Coupling the SHARON process with Anammox: Model-based scenario analysis with focus on operating costs

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Abstract The combined SHARON-Anammox process for treating wastewater streams with high ammonia concentration is discussed. Partial nitritation in the SHARON reactor should be performed to such an extent that an Anammox-optimal nitrite:ammonium ratio is generated. The SHARON process is typically applied to sludge digestion rejection water in order to relieve the ammonium load recycled to the main plant.
A simulation study for realistic influent conditions on a SHARON reactor with a fixed volume and operated with constant air flow rate reveals that the actual nitrite:ammonium ratio might deviate significantly from the ideal ratio and might endanger operation of the subsequent Anammox reactor. It is further examined how the nitrite:ammonium ratio might be optimized. A cascade pH control strategy and a cascade O_2 control strategy are tested. Simulation results are presented and the performance of the different strategies is assessed and quantified in an economic way by means of 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.

Keywords Anammox; nitrogen removal; economy; partial nitritation; process control; SHARON; modelling and simulation

Introduction

In the search of improving the sustainability of nitrogen removal from wastewater, nitritation techniques have been denoted for quite a while as very promising (Abeling and Seyfried, 1992). Nitritation comprises conversion of ammonium to nitrite, while further oxidation of nitrite to nitrate is prevented, thus realizing aeration cost savings in comparison with conventional nitrification to nitrate. In the SHARON (Single reactor High activity Ammonia Removal Over Nitrite) process (Hellinga *et al.*, 1998), nitritation is achieved by working at high temperature (30–40°C) and neutral pH (about 7.5). An appropriate sludge retention time (SRT) is maintained in order to wash-out the nitrite oxidizing biomass, which under these conditions grows more slowly than the ammonium oxidizing biomass. The SHARON reactor can be operated as a continuously stirred tank reactor (CSTR, chemostat) without biomass retention, so the SRT equals the hydraulic retention time (HRT). The first full-scale SHARON process is operational since January 1999 at the Rotterdam Sluisjesdijk sludge treatment plant (van Kempen *et al.*, 2001). In its original configuration, the SHARON process is operated under alternating aerobic and anoxic conditions, the latter serving for pH control by denitrification. However, the SHARON process can also be operated without denitrification. This operation mode is especially interesting in view of its coupling with a so-called Anammox (ANaerobic

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AMMonia OXidation) process, in which ammonium and nitrite are converted to nitrogen gas under anaerobic conditions by autotrophic micro-organisms (Jetten *et al.*, 1999). With the combined SHARON-Anammox process (van Dongen *et al.*, 2001), which has gained a lot of interest in the last few years, low nitrogen effluent concentrations can be obtained and high savings on aeration energy (up to 63%) and carbon source addition costs (up to 100%) are realized, while sludge production is negligible in comparison with conventional nitrification-denitrification. In case the SHARON influent contains ammonium and bicarbonate on an equimolar basis, which can be reasonably assumed for sludge digestion reject water, the protons produced during conversion of half of the ammonium are balanced 'exactly' via carbon dioxide stripping. For such high-concentrated streams, the protons produced during ammonium conversion completely destroy the bicarbonate buffer, causing a significant pH drop that prevents further nitrification. So theoretically, when assuming equimolar amounts of ammonium and bicarbonate in the influent of the SHARON reactor, its effluent will contain the required nitrite:ammonium ratio of 1:1 that is needed to feed the Anammox reactor. This simplified reasoning is represented schematically in Figure 1. In practice, the actual nitrite:ammonium ratio *needed* by the Anammox process will depend on the Anammox-biomass yield. When the nitrite:ammonium ratio in the Anammox feed deviates from the ideal ratio, its conversion efficiency will decrease. This may be acceptable in case the Anammox effluent is recycled to the main WWTP. Things become worse when the Anammox influent nitrite:ammonium concentration is too high and nitrite accumulates in the Anammox reactor. Treating the high loads coming from the SHARON process, one must take care that the nitrite level in the Anammox reactor doesn't rise above the toxic level. The nitrite:ammonium ratio *produced* in practice by the SHARON process depends on a number of factors, e.g. influent alkalinity, actual SRT and reactor oxygen and pH level (van Dongen *et al.*, 2001).

In this contribution, the nitrite:ammonium ratio produced by the SHARON process, as well as its effect on the subsequent Anammox process, is examined for realistic influent conditions by means of a simulation study. Two control strategies are proposed to optimize this ratio: cascade feedback control of the effluent nitrite:ammonium ratio, setting the pH set-point for a slave controller that acts by acid/base addition and cascade feedback control of the effluent nitrite:ammonium ratio, setting the O_2 set-point for a slave controller that acts by adjusting the air flow rate. Simulation results are presented. The performance of the different operation modes is assessed in an economic way by means of an operating cost index (OCI).

The SHARON and Anammox models

The SHARON reactor model, implemented in Matlab-Simulink, is based on the model by Hellinga *et al.* (1999) and has been further developed and described by Volcke *et al.* (2002). As significant pH-effects occur during nitrification of high-concentrated streams, a distinction is made between the different forms of components involved in chemical equilibria. The reactor pH is calculated at every time step from the charge balance in the

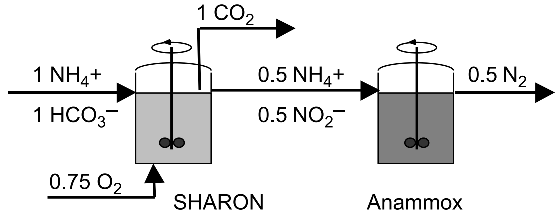

Figure 1 Simplified scheme of the SHARON-Anammox process

reactor, in order to assure the sum of all charges is zero. pH dependency of the biomass growth rate is taken up implicitly through the concentrations of the uncharged ammonia and nitrous acid, which are pH dependent. Explicit pH dependency of the biomass growth rate has not been considered in this study.

The Anammox reactor model, implemented in WEST® (Vanhooren *et al.*, 2003; Hemmis N.V., Kortrijk, Belgium), consists of a continuously stirred tank reactor with almost complete (99.9%) biomass retention. Anammox kinetics are based on the model proposed by Dapena-Mora *et al.* (2004). Inhibition of Anammox growth by nitrite was incorporated by a Haldane dependency, with an inhibition coefficient of 1 mole/m^3, in accordance with Strous *et al.* (1999).

Simulation results

The behaviour of the SHARON reactor is simulated over a period of 100 days under realistic influent conditions. An operating mode without process control and constant air flow rate is compared with an operating mode with cascade pH control of the nitrite:ammonium ratio produced in the SHARON reactor and one with cascade O_2 control of this ratio.

Influent conditions

In order to obtain a realistic influent file, daily averaged on-line measurements for flow rate and ammonium concentrations, as well as periodic (1–2 per week) lab analyses for bicarbonate alkalinity and pH measurements (on 24 hour collected samples) from the full-scale SHARON process in Rotterdam were used. All data were linearly interpolated to obtain a smooth profile. Figure 2 gives the resulting load profiles for ammonium and bicarbonate. The influent pH varies between 8 and 8.2 (mean 8.08), the influent bicarbonate:ammonium molar ratio varies between 0.40 and 3.59 (mean 1.06). The influent sludge digestion centrate water was further assumed not to contain any nitrite or nitrate, its temperature was assumed constant at 35°C. The dissolved oxygen and nitrogen (N_2) concentrations were calculated as the equilibrium concentrations with air. The concentrations of incoming autotrophic and heterotrophic biomass were set at 0.01 C-mole/m^3 (0.25 gVSS/m^3) and 5 C-mole/m^3 (125 gVSS/m^3) respectively, in order to simulate ingrowth of biomass in the reactor.

The SHARON reactor at the Sluisjesdijk treatment plant in Rotterdam has a volume of 1,710 m^3 and was originally cyclically aerated to establish nitrification and denitrification. For the future coupling with Anammox, denitrification will no longer be necessary. To maintain a sufficiently short aerobic retention time to prevent complete oxidation of ammonium to nitrate, the cyclically aerated operation mode will be maintained, but methanol will no longer be added during the non-aerated phase so no denitrification will take place. In case a new SHARON reactor should be built, it is more logical to build a smaller reactor. For the given influent flow rate (varying between 0 and 921 m^3/day, yearly mean 422 m^3/day), the same mean aerobic retention time (1.25 days) as in the full-scale Sluisjesdijk plant would be established by continuously aerating (instead of

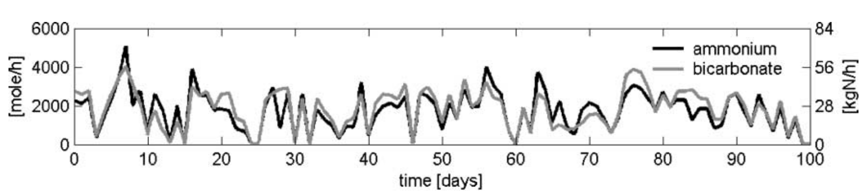

Figure 2 Typical SHARON influent ammonium and bicarbonate loads

cyclically operating) a reactor with a constant volume of 528 m^3. In this simulation study we used this volume and three different operating modes for evaluating the continuously aerated SHARON reactor.

Operating mode 1: no control

Figure 3 shows the simulation results, obtained in case the SHARON reactor is operated without process control and with a constant air flow rate of $\Phi_{G,in} = 5{,}000\ m^3/h$, a low value in order to avoid nitrite inhibition in the Anammox reactor that would result in a lower N-removal efficiency. At the prevailing varying HRT(= SRT)-values, the oxygen supply in the SHARON reactor is most of the time insufficient to convert sufficient ammonium to reach the desired nitrite:ammonium ratio. During periods with low influent ammonium loads, however, still too much nitrite is produced and the Anammox reaction is strongly inhibited because of the resulting unfavourable nitrite:ammonium ratio. These results suggest that it is highly recommended to strictly control the nitrite:ammonium ratio produced by the SHARON reactor to its Anammox-optimal ratio, not only to increase the conversion efficiency of the Anammox reactor, but especially to avoid toxic nitrite concentrations, which inhibit the Anammox conversion. This option is evaluated in the following paragraphs.

Operating mode 2: cascade pH control of produced nitrite:ammonium by acid/base addition

The nitrite:ammonium ratio in the SHARON effluent can be controlled by adding acid or base, affecting pH and consequently also the ammonium conversion. The proposed cascade feedback controller (Figure 4) consists of a master controller, maintaining the desired nitrite:ammonium set-point ($R^{sp} = 1.2$) by setting the pH-set-point (limited between 6–8.5) for the slave controller that acts by acid/base addition. The acid/

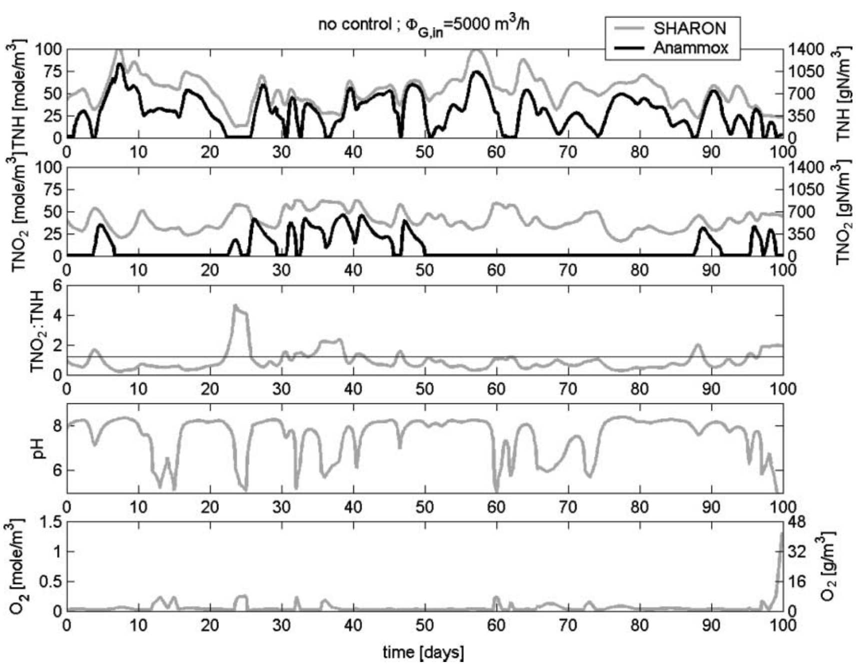

Figure 3 (from top to bottom): Concentration profiles of total ammonium (TNH), total nitrite (TNO_2) and nitrate in SHARON reactor and in subsequent Anammox reactor. Nitrite:ammonium ratio (TNO_2:TNH), pH and O_2 concentration profiles in SHARON reactor. Operation mode of non-controlled SHARON reactor with constant air flow rate $\Phi_{G,in} = 5{,}000\ m^3/h$

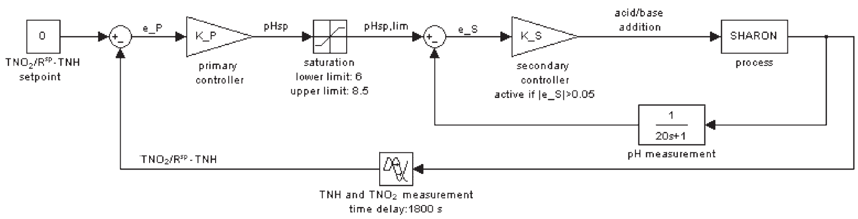

Figure 4 Structure of the proposed cascade pH controller

base addition was constrained by requiring a minimum deviation of 0.05 from the pH-set-point before adding acid/base. The on-line measurements of ammonium and nitrite were modelled as being ideal, but with a delay of 0.5 h. The pH sensor is modelled as a first order system with a time constant of 20 s. The secondary and primary controllers are both proportional controllers.

Figure 5 gives the simulation results. The cascade pH controller, working under constant air flow rate, performs somewhat better in terms of realizing the optimal nitrite:amonium ratio than the scenario with the same constant air flow rate ($\Phi_{G,in} = 5000\,m^3/h$) but without control. This is associated with a slightly increasing nitrate concentration in the Anammox reactor (not shown). A drawback of this operation mode is the large amount of acid/base that has to be added. However, this amount could be reduced by optimizing the pH controller.

Operating mode 3: cascade O_2 control of produced nitrite:ammonium by adjusting air flow rate

The cascade O_2 controller (Figure 6) consists of a master controller, maintaining the desired nitrite:ammonium set-point ($R^{sp} = 1.2$) by setting the O_2-set-point (limited between 0–8 g/m^3) for the slave controller that acts by adjusting the air flow rate (limited

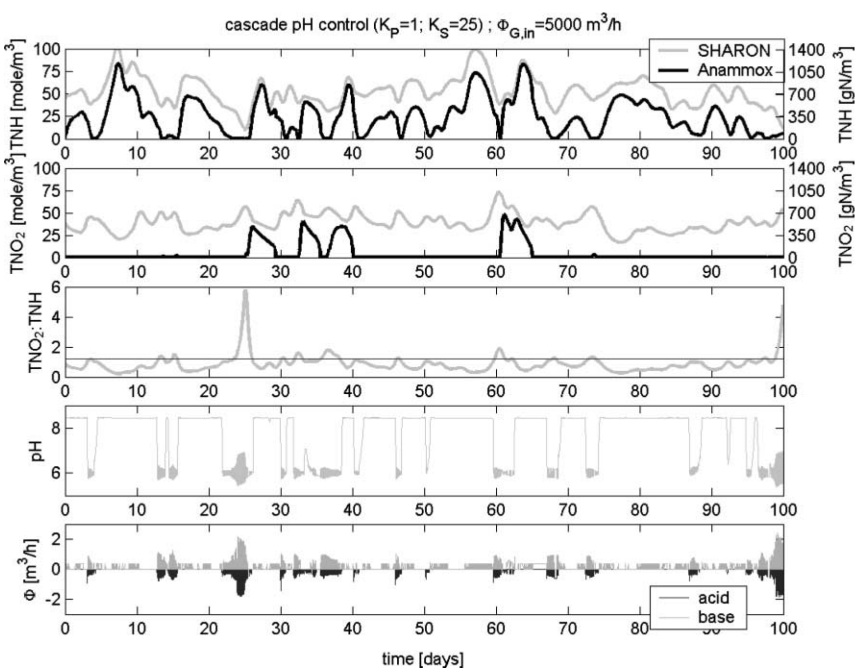

Figure 5 (from top to bottom): Concentration profiles of total ammonium (TNH) and total nitrite (TNO_2) in SHARON reactor and in subsequent Anammox reactor. Nitrite:ammonium ratio (TNO_2:TNH), pH and acid/base addition profile for SHARON reactor. Operation mode of cascade pH controlled SHARON reactor with constant air flow rate $\Phi_{G,in} = 5{,}000\,m^3/h$

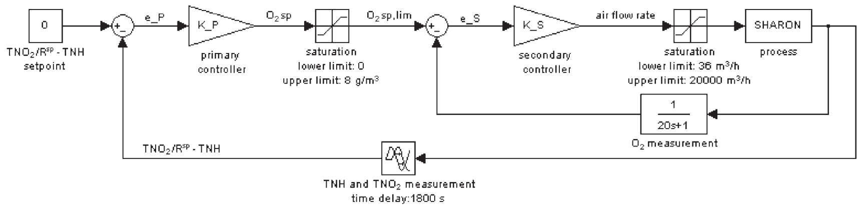

Figure 6 Structure of the proposed cascade O_2 controller

between 36-20,000 m^3/h). The on-line measurements of ammonium and nitrite were modelled as being ideal, but with a delay of 0.5 h. The O_2 sensor is modelled as a first order system with a time constant of 20 s. The secondary and primary controllers are both proportional controllers.

The simulation results are given in Figure 7. Although individual nitrite and ammonium concentrations in the SHARON reactor still vary, their profile is very similar and the produced nitrite:ammonium ratio remains quite constant. As a result, the Anammox reactor performs very well. The nitrite concentration stays very low and no nitrite inhibition occurs.

Evaluation procedure: use of an operating cost index (OCI)

The optimal design and operating mode 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 in simplifying this cost analysis. It includes the most important operating cost factors and indicates possible cost savings that can be made with control. Information on investment costs for the necessary equipment will then only be gathered for those control strategies that promise substantial operational cost savings. Vanrolleghem and Gillot

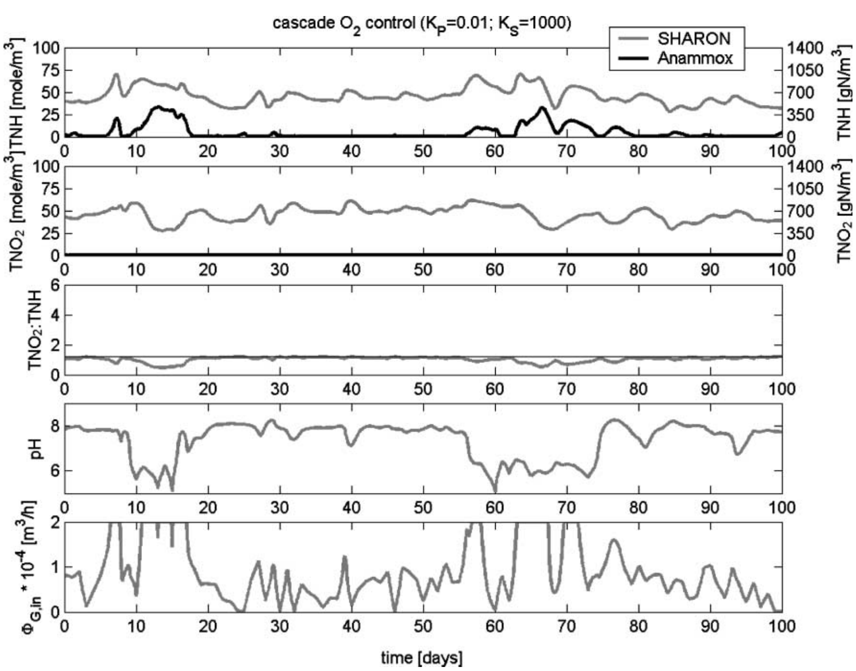

Figure 7 (From top to bottom): Concentration profiles of total ammonium and total nitrite in SHARON reactor and in subsequent Anammox reactor. Nitrite:ammonium ratio (TNO_2:TNH), pH and air flow rate profile for SHARON reactor. Operation mode of cascade O_2 controlled SHARON reactor

(2002) have previously demonstrated the use of an OCI to compare control strategies through the COST benchmark (Copp, 2002).

In this study, an OCI is defined on the basis of the following considerations. As the Anammox effluent doesn't comply with prevailing legislation, it will be most likely recycled to the main wastewater treatment plant (WWTP). It can be reasonably assumed that nitrite and nitrate in the Anammox effluent will be denitrified in the recycle stream, where they are mixed with other streams, containing COD. Ammonium that is recycled to the main plant, which is assumed here to have a lack of aeration capacity, will end up in the effluent and will be fined by the effluent quality term EQ (in kg Pollution Units/day). This term is calculated as in the benchmark approach (Copp, 2002), but in this study only covers ammonium. The differences in the SHARON reactor air flow rates for the different scenarios are accounted for through the aeration energy term AE (in kWh/day), which is also calculated as in the benchmark approach. For the operating mode with acid and base addition, the costs for addition of these chemicals (96% H_2SO_4 and 50% NaOH) are taken into account as well. The resulting OCI is written as follows:

$$OCI = \gamma_1 \cdot EQ + \gamma_2 \cdot AE + \alpha_{acid} \cdot \Phi_{acid} + \alpha_{base} \cdot \Phi_{base} \qquad (€/year)$$

The cost coefficients for the pollution units, aeration energy and acid and base additions are summarized in Table 1, based on Vanrolleghem and Gillot (2002) (for EQ and AE terms) and http://ed.icheme.org/costchem.html (for acid and base addition). Note that the OCI only includes the operating costs that differ between the scenarios under study. As the volume of the SHARON reactor is considered fixed on a predefined value and is constant throughout the operation, reactor investment costs are the same for all scenarios examined. Savings in operation costs between two operating modes thus equal the investment costs that can be supported for extra control equipment.

Table 2 summarizes the results of the economic evaluation. The operating mode with cascade pH control improves the effluent quality in comparison to the operating mode without control for the same value of the air flow rate (5,000 m^3/h) but requires such large acid/base addition that the operating costs are even higher (89,120 €/year). Hence, this operating mode is not worth implementing. The operating mode with cascade O_2 control performs very well in terms of effluent quality. Even though the aeration costs are much higher, the overall OCI is much lower than for the non-controlled operating mode: potential cost savings of more than 137,000 €/year are realized by implementing the cascade O_2 control. This certainly warrants the investment costs for the ammonium and nitrite measuring system (assumed to cost 2 × 25,000 €) and additional costs for adjustable air supply equipment. Note that the OCI considers effluent fines but it doesn't take into account a maximum discharge limit above which the permit of the WWTP is endangered. This gives an extra reason for implementing the cascade O_2 control, which yields a very good effluent quality.

It must be stressed that the performance of the different operating modes is highly dependent on the kinetics of both the SHARON and the Anammox process. It seems recommendable to investigate to what extent direct pH-dependency of the biomass

Table 1 Cost multiplication factors

Economic weight	Value	Unit
γ_1	50	€/EQ/year (EQ in kgPU/d)
γ_2	25	€/AE/year (AE in kWh/d)
α_{acid}	62.3	€/m^3
α_{base}	93.4	€/m^3

Table 2 OCI economic evaluation

Cost factor (€/year)	No control	Cascade pH control	Cascade O_2 control
Effluent fines	207,000	179,000	30,160
Aeration costs	25,520	25,530	65,090
Chemical addition	0	117,100	0
OCI (€/year)	232,480	321,600	95,250
Savings (€/year)	0	−89,120	137,200

growth rate in the SHARON reactor, which was not included in the model, influences the results. Concerning the Anammox reactor, in particular the degree of nitrite inhibition, translated into the nitrite inhibition coefficient, determines the usefulness of controlling the SHARON reactor and the choice of the control strategy.

Conclusions and perspectives

The usefulness of controlling a SHARON process in order to generate an Anammox-optimal nitrite:ammonium ratio has been examined by means of a simulation study. Control of the nitrite:ammonium ratio produced by the SHARON reactor is crucial to avoid inhibitory nitrite concentrations in the Anammox reactor. 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. An economic analysis by means of an operating cost index shows that implementation of this operation mode warrants the associated investment costs. As a side-result of this work, the authors want to stress the need for research on the nitrite inhibition of the Anammox reaction, since it appears a bottleneck for the efficiency of the Anammox process when coupled with a partial nitrification process for the treatment of ammonium-rich streams. In future, explicit pH dependency of the SHARON biomass growth rate will be included in the model and its effect on the simulation results will be examined.

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