CONTROL OF EXTERNAL CARBON ADDITION TO PREDENITRIFYING SYSTEMS

By Zhiguo Yuan,[1] Herwig Bogaert,[2] Peter Vanrolleghem,[3] Chris Thoeye,[4] Ghislain Vansteenkiste,[5] and Willy Verstraete[6]

ABSTRACT: The external carbon dosage control is studied for the predenitrification processes without the on-line controllability of the nitrate recirculation flow. The control objective is to minimize the external carbon use while keeping the average effluent nitrate concentration below its standard. The proposed strategy is to control the nitrate concentration in the anoxic zone at a low set-point. A model-based analysis of the denitrification process reveals that the optimal set-point for the nitrate concentration in the anoxic zone is about 1 $mg \cdot l^{-1}$. Three control laws are designed to control the anoxic zone nitrate concentration at its set-point for different measurement conditions. An effort is made in all the designs to make the control system as simple as possible. This includes the usage of simple control laws and few sensors, which reduces the implementation and maintenance cost of the control system. The analyses and designs are validated by simulation and experimental studies on a full-scale plant.

INTRODUCTION

Biological nitrogen removal occurs in two major steps: (1) nitrification, where ammonium is converted to nitrate under aerobic conditions; and (2) denitrification, where nitrate is converted to nitrogen gas by heterotrophic biomass under anoxic conditions with the use of organic compounds as reducing agent (Focht and Verstraete 1977). The most economic configuration for nitrogen removal is the predenitrification system (Henze 1991). An obvious advantage of such a configuration, compared with a postdenitrification system, is that the influent chemical oxygen demand (COD) is directly used for denitrification, which makes the system more economic in terms of no or less external carbon demand, less oxygen consumption, and less sludge production.

For successful denitrification, a sufficiently high-influent carbon:nitrogen ratio is required (Focht and Verstraete 1977). When this requirement is not met, an external carbon source has to be added. The dosing rate of that carbon is important. Dosing an insufficient amount will result in a high effluent nitrate concentration. Dosing too much will increase the costs considerably due to a higher external carbon use, a higher sludge production, and an increased oxygen demand. This, together with the strong variation of influent flow and composition, which is typical for waste water treatment plants, initiates a demand for on-line control of the denitrification process to guarantee a sufficiently low effluent nitrate concentration, with optimal use of the available carbon and, hence, minimum dosage of external carbon. Two variables can be manipulated to achieve this objective: (1) the external carbon dosage, to guarantee that (almost) all the recirculated nitrate is removed in the anoxic zone; and (2) the nitrate recirculation flow rate, to control the amount of nitrate that is recirculated. For optimal control of the process, the two variables should be controlled simultaneously to form a multivariable control system.

The problem addressed in this paper is the control of the carbon dosage for a fixed nitrate recirculation flow rate. Optimal control is not possible by manipulating just one variable, but careful choice of the control strategy still allows for significant savings. One strategy is the so-called ratio control: keeping the carbon:nitrate (C:N) ratio to the anoxic zone at a certain level by dosing external carbon, applied when the effluent nitrate concentration exceeds its limit (Londong 1992; Hoen et al. 1996). The approach adopted in this work is to control the nitrate concentration in the anoxic zone at a set-point by manipulating the external carbon dosing rate. The set-point is determined using a mathematical process model, such that the effluent standards are met with a minimum use of external carbon. The corresponding constant nitrate recirculation flow rate is also calculated. Three controllers are designed to control the anoxic zone nitrate concentration at this set-point for different measurement conditions. The main feature of the designed controllers, compared to previous work (Londong 1992; Hoen et al. 1996; Hallin et al. 1996), is their simplicity. All employ simple control laws and require only a nitrate sensor in addition to some flowmeters. The analyses and designs are finally validated by simulation and a full-scale experiment.

MODEL BASED ANALYSIS

Process Model for Anoxic Zone

The denitrification model used for the analysis is based on the International Association on Water Quality (IAWQ) model no. 1 (Henze et al. 1987) with the following assumptions and modifications:

- The concept of endogeneous respiration is used rather than the death-regeneration hypothesis.
- Two types of readily biodegradable carbon are present in the model. One type is the carbon present in the influent; the other is the external carbon source. Their metabolism is described by identical maximum specific growth rates and yields, but different saturation constants.
- There is no nitrogen limitation for biomass growth.
- The oxygen that enters the anoxic zone via the influent and the nitrate recirculation is removed instantaneously (with concomitant carbon removal), and the dissolved oxygen concentration in the anoxic zone is always zero.

[1]Postdoctoral Res. Fellow, Dept. of Appl. Mathematics, Biometrics and Process Control, Univ. of Gent, Coupure 653, B9000 Gent, Belgium.
[2]Res. Asst., Dept. of Microbial Ecology, Univ. of Gent, Coupure 653, B9000 Gent, Belgium.
[3]Asst. Prof., Dept. of Appl. Mathematics, Biometrics and Process Control, Univ. of Gent, Coupure 653, B9000 Gent, Belgium.
[4]Mgr., R&D Dept., Aquafin N.V., Dijkstraat 8, B2630, Aartselaar, Belgium.
[5]Head, Dept. of Appl. Mathematics, Biometrics and Process Control, Univ. of Gent, Coupure 653, B9000 Gent, Belgium.
[6]Head, Dept. of Microbial Ecology, Univ. of Gent, Coupure 653, B9000 Gent, Belgium.

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- The anoxic zone is completely mixed.

The denitrification process is characterized by the following mass balance equations (for explanation of the symbols, see the Notation appendix).

$$\frac{dS_{NO,AN}}{dt} = -\frac{(1 - Y_H)}{2.86Y_H}(\mu_L + \mu_D)X_{BH} - \frac{(1 - f'_P)}{2.86} b'_H X_{BH} + \frac{(Q_{int} + Q_r)}{V_{AN}} S_{NO,AE} - \frac{Q}{V_{AN}} S_{NO,AN} \quad (1a)$$

$$\frac{dS_{DS,AN}}{dt} = -\frac{\mu_D}{Y_H} X_{BH} + \frac{Q_D}{V_{AN}} S_{DS,in} - \frac{Q}{V_{AN}} S_{DS,AN} - \frac{R_{DS,O}}{V_{AN}} \quad (1b)$$

$$\frac{dS_{LS,AN}}{dt} = -\frac{\mu_L}{Y_H} X_{BH} + \frac{Q_{inf}}{V_{AN}} S_{LS,in} - \frac{Q}{V_{AN}} S_{LS,AN} - \frac{R_{LS,O}}{V_{AN}} \quad (1c)$$

with

$$\mu_L = \mu_{H,max} \frac{S_{LS,AN}}{K_{LS} + S_{LS,AN}} \frac{S_{NO,AN}}{K_{NO} + S_{NO,AN}} \quad (2a)$$

$$\mu_D = \mu_{H,max} \frac{S_{DS,AN}}{K_{DS} + S_{DS,AN}} \frac{S_{NO,AN}}{K_{NO} + S_{NO,AN}} \quad (2b)$$

The model describes the dynamics of three components in the anoxic zone: (1) The nitrate ($S_{NO,AN}$); (2) the readily biodegradable carbon ($S_{LS,AN}$) present in the influent and/or generated via hydrolysis of the influent slowly biodegradable carbon; and (3) the external carbon source ($S_{DS,AN}$). The nitrate concentration changes due to microbial uptake (using $S_{LS,AN}$ and $S_{DS,AN}$), endogenous respiration, inflow and outflow. The nitrate concentration in the influent is assumed to be negligible. The dynamics of the two carbon components are determined by (1) nitrate respiration, (2) inflow, (3) outflow, and (4) instantaneous oxygen respiration using the oxygen from the nitrate recirculation flow and from the influent ($R_{LS,O}$ and $R_{DS,O}$). The biodegradable carbon concentration in the nitrate recirculation flow is neglected. $R_{DS,O}$ and $R_{LS,O}$ are calculated with the following equations:

$$R_{DS,O} + R_{LS,O} = (Q_{int}S_{O,AE} + Q_{inf}S_{O,inf})/(1 - Y_H) \quad (3a)$$

$$\frac{R_{DS,O}}{R_{LS,O}} = \frac{S_{DS,AN}/(K_{DS} + S_{DS,AN})}{S_{LS,AN}/(K_{LS} + S_{LS,AN})} = \frac{S_{DS,AN}(K_{LS} + S_{LS,AN})}{S_{LS,AN}(K_{DS} + S_{DS,AN})} \quad (3b)$$

which solves into

$$R_{LS,O} = \frac{(K_{DS} + S_{DS,AN})(Q_{int}S_{O,AE} + Q_{inf}S_{O,inf})S_{LS,AN}}{(1 - Y_H)(2S_{DS,AN}S_{LS,AN} + K_{DS}S_{LS,AN} + K_{LS}S_{DS,AN})} \quad (4a)$$

$$R_{DS,O} = \frac{(K_{LS} + S_{LS,AN})(Q_{int}S_{O,AE} + Q_{inf}S_{O,inf})S_{DS,AN}}{(1 - Y_H)(2S_{DS,AN}S_{LS,AN} + K_{DS}S_{LS,AN} + K_{LS}S_{DS,AN})} \quad (4b)$$

Determination of Optimal Set-Point for Anoxic Zone Nitrate Concentration

The choice of the set-point for the nitrate concentration in the anoxic zone ($S_{NO,AN,sp}$) is important to the performance of the controller since it will determine the consumption of the external carbon. Intuitively, this can be shown as follows:

- The denitrification rate is

$$r_{den} = \mu_{H,max} \frac{S_{S,AN}}{K_S + S_{S,AN}} \frac{S_{NO,AN}}{K_{NO} + S_{NO,AN}} X_{BH}$$

  The lower the $S_{NO,AN}$ is, the higher the $S_{S,AN}$ should be to have the same denitrification rate. Hence, $S_{NO,AN}$ should not be too low in order to minimize the leakage of COD to the aerobic zone, which is proportional to $S_{S,AN}$.

- Assuming that all the incoming Kjeldahl nitrogen is either transformed into nitrate (fraction $1 - \gamma$) or directly consumed by incorporation into new biomass (fraction γ), one obtains

$$S_{NO,AE} = S_{NO,AN} + (1 - \gamma)Q_{inf}S_{N,in}/Q \quad (5)$$

  By expanding Q, (5) can be rewritten as follows:

$$Q_{int} = (1 - \gamma)Q_{inf}S_{N,in}/(S_{NO,AE} - S_{NO,AN}) - Q_{inf} - Q_r \quad (6)$$

  Given the nitrogen load ($Q_{inf}S_{N,in}$) and the nitrate concentration in the anoxic zone ($S_{NO,AN}$), (6) gives the Q_{int} which is necessary to keep the effluent nitrate concentration at the desired level ($S_{NO,AE}$). Eq. (6) shows that a higher $S_{NO,AN}$ requires a higher nitrate recirculation flow rate for identical $S_{NO,AE}$. A higher recirculation rate causes more COD leakage to the aerobic zone and recirculates more oxygen to the anoxic zone, hence, requiring more external carbon source.

The preceding arguments suggest that the amount of carbon that leaks to the aerobic zone, and, hence, is no longer available for denitrification, is minimal with some intermediate value of $S_{NO,AN}$. The optimization problem is therefore formulated as: given the average influent parameters (Q_{inf}, $S_{LS,in}$, $S_{N,in}$) and the effluent standard ($S_{NO,AE}$), determine the optimal anoxic zone nitrate concentration set-point $S_{NO,AN,sp}$ such that the amount of the external carbon dosed ($Q_D S_{DS,in}$) is minimized. The problem of finding the optimal set-point is solved via a steady state analysis.

Solving the second equation of model 1 for its steady state and substituting (6) and (4) into the solution, the external carbon dosing rate to reach a steady state with $S_{NO,AN} = S_{NO,AN,sp}$ is obtained as

$$Q_D S_{DS,in} = \frac{\mu_{H,max}V_{AN}X_{BH}}{Y_H} \frac{S_{DS,AN}}{K_{DS} + S_{DS,AN}} \frac{S_{NO,AN,sp}}{K_{NO} + S_{NO,AN,sp}} + \frac{(1 - \gamma)Q_{inf}S_{N,in}}{(S_{NO,AE} - S_{NO,AN,sp})} S_{DS,AN} + \frac{(K_{LS} + S_{LS,AN})(Q_{int}S_{O,AE} + Q_{inf}S_{O,inf})S_{DS,AN}}{(1 - Y_H)(2S_{DS,AN}S_{LS,AN} + K_{DS}S_{LS,AN} + K_{LS}S_{DS,AN})} \quad (7)$$

where $S_{DS,AN}$ and $S_{LS,AN}$ can be obtained as functions of $S_{NO,AN,sp}$ from the steady-state solution of the first and third equations of model 1.

The optimal $S_{NO,AN,sp}$ can be found from

$$\partial(Q_D S_{DS,in})/\partial S_{NO,AN,sp} = 0 \quad (8)$$

The analytical solution of (8) is mathematically troublesome. However, given the influent conditions, the effluent standard, and the related parameter values, the optimal $S_{NO,AN,sp}$ can be found numerically. The corresponding Q_{int}, which will produce the specified effluent standard, is calculated using (6), with $S_{NO,AN} = S_{NO,AN,sp}$.

The following example shows that the $S_{NO,AN,sp}$ and Q_{int} obtained with the preceding procedure are in line with those that are commonly used:

influent: $S_{N,in} = 60$ mg·L^{-1}; $S_{LS,in} = 200$ mg·L^{-1};
$Q_r = Q_{inf} = 4500$ m^3·d^{-1}
sludge: $X_{BH} = 1200$ mg·L^{-1}; $\gamma = 0.25$
effluent requirement: $S_{NO,AE} = 9$ mg·L^{-1}; $S_{O,AE} = 2$ mg·L^{-1};
$S_{O,inf} = 3$ mg·L^{-1}
volume of the anoxic zone: $V_{AN} = 750$ m^3
parameters: $\mu_{H,max} = 6$ d^{-1}; $Y_H = 0.67$; $K_{LS} = 20$ mg·L^{-1};
$K_{NO} = 0.5$ mg·L^{-1}; $K_{DS} = 2$ mg·L^{-1}; $f'_P = 0.2$;
$b'_H = 0.2$ d^{-1}

The optimal $S_{NO,AN,sp}$ is calculated as 1.1 mg·L^{-1}. The corresponding Q_{int} is 16,500 m^3·d^{-1}, which is about four times the influent flow rate.

With the complete knowledge of the influent composition and the sludge characteristics, the preceding procedure can be used to determine the optimal $S_{NO,AN,sp}$. When this information is not available, an appropriate set-point can still be found. Indeed, doing a large number of numerical solutions for (7) for different influent conditions (Q_{inf}, $S_{LS,in}$, and $S_{N,in}$), model parameters ($\mu_{H,max}$, K_{LS}, K_{NO}, and K_{DS}), and other factors (X_{BH}, $S_{NO,AE}$, etc.) revealed that

- The function to be optimized is rather smooth around its optimum point, which means that the performance will not degrade much as long as $S_{NO,AN}$ is not too far away from the optimum
- The optimal $S_{NO,AN}$ is always close to 1 mg·L^{-1}

For example, the external carbon dosing rates for different values of $\mu_{H,max}$ (the maximum specific growth rate of the heterotrophs) and $S_{NO,AE}$ (the effluent standard), as function of the anoxic zone nitrate concentration, are plotted in Fig. 1 (The influent conditions and other model parameters took the same values as those used in the preceding example). Hence, when detailed knowledge of the influent composition and sludge characteristics is not available, the following procedure can be used:

- Choose 1 mg·L^{-1} as the set-point for the nitrate concentration in the anoxic zone ($S_{NO,AN}$). This guarantees that (almost) all the recycled nitrate is removed without using an excessive amount of carbon.
- Calculate the corresponding constant nitrate recirculation flow rate using (6) with $S_{NO,AE}$ equal to the desired average effluent nitrate concentration. This flow rate determines the fraction of nitrate that is recirculated and hence the overall nitrogen removal efficiency.

Linearization Analysis

Linearizing model 1 with different nonlinear parameter values and around different working points reveals that the control channel (from ΔQ_D to $\Delta S_{NO,AN}$) can be represented with the following transfer function:

$$\frac{\Delta S_{NO,AN}(s)}{\Delta Q_D(s)} = \frac{K_p(s + z_1)}{(s + p_1)(s + p_2)}$$

where K_p is the process gain; p_1, p_2, and z_1, which are all stable, are the poles and zero of the transfer function, respectively. It was further observed that the zero z_1 is quite close to one of the poles (p_1), while the latter has a magnitude that is much smaller (about one-tenth) than that of the other pole (p_2). K_p, p_1, p_2, and z_1 are all time-varying, depending on the time-varying nonlinear model parameters and the working conditions.

Using the root locus technique, it is easy to show that, when a proportional feedback control with high feedback gain is applied to the process, the closed-loop system is approximately a first-order one due to the approximate cancellation of the zero z_1 and the closed-loop pole that approaches to z_1.

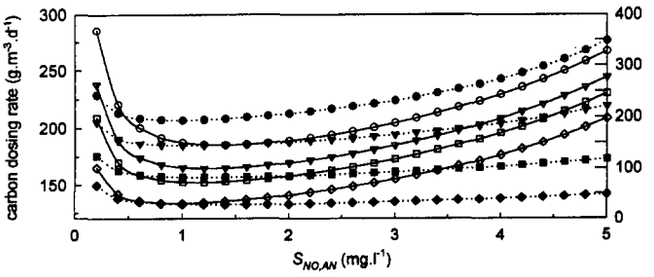

FIG. 1. Carbon Dosing Rate as Function of Anoxic Zone Nitrate Concentration for Different Values of $\mu_{H,max}$ (Opened Symbols, Left Axis, Varying from 2 to 7 d^{-1}) and $S_{NO,AE}$ (Filled Symbols, Right Axis, Varying from 7 to 13.5 mg N·L^{-1})

CONTROL LAW DESIGN

One may consider either a model based or a nonmodel-based control law. For model-based control, the time-varying parameters have to be estimated on-line, which requires more on-line measurements. Furthermore, the convergence of the parameter estimation can hardly be guaranteed given the many uncertainties in the wastewater treatment process. Compared with model-based control, nonmodel-based control is usually less complicated and requires less measurements. When appropriately designed, a nonmodel-based controller can perform well, although the control may not be optimal. The following discussion is therefore limited to nonmodel-based controllers.

Proportional Feedback Control with High Gain

As stated in the previous section, the control channel allows the application of a high feedback gain. Thus a simple proportional feedback controller with a high gain can be used, provided that the nitrate measurement is perfect. Perfect measurement implies here a sufficiently high sampling rate, a small measurement delay, and small measurement noise. With such a control law, $S_{NO,AN}$ can be closely controlled around $S_{NO,AN,sp}$. This is illustrated by the simulation studies in the next section.

The frequent accurate measurement without time delay, required by the preceding control law, is difficult to realize. When such a sensor is not available, a high feedback gain can no longer be applied, and thus more advanced control schemes should be designed such that the burden on the sensor is reduced. This is the main concern in the design of the following control laws.

Proportional Feedback Enhanced with Feedforward

An appropriately designed feedforward component can significantly diminish the influence of the disturbances on the controlled variable so that the burden on the feedback loop is reduced. The price to pay is that the magnitudes of the major disturbances have to be obtained on-line. The objective of this subsection is to design a feedforward control law that minimizes the need for extra measurements.

Again consider model 1. The second equation gives

$$\frac{\mu_D}{Y_H} X_{BH} = -\frac{dS_{DS,AN}}{dt} + \frac{Q_D S_{DS,in}}{V_{AN}} - \frac{Q}{V_{AN}} S_{DS,AN} - \frac{R_{DS,O}}{V_{AN}} \quad (9)$$

The design objective of the feedforward law is to have

$$\left.\frac{dS_{NO,AN}}{dt}\right|_{S_{NO,AN}=S_{NO,AN,sp}} = 0 \quad (10)$$

Solving (10), one obtains the following feedforward law:

$$Q_D S_{DS,in} = \frac{2.86}{(1 - Y_H)} [(Q_{int} + Q_r) S_{NO,AE} - Q S_{NO,AN,sp}] + \Delta \quad (11)$$

where

$$\Delta = -\frac{\mu_L}{Y_H} V_{AN} X_{BH} + Q S_{DS,AN} - \frac{V_{AN}(1 - f'_P)}{(1 - Y_H)} b'_H X_{BH} + V_{AN} \frac{dS_{DS,AN}}{dt} + R_{DS,O} \quad (12)$$

With $S_{NO,AE}$ being measured with a nitrate sensor, which may be the same one used for $S_{NO,AN}$ measurement, the problem to be solved is to get Δ on-line. The direct determination of Δ is quite difficult since it involves the measurement of the COD and the biomass concentration and requires the knowledge of some model parameters. It is therefore proposed to estimate Δ on-line with the available information. Integrating the first two equations in model 1 over a time interval of $(t - T, t)$, assuming that Δ remains a constant over interval $(t - T, t)$ and neglecting the change of $S_{DS,AN}$ over $(t - T, t)$, which is small because K_{DS} is small, one obtains

$$\hat{\Delta}(t) = \frac{2.86}{T(1 - Y_H)} \int_{t-T}^{t} [(Q_{ini} + Q_r)S_{NO,AE} - QS_{NO,AN}]\, d\tau - \frac{2.86}{T(1 - Y_H)} V_{AN}[S_{NO,AN}(t) - S_{NO,AN}(t - T)] - \frac{1}{T} \int_{t-T}^{t} Q_D S_{DS,in}\, d\tau \quad (13)$$

Eq. (13) gives an estimate of Δ at time t. The estimation requires only nitrate and flow measurements and, hence, does not require additional sensors. A problem of the scheme is that the estimate is always delayed. The error caused by the delay will have to be compensated by the feedback loop. To shorten the delay, T should be small. However, a smaller T makes the estimate more sensitive to measurement errors. T should be chosen according to the measurement sampling rate, the measurement accuracy and the variation of the disturbances. The recommended value of T is between 1 and 2 h for diurnal disturbances. Another remark is that the term $2.86V_{AN}[S_{NO,AN}(t) - S_{NO,AN}(t - T)]/[T(1 - Y_H)]$ is small compared to other terms in (13), and it is most sensitive to measurement errors. It may be dropped when the measurement is too noisy.

Proportional Feedback with Average Dosing and Variable Gain

When $S_{NO,AE}$ is not measured, the time-varying feedforward law can be replaced by a constant feedforward designed for the average load conditions. The ameliorating effect of introducing such a constant dosing can be shown as follows. Assume that the constant dosing rate is $Q_{D,0}$ and the negative feedback gain is K_{FB}, then the total dosing rate produced by the controller will be $Q_D = Q_{D,0} + K_{FB}e$, where $e = S_{NO,AN,sp} - S_{NO,AN}$ is the error signal of the feedback loop. Thus, when a certain dosing rate $Q_{D,req}$ is required, the corresponding error signal should be $e_{req} = (Q_{D,req} - Q_{D,0})/K_{FB}$. When $Q_{D,req} > Q_{D,0}$, the negative error signal required to produce $Q_{D,req}$ will be much smaller than for the case where $Q_{D,0}$ does not exist. This improves the controller performance. However, a problem arises when $Q_{D,req} < Q_{D,0}$, because a positive error signal is then required to compensate for the constant dosing. Since K_{FB} should be small to prevent oscillations, the carbon dosage will not be stopped even when $S_{NO,AN}$ is very low. This would cause substantial waste of the external carbon source during low nitrogen load. This drawback can be alleviated by applying a variable feedback gain. Indeed, whether or not an oscillation exists is determined by the magnitude of the open-loop gain which is the product of the feedback gain and the process gain (the gain of the control channel). Analysis shows that the process gain is variable and particularly affected by $S_{NO,AN}$ especially when it is low.

- The denitrification rate shown in (2) clearly shows that the carbon dosage is less effective when $S_{NO,AN}$ is low than when it is high. In other words, the gain of the control channel is smaller when $S_{NO,AN}$ is lower.

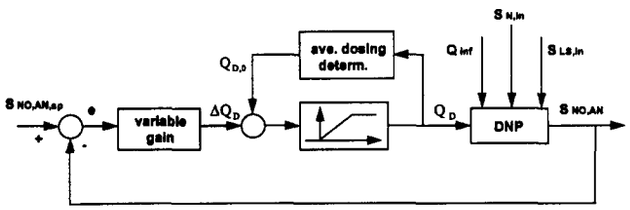

FIG. 2. Proportional Feedback Control with Average Dosing and Variable Gain

- The influent COD has a leveling effect on the effectiveness of the carbon dosage: when more external COD is dosed, less influent COD will be consumed due to the decrease of $S_{NO,AN}$ and vice versa. This leveling effect is stronger at low $S_{NO,AN}$ values, which makes the process gain become smaller at lower $S_{NO,AN}$ values.

This means that a higher feedback gain can be applied when $S_{NO,AN}$ is low. Therefore, a variable feedback gain is designed for the situation where $e \geq 0$

$$K_{FB} = K_{FB,0}/(S_{NO,AN,sp} - e) = K_{FB,0}/S_{NO,AN} \quad \text{when } e \geq 0 \quad (14)$$

where $K_{FB,0}$ is the normal feedback gain, a design parameter. With such a design, the carbon dosage will be reduced quite rapidly when $S_{NO,AN}$ drops below $S_{NO,AN,sp}$. In the meanwhile, the open-loop gain of the controlled process is not significantly affected and, hence, the danger of oscillation remains almost the same.

As explained above, constant dosing can significantly reduce the magnitude of the negative error. For situations where the variation of the load conditions is extremely large, constant dosing alone may not be sufficient to limit the negative error to a satisfactory level. To further reduced the negative error, a variable gain can also be applied in conditions where $e \leq 0$

$$K_{FB} = K_{FB,0}/(S_{NO,AN,sp} + e/e_{max}) \quad \text{when } e \leq 0 \quad (15)$$

where $e_{max} > 0$ is a parameter which determines how fast K_{FB} increases with the increase of e. With this design, a larger feedback gain will be used when the error signal becomes bigger. Different from the case of $e > 0$, the increase of K_{FB} in this case increases the open-loop gain and hence the danger of oscillation. Therefore, e_{max} should not be too small. With a large e_{max}, the danger for oscillation exists only when $S_{NO,AN}$ is high. Oscillations at high nitrate concentrations will not cause inefficient external carbon usage.

Since a plant may be subject to long-term (for instance seasonal) load variations, it is necessary to determine the constant dosing on-line to adapt it to the long-term load variations. This can be achieved by monitoring the load to the plant. A better way is to add another feedback loop into the control system (see Fig. 2), which adjusts the constant dosing by making a long-term moving average of the actual dosing

$$Q_{D,0}(t + 1) = \alpha Q_{D,0}(t) + (1 - \alpha)Q_D(t) \quad (16)$$

where $Q_{D,0}(t)$ is the constant dosing rate applied during day t, $Q_D(t)$ is the average dosing rate over day t, α is the forgetting factor.

VALIDATION BY SIMULATION

The wastewater treatment plant (WWTP) at Zwalm in Belgium is a predenitrification plant that treats domestic wastewater (Table 1). A simulation system of this plant has been built. Both reactors are assumed completely mixed and modeled with an expanded version of the IAWQ model no. 1 (Henze et al. 1987) in which two types of readily biodegradable COD are considered. The settler is modeled with the Tak-

TABLE 1. Details about Treatment Plant of Zwalm

Plant specifications (1)	Values (2)
Reactor volume (m^3)	2,273
Anoxic zone (m^3)	750
Aerobic zone (m^3)	1,523
Settler volume (m^3)	1,600
Sludge residence time (d)	15
Settled sewage	
Dry weather flow rate ($m^3 \cdot d^{-1}$)	4,095
Average COD (mg $O_2 \cdot L^{-1}$)	250
Average BOD_5 (mg $O_2 \cdot L^{-1}$)	108
Average TN (mg $N \cdot L^{-1}$)	36
Nitrate recirculation flow rate ($m^3 \cdot d^{-1}$)	20,500
Sludge recirculation flow rate ($m^3 \cdot d^{-1}$)	5,000

ács model (Takács et al. 1991). For control evaluation purposes, the precise calibration of the models is not necessary because a properly designed controller should be able to tolerate variable conditions and modeling errors. Therefore, the default parameter values recommended in the literature (Henze et al. 1987; Takács et al. 1991) were used.

Extensive simulation studies on the control laws have been performed. In the simulations reported below, the following influent conditions are used:

$S_{N,in}$ = average concentration of 80 mg $\cdot L^{-1}$ with random variations (normal distribution with zero mean and standard deviation 6 mg $\cdot L^{-1}$, changing every 1.2 h)
$S_{LS,in} = 400 + 140 * \sin(2\pi t)$ mg $\cdot L^{-1}$
$Q_{inf} = 5000 + 2500 * \sin(2\pi t)$ $m^3 \cdot d^{-1}$.

Note that the time-varying $S_{LS,in}$ and the constant $S_{N,in}$ produce a time-varying influent COD:N ratio. It has been observed that influent flow variations affect the COD:N ratio of the influent in a similar way to the artificial influent conditions used in this simulation (Butler et al. 1995; Rouleau and Lessard 1996). With $S_{NO,AE,req}$ = 10 mg $\cdot L^{-1}$, $S_{NO,AN,sp}$ is determined as 1 mg $\cdot L^{-1}$. Q_{int} is correspondingly determined as 20,000 $m^3 \cdot d^{-1}$. The measurement conditions and the controller parameters used in the simulations are summarized in Table 2.

The simulation results are shown in Figs. 3–5. The following conclusions can be drawn:

- Perfect performance is achieved for the first control law. This is in agreement with the analysis presented in the previous sections.
- In spite of the measurement deficiency, the second and third control laws both produce satisfactory control on $S_{NO,AN}$.
- The performance of the second control law is only marginally better than that of the third one. The differences are more pronounced when the influent variations are larger (data not shown). On the other hand, the implementation of the second control law requires either two nitrate sensors or a multiplexed sensor that has to measure twice as fast as with the third one.

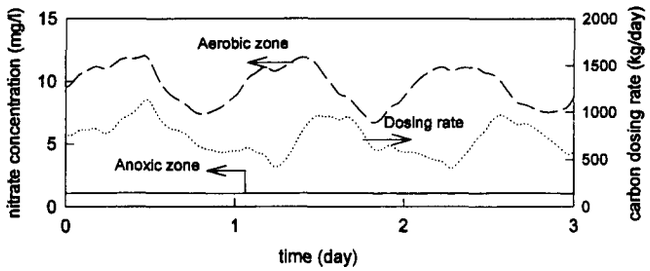

FIG. 3. Nitrate Concentration and Carbon Dosing Rate for Proportional Feedback Controller with High Gain

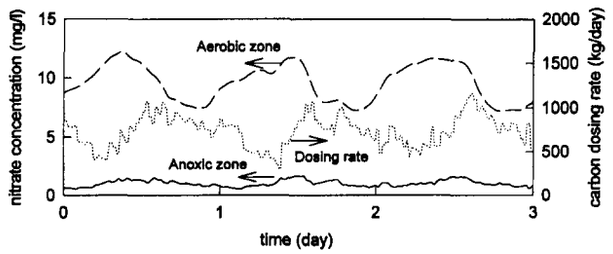

FIG. 4. Nitrate Concentration and Carbon Dosing Rate for Proportional Feedback Controller with Feedforward

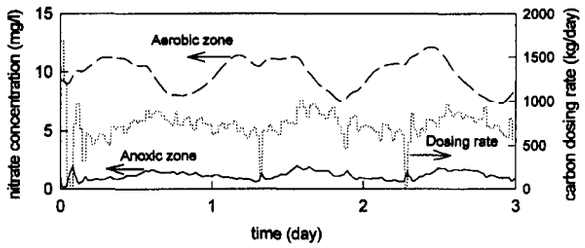

FIG. 5. Nitrate Concentration and Carbon Dosing Rate for Proportional Feedback Controller with Constant Feedforward and Variable Gain

- The average $S_{NO,AE}$ is about 10 mg $\cdot L^{-1}$ for the three cases. Small diurnal variations are observed, which could be avoided by controlling the carbon dosage and the nitrate recirculation flow rate together. However, there is no practical reason at present why these variations should be avoided.

FULL SCALE EXPERIMENT

The third control law has also been validated with a full-scale experiment conducted on the WWTP at Zwalm in Belgium (Table 1). This 30,000 population equivalent (p.e.) plant treats domestic wastewater plus the wastewater of a small slaughterhouse. As can be seen in Table 1, the COD:N ratio in the influent is low. Therefore, acetic acid was dosed as an external carbon source to support the denitrification.

The nitrate concentration in the anoxic zone was measured using DECADOS, a newly developed biological nitrate sensor

TABLE 2. Measurement Conditions and Controller Parameters

Control laws (1)	Measurement conditions (2)	Controller parameters (3)
Proportional with high gain	$S_{NO,AN}$ perfectly measured	K_{FB} = 10,000 kg COD $\cdot d^{-1} \cdot$ (mg $N \cdot L^{-1})^{-1}$
Proportional with feedforward	$S_{NO,AN}$, $S_{NO,AE}$ measured sampling rate (both): 2 h^{-1} Delay: 30′ Standard deviation: 0.25	K_{FB} = 200 kg COD $\cdot d^{-1} \cdot$ (mg $N \cdot L^{-1})^{-1}$ T = 2 h
Proportional with average dosing and variable gain	$S_{NO,AN}$ measured sampling rate: 2 h^{-1} Delay: 30′ Standard deviation: 0.25	$K_{FB,0}$ = 200 kg COD $\cdot d^{-1} \cdot$ (mg $N \cdot L^{-1})^{-1}$ e_{max} = 10 mg $\cdot L^{-1}$ $Q_{D,0}$ = 700 kg COD $\cdot d^{-1}$ α = 0.94

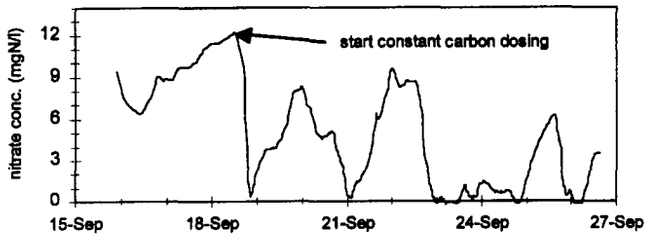

FIG. 6. Anoxic Zone Nitrate Concentration during Period without Automatic Carbon Dosage Control

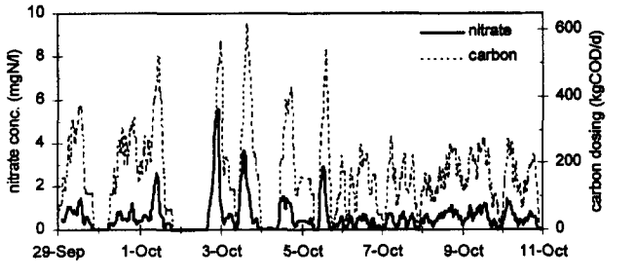

FIG. 7. Anoxic Zone Nitrate Concentration and Carbon Dosing Rate during Period with Automatic Carbon Dosage Control. The Few Large Peaks Were Caused by Power Failures

(Bogaert et al. 1997). The sampling period and the measurement delay are both about 30 min. The measurement accuracy is about ± 1 mg $N \cdot L^{-1}$.

Period without Automatic Control

This period started on September 15, 1995, ended on September 27, 1995. The nitrate concentration in the anoxic zone measured by DECADOS is shown in Fig. 6 (measurement noise smoothed out with a moving average over a period of 2 h). In the first 3 d, no external carbon was dosed. The high nitrate concentration in the anoxic zone was striking. From September 18 on, the external carbon was dosed with a constant rate of 185 kg $COD \cdot d^{-1}$. The average nitrate level was reduced. The large variation of the nitrate concentration clearly demonstrated the need for an automatic control of the carbon dosage.

Period with Automatic Carbon Dosage Control

The controller was designed as: $S_{NO,AN,sp} = 1$ mg $\cdot L^{-1}$; $K_{FB,0} = 100$ kg $COD \cdot d^{-1}$ (mg $N \cdot L^{-1})^{-1}$; $e_{max} = 10$ mg $\cdot L^{-1}$; $Q_{D,0}(0)$, the initial constant dosing rate, was 300 kg $COD \cdot d^{-1}$. The results of the dosing experiment are shown in Fig. 7 (measurement noise smoothed out). The large peaks in the nitrate concentration are due to power failures. The power to the plant has been interrupted a few times for a very short instance. However, the nitrate recirculation pump of the plant did not start automatically after these interruptions. This explains the periods of zero nitrate concentration and zero carbon dosing just before the peaks. The nitrate concentration was successfully controlled at a low level. Due to a too high initial constant dosing rate [$Q_{D,0}(0)$], the nitrate concentration in the anoxic zone was for almost the whole period lower than the set-point. If the experiment would have been continued over a longer time, this rate would have been reduced by the internal feedback loop [(16), Fig. 2].

The full-scale experiments ran from September 15 until October 11, 1995 during a period of about 1 month. A diurnal pattern can be distinguished in the carbon dosing rate in Fig. 7. The variations from September 19–23 (Fig. 6) are not diurnal because of the heavy rainfall during that period. The impact of the higher influent COD:N ratio during the weekends of September 23–24 and September 30–31, when the slaughterhouse did not discharge, is visible in Figs. 6 and 7. The controller also successfully overcame the consequences of the exceptional power failures.

CONCLUSIONS

A model-based analysis on the predenitrification process revealed that the optimal nitrate concentration in the anoxic zone is about 1 mg $\cdot L^{-1}$. The analysis also showed that external carbon dosage is an effective control action for the denitrification process and that, if an accurate, high frequency nitrate measurement is available, a simple proportional feedback controller suffices. Two more enhanced control laws were designed, which take measurement limitations, such as a low measurement frequency, a time delay, and/or a low accuracy, into account. One employed a feedforward component to release the feedback gain, another used the concept of average dosing and variable feedback gain to improve the control accuracy. A common advantage of the two control laws is that both require only a nitrate sensor, in addition to some flowmeters, which reduces the implementation and maintenance cost of the control system. Simulation and full-scale experimental studies showed that both perform well.

ACKNOWLEDGMENTS

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APPENDIX I. REFERENCES

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APPENDIX II. NOTATION

The following symbols are used in this paper:

b'_H = endogenous respiration coefficient of heterotrophic biomass (d^{-1});
f'_p = inert organic fraction of the biomass;
K_{DS} = saturation constant for external carbon (g $COD \cdot m^{-3}$);
K_{LS} = saturation constant for influent carbon (g $COD \cdot m^{-3}$);

K_{NO} = saturation constant for nitrate (g $N \cdot m^{-3}$);
Q = total flow rate to the anoxic zone ($m^3 \cdot d^{-1}$), $Q = Q_{inf} + Q_{int} + Q_r$;
Q_D = external carbon dosage flow rate ($m^3 \cdot d^{-1}$);
Q_{inf} = influent flow rate ($m^3 \cdot d^{-1}$);
Q_{int} = nitrate recirculation flow rate ($m^3 \cdot d^{-1}$);
Q_r = sludge recycling flow rate ($m^3 \cdot d^{-1}$);
$R_{DS,O}$ = external carbon consumption rate by oxygen respiration in anoxic zone ($g \cdot d^{-1}$);
$R_{LS,O}$ = influent carbon consumption rate by oxygen respiration in anoxic zone ($g \cdot d^{-1}$);
$S_{DS,AN}$ = external carbon source concentration in the anoxic zone (g $COD \cdot m^{-3}$);
$S_{DS,in}$ = COD concentration in the external carbon dosage flow (g $COD \cdot m^{-3}$);
$S_{LS,AN}$ = influent carbon concentration in the anoxic zone (g $COD \cdot m^{-3}$);
$S_{LS,in}$ = COD concentration in the influent flow (g $COD \cdot m^{-3}$);
$S_{N,in}$ = Kjeldahl nitrogen concentration in the influent flow (g $N \cdot m^{-3}$);
$S_{NO,AE}$ = nitrate concentration in the nitrate recirculation flow (g $N \cdot m^{-3}$);
$S_{NO,AN}$ = nitrate concentration in the anoxic zone (g $N \cdot m^{-3}$);
$S_{O,AE}$ = oxygen concentration in the nitrate recirculation flow [g $(-COD) \cdot m^{-3}$];
$S_{O,inf}$ = oxygen concentration in the influent flow [g $(-COD) \cdot m^{-3}$];
V_{AN} = volume of the anoxic zone (m^3);
X_{BH} = heterotrophic biomass concentration (g $COD \cdot m^{-3}$);
Y_H = yield for heterotrophic biomass;
γ = fraction of the nitrogen directly consumed by biomass growth;
μ_D = specific growth rate on external carbon (d^{-1});
$\mu_{H,max}$ = maximum specific growth rate of the heterotrophic biomass (d^{-1}); and
μ_L = specific growth rate on influent carbon (d^{-1}).