Control of nitrate recirculation flow in predenitrification systems

Zhiguo Yuan*, Adrian Oehmen* and Pernille Ingildsen**

* The Advanced Wastewater Management Centre (AWMC), The University of Queensland, St Lucia, QLD 4072, Australia. (E-mail: Zhiguo@awmc.uq.edu.au)
** IEA, Lund University and Danfoss Analytical, Ellegaardsvej 36, 6400 Soenderborg, Denmark

Abstract The control of the nitrate recirculation flow in a predenitrification system is addressed. An elementary mass balance analysis on the utilisation efficiency of the influent biodegradable COD (bCOD) for nitrate removal indicates that the control problem can be broken down into two parts: maintaining the “anoxic” zone anoxic (i.e. nitrate is present throughout the anoxic zone) and maximising the usage of influent soluble bCOD for denitrification. Simulation studies using the Simulation Benchmark developed in the European COST program show that both objectives can be achieved by maintaining the nitrate concentration at the outlet of the anoxic zone at around 2 mgN/L. This setpoint appears to be robust towards variations in the influent characteristics and sludge kinetics.

Keywords Nitrate recirculation; optimisation; predenitrification; process control; Simulation Benchmark

Introduction

Nitrate recirculation flow rate has long since been identified as a manipulated variable in a predenitrification system (Olsson and Jeppsson, 1994). The on-line control of this variable to improve nitrate removal has been studied by several researchers (see e.g. Londong, 1992; Balslev et al., 1996; Onnerth et al., 1996; Van Loosdrecht et al., 1998; Sorensen et al., 2000). The control strategies proposed include:

1. Controlling the nitrate concentration at the outlet of the denitrification zone at a low level (Londong, 1992). The nitrate level is sometimes inferred from the redox measurement (Londong, 1992; Van Loosdrecht et al., 1998).
2. Controlling the ratio of the amount of biodegradable COD (bCOD) to the amount of nitrate entering the denitrification zone at such a level that there is enough bCOD available for nitrate removal (Londong, 1992).
3. Rule based control strategies were designed in Balslev et al. (1996) and Onnerth et al. (1996) such that anaerobic phosphorus release in the anoxic zone was prevented while nitrate recirculation was minimised.

All these control strategies were proposed in a rather intuitive way. In this paper, we perform an elementary analysis of the denitrification process, and derive a control strategy for the nitrate recirculation flow rate on the basis of this analysis. This strategy, together with those described above, is then evaluated using dynamic simulation and the results are compared.

Methods

The COST Simulation Benchmark model (Spanjers et al., 1998, Dochain et al., 1999) was utilised as the basis for the dynamic simulation. The simulation benchmark model was chosen because it is widely accepted as the means by which control strategies for wastewater treatment systems can be compared in an unbiased fashion. A diagram outlining the basic setup of the benchmark model is shown in Figure 1.

The differences between the model used in this paper and the benchmark model are as follows:
1. The biological process model chosen for this paper was IAWQ’s Activated Sludge Model #3 (ASM3 (Gujer et al., 1999)), instead of IAWQ’s ASM1 (Henze et al., 1987). ASM3 was chosen because it is the most up-to-date model for COD and nitrogen removal activated sludge systems. ASM3 was developed based on ASM1 and has a number of improvements over its predecessor.

2. The simulation benchmark also consists of three influent data files for dry weather, rain weather and storm weather, respectively. The dry weather influent data was used in this study. Since the influent data was originally developed for ASM1, the data was converted according to ASM3 format.

3. The settler used in the simulation study was simply modeled as a point settler as the settler dynamics was not critical to the study on internal nitrate recirculation rate.

4. The dissolved oxygen concentration was fixed at 2 mg/L in the aerobic reactors in order to improve simulation speed.

**Control problem formulation**

The nitrate recirculation control problem can be formulated as to control the recirculation flow rate such that the following cost function is minimised,

\[
\text{Cost} = \int_{t}^{t+T} \left( \gamma_1 Q_{\text{eff}}(\tau) S_{\text{no, eff}}(\tau) + \gamma_2 Q_{\text{int}}(\tau) \right) d\tau
\]

where \(Q_{\text{int}}\) is the recirculation flow rate; \(S_{\text{no, eff}}\) and \(Q_{\text{eff}}\) are the effluent nitrate nitrogen concentration and the effluent flow rate respectively; \(T\) is an appropriately chosen integration interval (e.g. one day); \(\gamma_1\) and \(\gamma_2\) are the cost coefficients. The second term in the integration is the pumping cost, while the first one represents the cost of discharging nitrate, which can, but not necessarily, be the levy on nitrate discharge. One example for the non-levy cost is that of aeration due to the un-recovered oxygen from nitrate.

The usage of this control objective, however, is not limited to countries where fines need to be paid for the discharge of nitrogen. In the above cost function, the pumping cost is much smaller than the levy cost. If the pumping cost term were to be neglected, the levy cost would be the only term left to minimize, which is basically equivalent to maximizing nitrate removal. This would therefore achieve the maximum environmental benefit, which is the ultimate goal of all wastewater treatment plants.

The cost function established above, together with a dynamic model (e.g. IAWQ ASM3 (Gujer et al., 1999)), which predicts the effluent nitrate nitrogen concentration, formulates an optimal control problem, which may theoretically be solved by applying optimal control theory (for instance the Maximum Principle of Pontryagin). This approach is not only mathematically involved but also practically difficult, as it requires a precisely known model of the process and the up-front prediction of the influent characteristics. A sub-optimal solution to the problem can be much more easily implemented in a wastewater treatment system, and is searched for in this paper. A mass balance analysis of the biodegradable COD and a simulation study will be performed in order to solve this control problem.
**Elementary mass balance analysis**

**Carbon balance for control strategy development**

In a biological nitrogen removal plant, denitrification is often limited by the availability of biodegradable COD (bCOD). A complete mass balance for bCOD will assist in gaining some insight into the process. Influent bCOD consists of two parts: soluble bCOD and particulate bCOD with fractions of $\beta$ and $1-\beta$, respectively. When contacting the sludge, the latter is normally entrapped on sludge flocs and then travels through the anoxic and aerobic reactors driven by the hydraulic flows. As the particulate bCOD has to be hydrolysed before being degraded, the degradation of this part of bCOD goes slowly. Therefore, it is reasonable to assume that the particulate bCOD is equally available for anoxic and aerobic reactors, because of this slow degradation process of the particulate bCOD. The fractions that are “removed” (oxidised plus assimilated) anoxically or aerobically depend on the fractions of the anoxic and aerobic volumes, provided that the electron acceptors are readily available in the respective reactors. Assuming that the anoxic fraction is $\alpha$, the fractions of the influent particulate bCOD that is “removed” anoxically and aerobically is thus $\alpha$ and $(1-\alpha)$, respectively.

In contrast, soluble bCOD is usually more available for the anoxic reactor than for the aerobic one in a pre-denitrification system, since the influent first enters the anoxic reactor (see plant diagram in Figure 1). Nevertheless, a significant part of the soluble bCOD may be leaked to the aerobic reactor, in particular when its affinity constant (half-saturation coefficient) is relatively large. Assuming that a $1-\eta$ fraction of the soluble influent bCOD is leaked to the aerobic reactor, the fractions of the influent soluble bCOD that is removed (oxidised plus assimilated) anoxically and aerobically are thus $\eta$ and $1-\eta$, respectively.

Therefore, of the incoming bCOD, a fraction of $\eta\beta+\alpha(1-\beta)$ is initially “removed” with nitrate as the electron acceptor (i.e. anoxic removal of soluble and particulate bCOD). The rest, which comprises a fraction of $(1-\eta)\beta+(1-\alpha)(1-\beta)$ is initially “removed” with oxygen as electron acceptor (i.e. aerobic removal of soluble and particulate bCOD).

Part of the initially “removed” bCOD (with a fraction of $1-Y_H$) is oxidized to carbon dioxide. The rest (fraction $Y_H$) is assimilated into biomass cells or built as cell storage products (see e.g. Majone et al., 1999), part of which is oxidised later via endogenous respiration. $Y_H$ is the short-term yield factor, which can be rather high. In IAWQ ASM1 (Henze et al., 1987), where cell assimilation is assumed, a value of 0.67 is recommended. In IAWQ ASM3 (Gujer et al., 1999), where COD storage is used as the mechanism for instant COD removal, a value of 0.8 is recommended. With the same reasoning as done for particulate COD, it can be assumed that cell COD is equally available for aerobic and anoxic oxidation as it is “carried” along with the sludge. The fraction of influent bCOD that is oxidized via endogenous respiration is $Y_H = Y_{H,obs}$ where $Y_{H,obs}$ is the observed yield factor (on bCOD) of the plant, which is

$$Y_{H,obs} = \frac{1}{1 + \frac{f_pb_H\theta_X}{b_H\theta_X + 1}} Y_H$$

where $b_H$, $\theta_X$ and $f_p$ are, respectively, the heterotrophic biomass decay rate, sludge retention time (SRT) in the plant and the fraction of inert COD contained in biomass cells.

Based on the above analysis, the fraction of influent bCOD used for nitrate reduction in a pre-denitrification system is obtained as,

$$\gamma = (1-Y_H)\beta\eta + (1-Y_H)\alpha(1-\beta) + \alpha(Y_H - Y_{H,obs})$$

$$= (1-Y_H)\beta\eta + (1-\beta(1-Y_H) - Y_{H,obs}) \alpha$$

where $(1-Y_H)\beta\eta$ is the amount of soluble bCOD removed in the anoxic zone by conversion.
to CO$_2$, $(1-Y_H)\alpha(1-\beta)$ represents the amount of particulate bCOD removed in the anoxic zone by conversion to CO$_2$, and $\alpha(Y_H - Y_{H,obs})$ is the amount of cell COD removed in the anoxic zone.

Maximising nitrate removal in a pre-denitrification system via manipulating nitrate recirculation is equivalent to maximising parameter $\gamma$. In Eq. (3), parameters $Y_H$, $Y_{H,obs}$ and $\beta$ are independent of nitrate recirculation. $\gamma$ is thus maximised when parameters $\alpha$ and $h$ are maximised, implying that nitrate recirculation flow needs to be controlled such that:

1. Rule 1: nitrate is present throughout the unaerated zone to ensure a full usage of this zone for nitrate removal (maximising $\alpha$). This justifies the strategy that the nitrate concentration at the outlet of the denitrification zone is controlled at a non-zero level (Londong, 1992). If the nitrate were controlled at a zero level, then part of the “anoxic” zone would actually be anaerobic, and this would limit the amount of denitrification taking place. Given the fact that endogenous nitrate uptake is inherently slow and its rate is hardly limited by a low nitrate concentration, it is proposed here to maintain the nitrate concentration at the outlet of the denitrification zone at a level no lower than 1 mgN/L. Another contributing method in maximising $\alpha$ is to minimise the oxygen that is recycled, in order to avoid formation of an aerobic zone at the beginning of the unaerated zone. This is best achieved by controlling the dissolved oxygen (DO) at the end of the aerobic reactor at a low level. Excessively high recycling flow rate should also be avoided in order to minimise the oxygen recycled.

2. Rule 2: the leakage of influent soluble bCOD to the aerobic reactor is minimised (maximising $h$), for which details will be discussed below.

3. Parameterisation of Eq. (3) with benchmark parameter values (i.e. $Y_H = 0.80$, $b_H = 0.2$, $f_p = 0.2$, $\theta_A = 7.8$ and $\beta = 0.24$) is shown below:

$$\gamma = 0.048h + 0.542\alpha.$$  \hspace{1cm} (4)

This shows that $\gamma$ is much more sensitive to parameter $\alpha$ than to parameter $h$, indicating Rule 2 should be overwritten by Rule 1 when a conflict arises.

**Maximising parameter $h$**

Minimising cost function (1) is equivalent to minimising

$$Cost = \int_t^{T+\tau} (-\gamma f(t) V_{AN} + \gamma_2 Q_{in}(t)) dt$$  \hspace{1cm} (5)

where $V_{AN}$ is the volume of the anoxic zone, $f(t)$ is the volumetric denitrification rate in the anoxic zone. That is to say minimising nitrate discharge is equivalent to maximising nitrate removal in the anoxic zone. According to the discussion given above, $r_d(t)$ can be decomposed into two parts,

$$r_d(t) = r_{d,\text{end}}(t) + r_{d,\text{ex}}(t).$$  \hspace{1cm} (6)

where $r_{d,\text{end}}(t)$ is the “endogenous” nitrate uptake rate (due to the oxidation of cell COD, cell storage product as well as particulate bCOD), which is independent of the nitrate recirculation flow rate (as long as the denitrification zone remains anoxic); $r_{d,\text{ex}}(t)$ is the nitrate uptake rate due to the oxidation of soluble bCOD. Maximising parameter $h$ is therefore equivalent to maximising parameter $r_{d,\text{ex}}(t)$, which is determined as

$$r_{d,\text{ex}}(t) = R_d \frac{S_{bCOD}(t)}{K_s + S_{bCOD}(t)} \frac{S_{NO}(t)}{K_{NO} + S_{NO}(t)}.$$  \hspace{1cm} (7)
where \( r_D \) is the maximum nitrate uptake rate of the sludge; \( S_{BCOD} \) and \( S_NO \) are the soluble bCOD and nitrate nitrogen concentrations in the denitrification zone, respectively (to simplify discussion, the denitrification zone is assumed to be completely mixed here); \( K_S \) and \( K_NO \) are the affinity constants for soluble bCOD and nitrate, respectively. \( r_{d,ex}(t) \) is obviously affected by the nitrate recirculation flow rate \( Q_{int} \) as both \( S_{BCOD} \) and \( S_NO \) are dependent on \( Q_{int} \). When \( Q_{int} \) is increased, \( S_NO \) will rise because more nitrate is recirculated, and \( S_{BCOD} \) will drop because bCOD from the influent is increasingly diluted. \( r_{d,ex}(t) \) may therefore be maximised by manipulating \( Q_{int} \).

The response of the nitrate concentration in the recirculation flow to a change in the nitrate recirculation flow rate is much slower than the response of the nitrate concentration in the anoxic zone to this change. This, together with the fact that the influent bCOD varies rather slowly (typically diurnally), allows transforming the dynamic optimisation problem to a pseudo-steady state one. The optimisation can therefore be done on an hourly basis by assuming a constant nitrate concentration in the recirculation flow and a constant influent soluble bCOD concentration during the optimisation horizon. An optimisation algorithm has been developed, which requires measuring influent bCOD concentration as well as the nitrate concentration in the recirculation flow. However, as will become clear in the simulation results, this optimisation algorithm is not needed.

**Simulation studies**

The control system developed above has been evaluated using dynamic simulation. There were seven separate simulation studies performed, each testing the effect of the nitrate recirculation flowrate on overall cost (i.e. levy cost plus pumping cost) and on the rate of soluble substrate wastage. In this paper, \( \gamma_1 \) was calculated by taking into account the existing fine for nitrate discharge, which is 0.0025 ECU per gram of nitrogen in Flanders, Belgium. There is also the cost associated with the increased aeration required due to the wastage of nitrate as an electron acceptor, which when combined with the fine yields a \( \gamma_1 \) of 0.0028 ECU per gram of nitrate. The value of \( \gamma_1 \) was determined from the cost of electricity associated with the pumping cost, and was found to be 0.0028 ECU/m³ of wastewater. These values of \( \gamma_1 \) and \( \gamma_2 \) were used throughout the simulation study. Each of these studies will be described below.

1. A constant nitrate recirculation rate was tested, with the flowrate ranging from 0–4 times the average influent flowrate.
2. The ratio of the amount of bCOD to the amount of nitrate entering the denitrification zone was controlled at values ranging from 6–30.
3. The nitrate at the outlet of the anoxic zone was controlled constantly at values ranging from 0.1–8 mg/L.
4. Case number 3 was repeated after changing the soluble substrate affinity constant \( (K_S) \) from 2 (the ASM3 default value) to 10 (the simulation benchmark value for ASM1). This value was changed in order to assess the variability of the optimum nitrate setpoint, given a change in \( K_S \).
5. Case number 3 was repeated after changing the nitrate affinity constant \( (K_NO) \) from 0.5 to 0.25.
6. Case number 3 was repeated after changing the nitrate affinity constant \( (K_NO) \) from 0.5 to 1. Case numbers 5 and 6 were performed to assess the dependence of cost on the value of the nitrate affinity constant.
7. Case number 3 was repeated using a COD/N ratio of 8. The COD/N ratio in the simulation benchmark was 5.66. Lowering the concentration of ammonia in the influent by 22.4% and decreasing the amount of organic nitrogen contained in the soluble substrate by a factor of 2.9 were both performed to achieve a COD/N ratio of 8. A COD/N ratio of
8 in the influent to a wastewater treatment plant is common, and thus, the reason for altering this parameter in the simulation study.

In cases 3–7, a proportional feedback controller was used. Parallel cases to those numbered 3–7 was also planned initially, with parameter \( \eta \) being maximised using the optimization algorithm. However, as will be shown below, parameter \( \eta \) is nearly 100% in cases 3–7, leaving no room for further optimisation. Consequently, the optimisation algorithm was not used. Cases 4–7 were designed based on the belief that \( K_S \), \( K_{NO} \), and the influent COD/N ratio are the most important factors influencing nitrate removal in the anoxic reactors.

Results and discussion

The simulation results for the constant nitrate recirculation rate are shown in Figure 2. The lowest total cost was 863 ECU/day and the highest anoxic removal of soluble substrate (\( \eta \)) was 97.8%. The flowrate that yielded the lowest total cost and the highest \( \eta \) was a nitrate recirculation rate equal to the average influent flowrate (18,446 m\(^3\)/day). Figure 3 shows the results for the bCOD to nitrate ratio-controlled case, where the optimum ratio (22) was much higher than the ratio suggested by Londoing (between 7 and 9). The total cost reached a minimum of 860 ECU/day and \( \eta \) reached a maximum of 97.8%, which is very similar to that observed in the constant recirculation rate scenario. It should also be noted that only minor variations are observed between ratios of 15 and 30 for both total cost and \( \eta \).

Figure 4 shows the total cost variation with controller setpoint for the final 5 simulation cases. Table 1 provides a summary of the observed optimal points for all 5 cases.

In all cases the optimum nitrate concentration was between 1 and 3 mgN/L, with a concentration of 2 mgN/L consistently being at or very near to the minimum in every case. This suggests that a setpoint of 2 mgN/L would be a good nitrate concentration for the benchmark plant and for the cases studied. It should be noted that there would be variations in the optimal nitrate setpoint between different plants. The influent characteristics (in particular the COD to N ratio), sludge kinetics and specific plant design (e.g. anoxic/aerobic fractions, hydraulic retention time) all affect the optimal nitrate setpoint. However, it is observed from Figure 4 that the cost curves are rather flat around their minimum values, indicating that a small variation from the optimal nitrate setpoint produces a minimal change in the total cost. This implies that the setpoint control strategy is very robust. In view of this observation and the theoretical analysis in previous sections, a setpoint of 2 mgN/L should be generally applicable despite variations among different plants.

It can be observed from Table 1 that an increase in \( K_S \) from 2 to 10 produced a minimal change in total cost and optimal setpoint, however, the soluble substrate wastage from the anoxic to aerobic zones rose by over 10% (i.e. \( \eta \) fell by over 10%). Lowering the value of \( K_{NO} \) caused a slight shift downward in the optimal setpoint and in total cost, while raising \( K_{NO} \) provided the opposite effect. A change in the COD/N ratio in the influent provided the largest change in total cost, by far. The optimal nitrate setpoint was also lower than the others were in this final case (1 mgN/L); however, from Figure 4 it should be observed that

<table>
<thead>
<tr>
<th>Case</th>
<th>Nitrate setpoint at minimum cost</th>
<th>Levy cost</th>
<th>Pumping cost</th>
<th>Total cost (ECU/day)</th>
<th>( \eta ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_S = 2 )</td>
<td>2</td>
<td>821</td>
<td>41</td>
<td>862</td>
<td>97.9</td>
</tr>
<tr>
<td>( K_S = 10 )</td>
<td>2</td>
<td>838</td>
<td>37</td>
<td>875</td>
<td>87.4</td>
</tr>
<tr>
<td>( K_{NO} = 0.25 )</td>
<td>1.5</td>
<td>793</td>
<td>41</td>
<td>834</td>
<td>98.1</td>
</tr>
<tr>
<td>( K_{NO} = 1 )</td>
<td>3</td>
<td>857</td>
<td>45</td>
<td>902</td>
<td>97.6</td>
</tr>
<tr>
<td>COD/N = 8</td>
<td>1</td>
<td>416</td>
<td>98</td>
<td>514</td>
<td>95.6</td>
</tr>
</tbody>
</table>
a setpoint of 2 still yields a very low total cost. It should also be noted from Table 1 that the pumping cost makes up a small percentage of the total cost in each case, and that the pumping cost is most significant when the COD/N ratio was 8.

The anoxic removal of soluble substrate for the final 5 simulation cases is shown in Figure 5. In comparison, it should be noted that the lowest substrate wastage is consistently achieved at the point of lowest total cost (this trend can also be observed in Figure 2 and Figure 3). Therefore, maximising parameter \( a \) in the control strategy also maximises parameter \( h \), and therefore minimises soluble substrate wastage at the same time as minimising total cost. This, along with the fact that the typical value of \( h \) was between 95–98%, justifies the reason for not trying to maximise \( h \) separately from \( a \). Very little bCOD leakage from the anoxic to aerobic reactors actually occurred. The variation of soluble substrate wastage near the optimum point is also minimal, which again highlights the robustness of the control strategy.

Upon comparison of cases 1, 2 and 3, it is apparent that there is little variation between minimum cost and maximum \( h \) in each case. The constant recirculation rate case (#1) would be the cheapest option, since no nitrate sensor would be required. However, it would also be quite difficult to find the optimal recirculation/influent flowrate ratio due to influent dynamics. When a simulation was run at a constant recirculation ratio of 1 and a COD/N ratio of 8, it was found that the total cost was 547 ECU/day and \( h \) was 87.04%. This total cost is higher and \( h \) is lower than in case 7, where a proportional controller was used at the same COD/N ratio. In fact, the result of case 7 suggested that the optimal recirculation/influent ratio should be around 1.8. Therefore, variations in influent characteristics may occur where the optimum recirculation rate is not equal to the influent flow rate. The ratio-controlled case (#2) would also be difficult to implement in a wastewater treatment plant since it requires the knowledge of the bCOD concentration, which currently cannot be measured on-line.

In contrast, the proportional controlled case (#3) was quite robust and feasible.
Furthermore, the average nitrate concentration exiting the last anoxic reactor was found to be 2.90 and 2.46 mgN/L for cases 1 and 2, respectively. The fact that this value is close to the optimum setpoint of 2 mgN/L further highlights the benefits of using a proportional controller over a constant recirculation rate or ratio-control.

Conclusions

• The nitrate recirculation flow in a predenitrification plant should be controlled on-line. An appropriately controlled recirculation flow improves nitrate removal and reduces recirculation pumping cost.

• The most important aspect for nitrate recirculation control is to ensure that the “anoxic” fraction is anoxic (i.e. nitrate is present throughout the anoxic zone). This can be achieved by keeping the nitrate at the outlet of the anoxic tank at a low but non-zero level.

• A nitrate concentration of 2 mgN/L has appeared to be a good setpoint for the nitrate concentration at the outlet of the anoxic zone. The proposed control strategy is very robust, with only minimal change in total cost occurring when the setpoint is altered around 2 mgN/L. There is also a minimal change in cost due to a change in influent characteristics and/or sludge kinetics.

• It is not necessary to optimize parameter $\eta$ separately from $\alpha$, since minimising both the levy cost and the pumping cost will simultaneously minimise the soluble bCOD leakage from the anoxic to aerobic reactors.

References


