Control of a Biological Nitrogen Removal Process in an Intensified Single Reactor Configuration

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Abstract: The nitrogen removing granular sludge process is a novel and intensified process. However, its stable operation and control remains a challenging problem. In this contribution, a new process oriented approach is used to develop, evaluate and benchmark control strategies to ensure stable operation and rejection of disturbances. Three control strategies were developed: a feedforward control (case 1), a rule-based feedback control (case 2), and a feedforward-feedback controller, in which the feedback loop updates the set point of the feedforward loop (case 3). The case 1 controller, based on influent measurements, showed the best performance against disturbances in the ammonium concentration, whereas case 2 was providing the best performance against disturbances in the organic carbon concentration. The case 3 controller rejected both disturbances satisfactorily. Thus, this controller provided versatility towards disturbance rejection, however through a less tight control, which meant a larger offset from the desired removal efficiency.

Keywords: Process control; Process intensification; Wastewater treatment; Nitrogen removal; Biological treatment; Biofilm; Anammox

1. INTRODUCTION

There is a general interest in process intensification to reduce costs and improve efficiency. For wastewaters containing high concentrations of nitrogen and low organic carbon to nitrogen ratios, complete autotrophic nitrogen removal (CANR) is a suitable, novel process that can increase the treatment capacity approximately five times. This process, originally designed as a two-stage SHARON-Anammox process (van der Star et al., 2007), is convenient for treating anaerobic digester liquor, landfill leachate, or special industrial wastewaters, because costs related to the need of aeration and carbon addition are lowered by 60% and 100%, respectively, compared to conventional nitrification-denitrification treatment. The complete conversion to nitrogen gas consists of a combination of two processes, which are catalyzed by two different microbial groups that grow under different conditions. In addition, other microbial groups are competing with these two desired microbial groups. Energy and capital costs can further be reduced by intensifying the process and performing it in a single biofilm reactor, where all processes take place simultaneously, e.g. in a granular sludge reactor. Previously, several control strategies for the two-stage process have been developed and tested (e.g. Volcke et al., 2007). However, results cannot be directly transferred to the intensified single-stage system, since fewer actuators are available and the process dynamics become more complex, which is often the case for intensified systems (Nikacevic et al., 2012).

In a previous modeling study the oxygen to ammonium loading ratio (RO), as opposed to the concentration ratio, was identified as a key factor for securing a high removal efficiency and conversion rate, while avoiding growth of undesired microbial groups (Vangsgaard et al., 2012). Additionally, ranges of ratios of nitrogen species consumed or produced, that indicate a suitable operation, have been formulated based on reaction stoichiometry and process knowledge (Mutlu et al., 2013). A ratio between the ammonium removal and the total nitrogen removal (R_{AmmTot}) has been formulated as a measure of the relative activity of microbial groups present in the system.

The aim of this work was to design a control system through a process oriented approach for a single-stage treatment utilizing process insights obtained from previous model and experimental studies. This has been illustrated through numerical simulations, utilizing an experimentally calibrated and validated model, for a case study, in which the controller kept the intensified process at a stable and efficient performance.

2. PROCESS ORIENTED APPROACH FOR CONTROLLER DEVELOPMENT

2.1 *Objective*

The objective of each controller was to obtain a high and stable nitrogen removal.

2.2 *Variable Analysis*

A list of the potential controlled variables (CVs), potential manipulated variable (MVs) and disturbances can be seen below. The concentrations of ammonium and organic carbon were identified as the two main disturbances.

Table 1. Possible manipulated variables (MVs), controlled variables (CVs), and disturbances

Variable	Unit	Candidate for
Q_{out}	L/d	MV
Heating	W	MV
Mixer	rpm	MV
k_La	1/d	MV
$NH_4^+{}_{out}$	mg N/L	CV
$NO_2^-{}_{out}$	mg N/L	CV
$NO_3^-{}_{out}$	mg N/L	CV
DO_{bulk}	mg COD/L	CV
pH	-	CV
T	°C	CV
RT	-	CV
R_{AmmTot}	-	CV
$NH_4^+{}_{in}$	mg N/L	Disturbance
S_S	mg COD/L	Disturbance

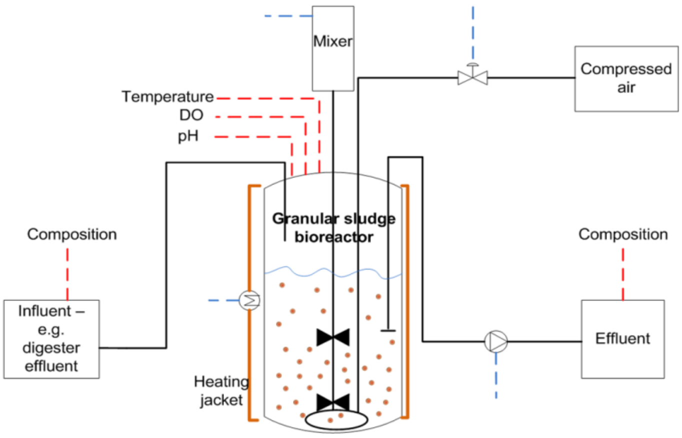

Figure 1. Schematic illustration of the reactor system with the possible MVs and CVs.

In Table 1 RT is the removal efficiency defined as the total nitrogen removed (ΔTN) over the total nitrogen in the influent (TN_{in}):

$$RT = \frac{\Delta TN}{TN_{in}} = \frac{NH^+_{4,in} + NO^-_{2,in} + NO^-_{3,in} - NH^+_{4,out} - NO^-_{2,out} - NO^-_{3,out}}{NH^+_{4,in} + NO^-_{2,in} + NO^-_{3,in}}$$

And R_{AmmTot} is the ammonium removal over the total nitrogen removal:

$$R_{AmmTot} = \frac{\Delta NH_4^+}{\Delta TN} = \frac{NH^+_{4,in} - NH^+_{4,out}}{NH^+_{4,in} + NO^-_{2,in} + NO^-_{3,in} - NH^+_{4,out} - NO^-_{2,out} - NO^-_{3,out}}$$

2.3 *Control Degree of Freedom Analysis*

Four potential actuators (MVs) were identified in the system; effluent pump, mixer, heating jacket, and air supply (Figure 1). The influent stream was assumed to originate from a sludge digester and was therefore a disturbance to the system. The effluent pump was assumed to perfectly control the level, and thus the hydraulic retention time (HRT) in the reactor at a given set point (a good assumption considering that flow variations are several orders of magnitude faster than the bioreactions). The heating jacket was assumed to perfectly control the temperature. Since the effect of mixing was not completely established, the mixer was not considered a suitable actuator. Therefore, the only available actuator for control was the air supply. For simplicity, this manipulated variable was represented by the oxygen transfer coefficient, k_La, in the model.

2.4 *Identification of Controlled Variable*

Since only one MV was available, pairing it with an appropriate CV was essential. The measured variables are indicated on Figure 1 and at first glance the obvious CV candidates are dissolved oxygen (DO) or failing that, effluent concentrations of ammonium, nitrite or nitrate. DO, which is often used as a CV in biological treatment of wastewater, was not a suitable CV in this case since its concentration was very low in the reactor, i.e. below the detection limit. Besides, none of the aforementioned variables could be directly related to nitrogen removal due to the complexity of the intensified process. Hence, RT was proposed directly as the CV.

2.5 *Control Structures*

Three control strategies were developed with RT as the CV and k_La as the MV.

Case 1: The first was a feedforward control (Figure 2A) based on the optimal oxygen to ammonium loading ratio (RO):

$$RO = \frac{L_{O_2}}{L_{TAN}} = \frac{k_La\left(S_{O2,sat}\right)}{S_{TAN,in} / HRT}$$

Case 2: The second control strategy (Figure 2B) consisted of a feedback loop where the control action was determined by the efficiency offset ($e(t) = RT_{sp} - RT(t)$) and the value of R_{AmmTot} was used to diagnose the system. A value above the set point of R_{AmmTot} indicated nitrite or nitrate accumulation leading to a lower total removal efficiency. The oxygen supply should therefore be decreased in order to return to a balanced activity state. If the value was below the set point value, the activities were balanced, and the k_La should increase, such that more ammonium could be removed and the efficiency be improved.

Case 3: The third control strategy (Figure 2C) was a feedforward-feedback control system, where the feedback loop updated the set point of the feedforward loop merging the strategies from case 1 and 2. The RO feedforward control acted as the “slave”, and its set point was controlled by the “master” loop where the offset in RT was the error and R_{AmmTot} was deciding the direction of the action of the controller, analogously to the previous strategy (case 2).

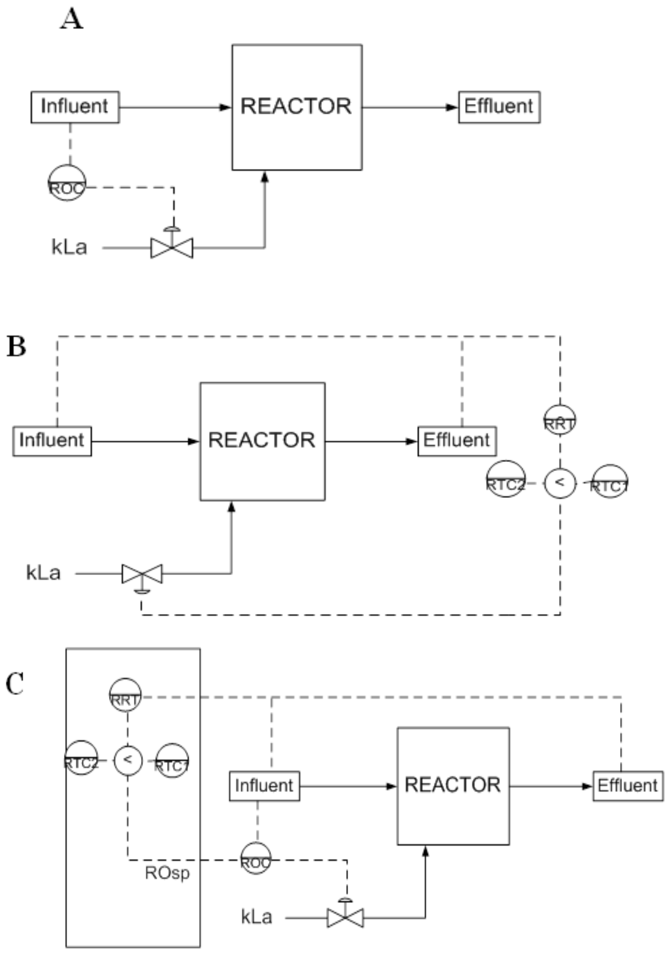

Figure 2. Layout of the three control strategies. A) Case 1: Feedforward control, B) Case 2: Rule based feedback control, and C) Case 3: Feedforward-feedback control.

2.6 Control Laws

The case 1 control law was derived from the steady state model to be:

$$RO_{sp} = \frac{k_L a\left(S_{O2,sat}\right)}{S_{TAN,in} / HRT} \iff k_L a = \frac{RO_{sp} S_{TAN,in}}{HRT\left(S_{O2,sat}\right)}$$

For case 2 a proportional-integral (PI) controller was implemented:

$$k_L a(t) = \begin{cases} k_L a_{\infty} - K * e(t) - \dfrac{K}{\tau_I}\displaystyle\int_0^{\tau} e(t)dt, & R_{AmmTot}(t) > R_{AmmTot,sp} \\ k_L a_{\infty} + K * e(t) + \dfrac{K}{\tau_I}\displaystyle\int_0^{\tau} e(t)dt, & R_{AmmTot}(t) \le R_{AmmTot,sp} \end{cases}$$

The plant transfer function was approximated to a first-order-plus-delay model using the half rule defined by Skogestad (2003). This model was used to tune the controller using the internal model control (IMC) guidelines (Skogestad, 2003). In order to avoid chattering, a deadband above 95% removal was used in this case.

Case 3 consisted of the controller designed in case 1 (eq. 4) as the slave controller, whose set point was set by the following proportional configuration:

$$RO_{sp}(t) = \begin{cases} RO_{sp,\infty} - K_C * e(t), & R_{AmmTot}(t) > R_{AmmTot,sp} \\ RO_{sp,\infty} + K_C * e(t), & R_{AmmTot}(t) \le R_{AmmTot,sp} \end{cases}$$

where $K_C \approx 2$ was obtained from the results of a perturbation of the $k_L a$ in the system with no controller implemented. The optimal set point values were obtained by deriving the optimal oxygen to nitrogen loading ratio as in Vangsgaard et al. (2012).

2.7 Control Performance Evaluation

The validated model and the three control strategies were implemented in the Matlab/Simulink software. Step changes of the concentration of two compounds in the influent were simulated, with two different levels of each. For ammonium a positive and negative perturbation were simulated in the form of a ±10% change in the default concentration of 500 mg N/L, while concentrations of 100 and 200 mg COD/L were used for soluble readily degradable organic carbon (S_s) in the influent. These two compounds were the ones of major concern, since i) the main objective of the process was to remove nitrogen from the influent stream, and ii) the COD concentration presented large variations, leading to the growth of microbial groups, which compete for substrates with the desirable microbial groups performing nitrogen removal. The ability of the controller to reject the disturbance was evaluated by the integral of the absolute error (IAE) defined as follows: $IAE = \int_0^{t_{end}} |e(t)| dt$. In all the three cases the RT was evaluated, and the IAE was calculated during an operating time of 10 days. The cost of the change of the actuator was measured as the total variation (TV), which was calculated as follows: $TV = \sum_{i=1}^{n} |u_{i+1} - u_i|$, where u_i is the value of the MV and subscripts i and i+1 indicate the consecutive sampling times.

3. RESULTS AND DISCUSSION

3.1 Input Disturbances: Step Change Analysis

In Table 2 and Figure 3A, it can be seen that the feedforward control strategy from case 1 was handling the ammonium step change best, with the lowest IAE and TV values. This was due to the almost immediate response of this control strategy to the incoming disturbance. However, the other control strategies were also doing much better than the open loop with no action.

Table 2. Responses of the open loop and the three control strategies to ±10% step changes in the ammonium concentration and organic carbon concentrations of 100 and 200 mg COD/L in the influent.

Control strategy	Disturbance	IAE [d]	TV	RT [-]
No control	+10% NH_4^+	2.708	0	0.890
	-10% NH_4^+	2.975	0	0.881
Case 1	+10% NH_4^+	0.068	0.002	0.964
	-10% NH_4^+	0.085	0.002	0.967
Case 2	+10% NH_4^+	0.628	0.087	0.950
	-10% NH_4^+	0.629	0.083	0.950
Case 3	+10% NH_4^+	0.072	0.003	0.964
	-10% NH_4^+	0.090	0.002	0.967
No control	100 mgCOD/L	0.344	0	0.954
	200 mgCOD/L	2.532	0	0.877
Case 1	100 mgCOD/L	0.406	0.003	0.951
	200 mgCOD/L	2.279	0.004	0.885
Case 2	100 mgCOD/L	0.298	0.000	0.957
	200 mgCOD/L	0.613	0.077	0.950
Case 3	100 mgCOD/L	0.411	0.002	0.951
	200 mgCOD/L	1.394	0.048	0.920

When simulating a disturbance scenario with an influent concentration of organic carbon of 100 mg COD/L, the increase in ammonium concentration in the effluent was lower than the removal of nitrate. This meant that the removal efficiency was not negatively impacted (right hand side of Table 1). For an organic carbon concentration of 200 mg COD/L, the competition for oxygen as electron acceptor became important, and case 1 failed to reject the disturbance whereas case 2 did a very good job of keeping a high removal efficiency by increasing the k_La, thus providing sufficient oxygen to oxidize both the ammonium and the organic carbon (Figure 3B). Case 1 failed, since it was designed to only handle the disturbances in the ammonium concentration. Since the removal efficiency decreased, but the balance between the desired microbial groups was intact (R_{AmmTot} was below its set point value), the oxygen supplied increased in case 2.

3.2 Dynamic influent profile simulation and set point changes

Set point changes were simulated and effluent from an anaerobic digester obtained from a simulation of the Benchmark Simulation Model no. 2 (BSM2) (Jeppsson et al., 2007) was used to simulate dynamic influent conditions. The control strategies were implemented and evaluated with similar observations as in the step change analyses.

3.3 Discussion/outlook

The control strategies presented here are novel for this process, since they are designed for an intensified system with limited actuator availability. Thanks to previous contributions, which assessed the operation of the reactor, it was possible to design control structures that addressed the regulation of the system while fulfilling the control objectives, which represents an advance compared to previous work on similar processes (Volcke et al., 2007). The strategy will be implemented at lab-scale and experimentally tested for validation.

4. CONCLUSIONS

Three control strategies for a granular sludge bioreactor removing ammonium from high strength streams were developed using a process oriented approach. Case 1 was best at handling disturbances in the ammonium concentration, whereas case 2 was best at rejecting disturbances in the organic carbon concentration in the influent. A combination of the two strategies in case 3 rejected both disturbances satisfactorily albeit not as well as case 1 and 2 for ammonium and organic carbon, respectively. Versatility toward disturbances could be obtained with the case 3 controller, at the expense of slower dynamic responses and a more complex structure. Hence the appropriate design will depend on the particular requirements of the process, in particular in disturbances originating in the upstream units. In any case, implementing the control strategy from case 3 will ensure the safest operation.

REFERENCES

Jeppsson, U., Pons, M.N., Nopens, I., Copp, J.B., Gernaey, K.V., Rosen, C., Steyer, J.P., Vanrolleghem, P.A. (2007) Benchmark simulation model no 2: general protocol and exploratory case studies. Water Sci. Technol. **56**(8), 67-78.

Mutlu, A.G., Vangsgaard, A.K., Sin G., Smets, B.F. (2013) An operation protocol for facilitating start-up of single-stage autotrophic nitrogen removing reactors based on process stoichiometry, Water Sci. Technol., *in press DOI:10.2166/wst.2013.157* .

Nikacevic, N. M., Huesman, A. E. M., Van den Hof, P. M. J., Stankiewicz, A. I. (2012) Opportunities and challenges for process control in process intensification. Chem. Eng. Process **52**, 1-15.

Skogestad, S. (2003) Simple analytic rules for model reduction and PID controller tuning. J. Process Control **13** (4), 291-309.

van der Star, W. R. L., Abma, W. R., Blommers, D., Mulder, J. W., Tokutomi, T., Strous, M., Picioreanu, C., Van Loosdrecht, M. C. M. (2007) Startup of reactors for anoxic ammonium oxidation: Experiences from the first full-scale anammox reactor in Rotterdam. Water Res. **41**(18), 4149-4163.

Vangsgaard, A.K., Mauricio-Iglesias, M., Gernaey, K.V., Smets, B.F. & Sin, G. (2012). Sensitivity analysis of autotrophic N removal by a granule based bioreactor: Influence of mass transfer versus microbial kinetics. Bioresource Technol. 123, 230-241.

Volcke, E. I. P., van Loosdrecht, M. C. M., Vanrolleghem, P. A. (2007) Interaction between control and design of a SHARON reactor: economic considerations in a plant-wide (BSM2) context. Water Sci. Technol. **56**(9), 117-125.