SHARON reactor volume: 220 m^3 (corresponding with a mean retention time of 1.25 days), 338 m^3 and 460 m^3 (corresponding to a hydraulic retention time of 1.25 and 1.75 days respectively for the 95-percentile value of the reject water flow rate, i.e. the value that is only exceeded 5% of the time). The effect of the reactor volume on the usefulness of the applied control strategies has been studied. Controlling the SHARON reactor is in the first place necessary to avoid wash-out of ammonium oxidizers while keeping out nitrite oxidizers, for varying influent flow rates, influent composition and process conditions. Besides, the nitrite:ammonium ratio produced by the SHARON reactor should be controlled to an Anammox-optimal value, being 1.23 for the stoichiometric coefficient in the applied Anammox reactor model. In particular, too high nitrite:ammonium ratios should be avoided to prevent nitrite inhibition of the subsequent Anammox conversion. In this study, the following control strategies have been applied to the SHARON reactor, as stand-alone strategies or combined with each other.

- Aerobic retention time control by working with aerobic/anoxic periods. It is important to note here that - for a high influent flow rate or a small reactor volume - the hydraulic retention time may be smaller than the set point for the aerobic retention time. In this case, the aeration will be kept on so the resulting aerobic retention time will equal the hydraulic retention time but will inevitably be lower than the set point for the aerobic retention time.

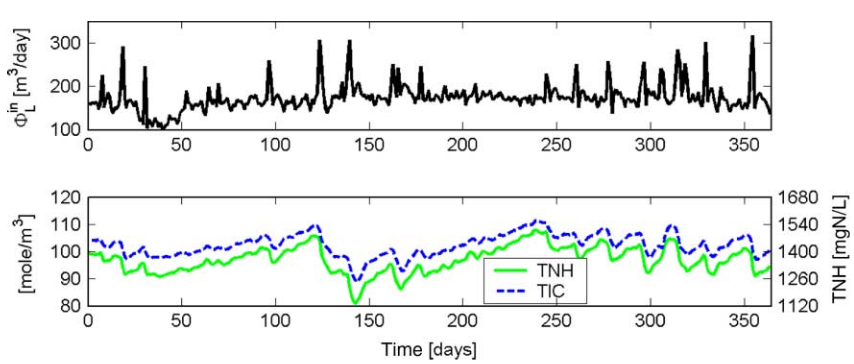

Figure 2 BSM2 reject water characteristics: flow rate (top), concentrations of total ammonium (TNH) and total inorganic carbon (TIC) (bottom)

- Oxygen control by adjusting the air flow rate (between 0 and $5000\,m^3\,h^1$) with a proportional controller.
- Cascade oxygen control, adjusting the oxygen setpoint (between 0 and $4\,g\,m^3$) to maintain a constant nitrite:ammonium ratio in the SHARON reactor. Both primary (master) and secondary (slave) controllers are proportional controllers.
- pH-control within a certain range around a set point $pH^{sp} = 7.23$, corresponding with a maximum growth rate as determined by Van Hulle *et al.* (2007). A proportional controller has been used. Both acid (96% H_2SO_4) and base (50% NaOH) addition have been limited to $50\,l\,h^{-1}$.

It has been decided not to use stand-alone pH-control or cascade pH-control, as the consumption of chemicals is costly and does not contribute to sustainable operation. Instead, the air flow rate will be used as much as possible as a control handle. Volcke (2006) found that the oxygen level in the reactor mainly determines whether ammonium is converted or not, while the extent of ammonium conversion can be controlled by switching between high and low oxygen levels, which can be seen as controlling the aerobic retention time. The aerobic sludge retention time (aerSRT) determines the actual growth rate μ^{amm} of the ammonium oxidizers; the corresponding ammonium conversion is higher for higher μ^{amm}. However, as the actual growth rate of ammonium oxidizers, μ^{amm}, cannot increase beyond its maximum value, μ^{amm}_{max}, increasing the aerobic retention time beyond this point will not lead to increasing ammonium conversion (and should be avoided to prevent nitrate formation). If still a higher ammonium conversion is desired, this can be achieved by increasing pH, through base addition. Besides, pH-control has also been applied to maintain the reactor pH within a range that allows sufficiently high maximum specific growth rates.

Economic evaluation by means of an operating cost index

Optimal design and operation of a process is a trade-off between effluent quality and the associated investment and operating costs. An Operating Cost Index (OCI) is a useful tool for simplifying the cost analysis necessary to make the trade-off. It includes relevant operating cost factors and indicates potential cost savings that can be made by introducing control strategies or plant design changes. Information on investment costs for the necessary equipment will then only be gathered for those control strategies that promise substantial operating cost savings. Vanrolleghem and Gillot (2002) previously demonstrated the use of an OCI to compare control strategies using the BSM1 (Copp, 2002). In this study, an OCI (in €/year) is defined which considers the plant-wide operating cost factors that differ between the applied operating strategies, similar as by Volcke *et al.* (2006c):

$$\begin{aligned} OCI_{PW} = & \gamma_1 \cdot EQ_{BSM2} + \gamma_2 \cdot \left(AE_{BSM2} + AE_{SH} + ME_{BSM2} + ME_{SH} + PE_{BSM2} + PE_{SH,An}\right) \\ & + \gamma_2 \cdot HE^{net} + \gamma_3 \cdot SP_{BSM2} + \gamma_3 \cdot (SP_{SH} + SP_{An}) + \gamma_4 \cdot EC - \gamma_5 \cdot MP \\ & + \alpha_{acid} \cdot \Phi_{SH,\,acid} + \alpha_{base} \cdot \Phi_{SH,\,base} \end{aligned}$$

The effluent quality term (EQ_{BSM2}) accounts for suspended solids (TSS), chemical oxygen demand (COD), biochemical oxygen demand (BOD), Kjeldahl-N (TKN) and nitrate (NO) in the effluent of the main WWTP. Aeration energy (AE), mixing energy (ME) and pumping energy (PE) are calculated for both the main plant ($_{BSM2}$) and the SHARON reactor ($_{SH}$). HE^{net} represents the heating energy which may be needed to heat the flow of sludge fed to the anaerobic digester. The sludge production SP_{BSM2} is calculated from accumulated and disposed solids of the plant, while also the solids accumulated in the SHARON and Anammox reactors (SP_{SH}, SP_{An}) are taken into account. Further, external carbon addition costs (EC) and cost savings as produced methane in the anaerobic digester (MP) are considered, as well as costs for acid and base addition in the SHARON reactor. The weights γ_i are taken from Vanrolleghem and Gillot (2002), or set relatively to Vrecko *et al.* (2006); the costs for acid and base addition have been based on http://ed.icheme.org/costchem.html. Besides the plant-wide operating cost index OCI_{PW}, an effluent quality term for the Anammox reactor EQ_{An} is defined (in kg pollution units PU/day), only considering ammonium in the Anammox effluent.

Results and discussion

Figure 3 summarizes the best results for the different reactor volumes in terms of the plant-wide operating cost index OCI_{PW}, which is a measure of the overall operating costs, and in terms of the effluent quality of the Anammox reactor (EQ_{An}), which indicates to which extent a good conversion efficiency is realized in the SHARON and Anammox reactors. More details are given in Table 1.

The best performance of the SHARON and Anammox reactor (lowest EQ_{An}) is obtained with combined cascade O_2-control and pH-control in the SHARON reactor. This operating mode ensures the production of a favourable nitrite:ammonium ratio in the SHARON reactor, which leads to a good conversion efficiency in the Anammox reactor. As the SHARON reactor volume increases from $V = 220\,m^3$ to $V = 460\,m^3$, the Anammox-optimal nitrite:ammonium set point ($R^{sp} = 1.1$) is tracked better in the SHARON reactor (Table 1), so the conversion efficiency of the Anammox reactor increases (lower EQ_{An}). For $V = 460\,m^3$, the nitrite:ammonium set point is tracked quite well (mean $R_{SH} = 1.06$), resulting in quasi complete conversion in the Anammox reactor (Figure 4). For smaller reactor volumes, the nitrite:ammonium ratios produced in the SHARON reactor are slightly suboptimal to feed the Anammox reactor. However, the ammonium concentrations that remain unconverted in the Anammox reactor ($98\,gN\,m^3$ for $V = 220\,m^3$ and $54\,gN\,m^3$ for $V = 338\,m^3$ on average) are to a large extent removed in the activated sludge tanks of the BSM2 plant, of which the aeration capacity seems to be not fully utilized, as can be seen from increased values of AE_{BSM2} for decreasing reactor volumes.

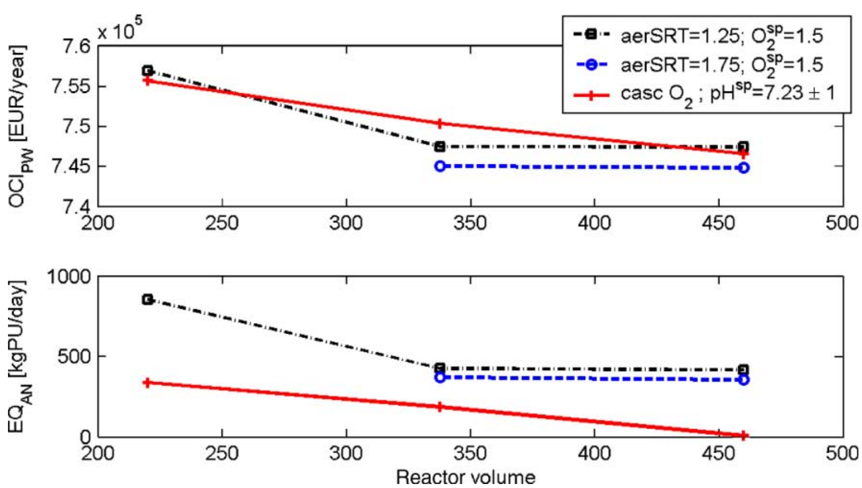

Figure 3 Plant-wide operating cost index (OCI_{PW}, top) versus Anammox reactor effluent quality (EQ_{AN}, bottom) for different operating modes in terms of SHARON reactor volume

Table 1 Performance indices and operating cost factors for operating modes under study

Reactor volume V (m^3) operating mode	338 aerSRT = 1.25 d O_2^{sp} = 1.5 g/m^3	338 aerSRT = 1.75 d O_2^{sp} = 1.5 g/m^3	338 cascade O_2 R^{sp} = 1.1 pH^{sp} = 7.23 ± 1	220 cascade O_2 R^{sp} = 1.23 pH^{sp} = 7.23 ± 1	460 cascade O_2 R^{sp} = 1.1 pH^{sp} = 7.23 ± 1
Nitrite:ammonium R_{SH}	0.86	0.88	0.94	0.89	1.06
EQ_{An} (€/year)	21 270	18 490	9 230	16 850	280
EQ_{BSM2} (€/year)	359 680	358 440	354 380	357 770	350 770
AE_{BSM2} (€/year)	181 080	180 950	180 530	180 880	180 090
AE_{SH} (€/year)	13 450	12 420	20 740	23 900	17 660
Base addition (€/year)	0	0	1 130	40	3 920
OCI_{PW} (€/year)	747 420	745 000	750 340	755 640	746 550

The best results in terms of the lowest plant-wide operating cost index (OCI_{PW}) have been obtained for an operating mode of the SHARON reactor in which the aerobic retention time is controlled through cyclic reactor operation at an aerobic SRT (aerSRT) of 1.75 days (maximum) and a fixed oxygen set point of $O_2^{sp} = 1.5\,g\,m^3$ is applied during the aerobic phases. Figure 5 displays the resulting performance of the SHARON and Anammox reactors in case $V = 338\,m^3$. A mean nitrite:ammonium ratio of 0.88 is produced in the SHARON reactor, resulting in an average ammonium concentration of 107 gN m^3 that remains unconverted in the Anammox reactor but again is removed to a large extent in the activated sludge tanks. This scenario has been found better than the case in which the aerSRT is controlled to 1.25 days for the same oxygen set point ($O_2^{sp} = 1.5\,g\,m^3$). Maintaining a larger aerobic retention time in the SHARON reactor results in a better Anammox effluent quality and consequently a better effluent quality of the main plant (although the difference is small) as well as a smaller aeration energy requirement in the activated sludge tanks (AE_{BSM2}). Surprisingly also less aeration energy is required in the SHARON reactor for aerSRT = 1.75 days compared to aerSRT = 1.25 days. This may be attributed to the fact that switching from anoxic to aerobic periods is always accompanied with large air flow rates (using a proportional controller to meet the oxygen set point), which are very energy-consuming. When an

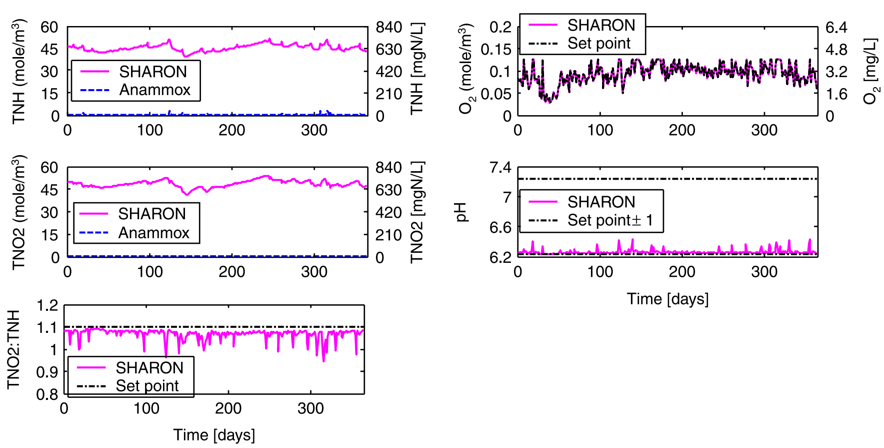

Figure 4 Total ammonium (TNH) and total nitrite (TNO2) concentrations in SHARON and Anammox reactors. Nitrite:ammonium ratio (TNO2:TNH), pH vs. pH^{sp}, O_2 vs. O_2^{sp} in SHARON reactor. Operating mode of SHARON reactor (V = 460 m^3) with cascade O_2-control ($R^{sp} = 1.1$) and pH-control at $pH^{sp} = 7.23 \pm 1$

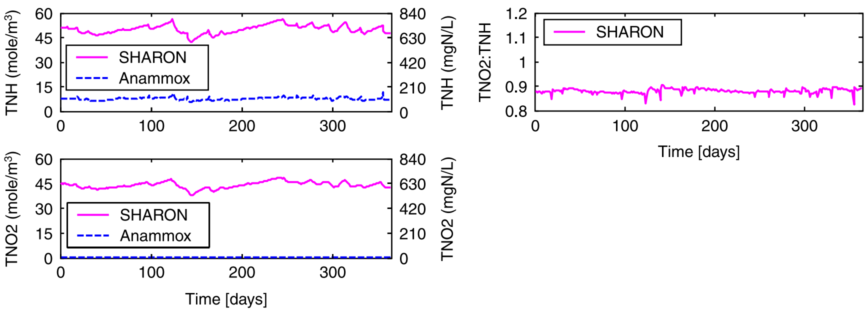

Figure 5 Total ammonium (TNH) and total nitrite (TNO2) concentrations in SHARON and Anammox reactors. Nitrite:ammonium ratio (TNO2:TNH) in SHARON reactor. Operating mode of SHARON reactor ($V = 338\,m^3$) with aerSRT = 1.75 days and O_2-control at $O_2^{sp} = 1.5\,gm^{-3}$

aerSRT of 1.75 days is applied, the reactor remains aerated for longer periods than for an aerSRT of 1.25 days, so there are less energy-consuming switches.

When applying combined aerobic retention time control (at aerSRT = 1.75 days) and oxygen control (at $O_2^{sp} = 1.5\,g\,m^3$) to a larger reactor ($V = 460\,m^3$ instead of $338\,m^3$), the yearly operating costs have been found only slightly lower (difference: 180 €/year, not shown), which will not warrant the additional investment costs for building a reactor of $460\,m^3$ compared to a reactor of $338\,m^3$. Using a smaller reactor volume ($V = 220\,m^3$), the operating strategy with combined aerobic retention time control (at aerSRT = 1.25 days) gives rise to insufficient ammonium conversion in the SHARON reactor during periods of high influent flow rates. This reactor volume is clearly too small to apply this type of control strategy, as the desired aerobic retention time can only be obtained 50% of the time. On the other hand, successful operation of a such a small SHARON reactor can be realized with cascade O_2-control, combined with pH-control. Cascade O_2-control for $R^{sp} = 1.23$ combined with pH-control between wide ranges (at $pH^{sp} = 7.23 \pm 1$) resulted in the lowest plant-wide operating costs for $V = 220\,m^3$ (OCI_{PW} = 755 640). Compared to the optimal scenario for $V = 338\,m^3$ (aerSRT = 1.75 days; $O_2^{sp} = 1.5\,g\,m^3$; OCI_{PW} = 745 000), the yearly operating costs are increased by 10 640 €/year, while the annual investment costs savings for building a reactor of $220\,m^3$ instead of $338\,m^3$ (depreciation period: 30 years; interest rate: 5%) are estimated at 1570 €/year, on the basis of a cost function given by Bohn (1993). As a result, operating a SHARON reactor of $338\,m^3$ with combined aerSRT (at 1.75 days) and O_2 control (at 1.5 g O_2 m^3) was judged as the best way to treat the BSM2 reject water.

Overall, when comparing the effluent quality of the Anammox reactor, expressed in terms of EQ_{An}, with the plant-wide operating cost index, OCI_{PW}, it is clear that a better conversion efficiency of the combined SHARON-Anammox process does not necessarily result in lower operating costs on a plant-wide scale. This is mainly attributed to the increased aeration energy needed to meet higher oxygen set points and to the base addition costs to maintain a minimal pH level in the SHARON reactor. The spare aeration capacity of the BSM2 activated sludge tanks also plays an important role: it is the reason why an improved effluent quality of the Anammox reactor does not result in an equivalent improvement of the effluent quality of the plant. It appears to be cheaper to remove residual ammonia in the main plant, provided it still has some aeration capacity left, rather than in the dedicated SHARON-Anammox reactor system.

It is interesting to note that, for the different scenarios examined in this chapter, the optimal nitrite:ammonium ratio needed to feed the Anammox reactor is never reached without pH-control (base addition). This is attributed to the relatively low alkalinity (bicarbonate):ammonium ratio in the BSM2 reject water: although it contains about equimolar amounts of inorganic carbon (TIC) and ammonium, more than 10% of the TIC is present as CO_2 and has no buffering capacity to compensate for the protons produced during nitritation. However, in the given case study, the amount of unconverted ammonium that remained in the Anammox reactor could be handled easily by the activated sludge tanks of the BSM2 plant, in which the aeration capacity was not fully utilized. For this reason, controlling the nitrite:ammonium ratio in the SHARON reactor more closely to the set point of 1.1 by adding base, also implying the implementation of a measurement system for ammonium and nitrite to monitor the produced nitrite:ammonium ratio, appears a waste of money. This situation is different from the one examined by Volcke *et al.* (2006a) for the influent conditions as observed at the full-scale SHARON reactor at Sluisjesdijk. In the latter case, monitoring of the produced nitrite:ammonium ratio is necessary, as the alkalinity:ammonium ratio in the reject water considered is so high that it would lead to a too high nitrite:ammonium ratio produced, leading to nitrite inhibition of the subsequent Anammox reactor. It is clear that the optimal operating strategy for a SHARON reactor depends on the reject water composition, in particular its alkalinity(bicarbonate):ammonium ratio.

Conclusions

The impact of the applied control strategy in the SHARON reactor for BSM2 reject water treatment with a combined SHARON-Anammox process has been assessed in terms of reject water treatment efficiency, as well as of the plant-wide operating costs. Particular attention has been paid to the interaction between reactor design (volume) and the controller performance.

The best performance of the SHARON and Anammox reactor in terms of Anammox effluent quality (ammonium) is obtained with combined cascade O_2-control and pH-control in the SHARON reactor. However, a better conversion efficiency of the combined SHARON-Anammox process does not necessarily result in lower operating costs on a plant-wide scale. This is due to the increased operating costs associated with more sophisticated control strategies, as well as to the spare aeration capacity of the activated sludge tanks in the BSM2 plant. These findings highlight the importance of considering the wastewater treatment plant as a whole when optimizing side stream treatment.

At different SHARON reactor volumes, different control strategies have been found optimal. For a moderately large reactor, good results have been obtained by controlling the aerobic retention time through cyclic reactor operation, and at the same time applying oxygen control during the aerobic phases. Because of the relatively low alkalinity:ammonium ratio of the BSM2 reject water, there is no risk in producing too high nitrite:ammonium ratios in the SHARON reactor which may lead to nitrite inhibition of the Anammox process. When using a smaller reactor volume, pH control becomes necessary as well.

Acknowledgements

The authors thank Dr. Ulf Jeppsson, IEA, Lund University, Sweden, Dr. Darko Vrecko, Jozef Stefan Institute, Slovenia and Dr. Krist Gernaey, DTU, Denmark, for providing the BSM2 implementation in Matlab and the useful recommendations on its use. Dr. Peter Vanrolleghem holds the Canada Research Chair in Water Quality Modelling.

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