Control of the aeration volume in an activated sludge process for nitrogen removal

P. Samuelsson and B. Carlsson
Department of Systems and Control, Uppsala University, P O Box 27, SE—751 03, Uppsala, Sweden.
(E-mail: psa@syscon.uu.se, bc@syscon.uu.se)

Abstract Biological nitrogen removal in an activated sludge process is obtained by two biological processes; nitrification and denitrification. Nitrifying bacteria need dissolved oxygen and a sufficiently large aeration volume for converting ammonium to nitrate in the wastewater. The objective of this paper is to develop an automatic control strategy for adjusting the aerated volume so that the effluent ammonium level can be kept close to a desired value despite major changes in the influent load. The strategy is based on applying exact linearization of the IAWQ Activated Sludge Process Model No 1. Simulation results show that the suggested controller effectively attenuates process disturbances.

Keywords Activated sludge process; aeration; automation; control; exact linearization; feedforward control; nitrification; nutrient removal

Introduction

During the last 15-20 years, the use of the activated sludge process (ASP) for biological nitrogen removal has increased in many countries. This is a result of stricter effluent demands. To remove the nitrogen from the wastewater in an ASP, the biological processes, nitrification and denitrification, are needed. In aerobic compartments, ammonium may be converted into nitrate (nitrification) and in anoxic compartments nitrate may be converted into gaseous nitrogen (denitrification). For the nitrification to work well, a sufficiently high concentration of dissolved oxygen (DO) is needed together with a sufficiently large aeration volume (see Henze et al., 1995).

A common way of controlling the aeration in an ASP is to keep the DO concentration at some pre-specified level. One way to do this is in a single loop arrangement, where the DO controller directly changes the air flow valve to adjust the DO level to the desired value (set-point). In order to decrease the impact of nonlinearities in the air flow valve, cascaded DO control can be used (see Olsson et al., 1985). A master control loop calculates the desired air flow rate for adjusting the DO to a given set-point. In an inner loop, a slave controller is then used to adjust the valve opening to get the desired air flow rate. The cascaded control method requires measurements of DO levels and air flow rates, while the direct method requires measurements of DO levels only. Many different strategies for the DO control have been suggested. An early interesting contribution is Flanagan et al. (1977) where a PI control strategy using feedforward from respiration rate and flow rate is used. In Carlsson et al. (1994) an auto tuning approach for control of the DO is described. An approach based on exact linearization of the nonlinear oxygen transfer function is made in Lindberg and Carlsson (1996. A comprehensive overview of different approaches to DO control is given in Olsson and Newell (1999).

One major drawback to the DO control methods above when a nitrifying aerobic process is used, is that neither feedback from effluent ammonium nor feedforward from influent ammonium concentrations are used. Since the load to a wastewater treatment plant may vary a factor six or more (see Van Impe et al., 1992), this may cause large variations of ammonium in the effluent water. Even with a constant load it is hard to manually choose the
set-point of the DO controller so that it corresponds to a desired level of ammonium in the effluent.

The problem described above can partly be solved by using supervisory control (cascade control) of the set-point of the DO controller. This is done by implementing a control law that adjusts the set-point of the DO controller so that the ammonium concentration in the effluent is kept at some pre specified level. Such an approach can be found in for instance Lindberg and Carlsson (1996).

However, the supervisory control structure may cause other problems. If the aerated volume is not sufficiently large, the air flow rate may saturate and the DO level may become high. When a pre-denitrifying structure is used for plant operation and the DO level in the internally recirculated water is too high, this may inhibit the denitrification (Olsson and Jeppson, 1994). On the other hand, too low a DO level may decrease the sludge quality and induce formation of nitrous oxide (N₂O). Also, mixers are generally needed when the DO level becomes too low. It is possible to use multivariable controllers for controlling the nitrification and denitrification simultaneously. Such an approach using quantitative feedback theory can be found in García-Sanz and Ostolaza (1998). Another multivariable approach using model predictive control is found in Weijers et al. (1997).

Since there are some drawbacks with the control methods described above, attempts to use other control variables have recently been made. For sequential batch reactors, an approach is to control the length of the aerated phase (see Nielsen and Lynggaard-Jensen, 1993). For continuous reactors Brouwer et al. (1998) suggest a model based feedforward control strategy of the aeration volume. A simple ASP model is used for calculating an aeration volume that in steady state gives the desired ammonium level. This strategy was also evaluated in a pilot plant.

In this paper, a method for controlling the aerobic volume of a wastewater treatment plant is suggested. The method relies on exact linearization together with estimation of the reaction rate of ammonium. The main difference compared to Brouwer et al. (1998) is that here a dynamical model based strategy, using both traditional feedback and feedforward information, for controlling the aeration volume is suggested. Also, another strategy for online estimation of the reaction rate of ammonium is here used, using no assumptions regarding the model structure of the reaction rate. In the derivation of the controller it is assumed that the volume can change continuously over time. In practice, wastewater treatment plants are often divided into compartments that can be either aerated or anoxic, so a continuously changing volume is not realizable. Therefore a suggestion on how to discretize the control law with respect to volume is made. It is believed that a combination of DO control and volume control could be an interesting alternative to pure DO control. During periods of high ammonium load, a larger aeration volume could then be used, and during periods of low load the aeration volume could be decreased, allowing a larger volume to be used for denitrification.

**The model**

In order to design a model based control strategy for how to select the aeration volume, it is of interest to model the dynamical behaviour of the ammonium concentration, \( S_{NH}(t) \) [mg/l]. By applying a simple mass balance using the notation in Figure 2 the following model structure is obtained:

\[
\frac{d}{dt} \left( V(t) S_{NH}(t) \right) = V(t) R_{S_{NH}}(t) + Q(t)(S_{NH, in}(t) - S_{NH}(t)) \tag{1}
\]

Evaluating (1) gives:
\[
\frac{dS_{NH}(t)}{dt} = R_{SNH}(t) + \frac{Q(t)}{V(t)}(S_{NH,in}(t) - S_{NH}(t)) - \frac{dV(t)}{dt} \frac{1}{V(t)} S_{NH}(t)
\]

where \(R_{SNH}(t)\) is the reaction rate of ammonium, \(S_{NH,in}(t)\) is the concentration of influent ammonium, \(Q(t)\) is the flow rate and \(V(t)\) is the volume. In the following it is assumed that the derivative \((dV(t)/(dt))\) is negligible, so that the last term in (2) can be neglected. The assumption is fulfilled by making the control law for the aeration volume change slowly, see (6) below.

In the general case when the influent flow consists of several partial flows, \(Q_1(t), Q_2(t), \ldots, Q_n(t)\), the influent concentration of \(S_{NH,in}(t)\) can be obtained as a weighted mean (assuming a perfect mix):

\[
S_{NH,in}(t) = \frac{1}{Q(t)} \sum_{j=1}^{n} Q_j(t) S_{NH, in,j}(t)
\]

The total flow rate \(Q(t)\) is here given by \(Q(t) = \sum_{j=1}^{n} Q_j(t)\), where \(Q_j(t)\) denotes the \(j\)th inflow to the compartment. The influent concentration corresponding to the flow \(Q_j(t)\) is denoted \(S_{NH, in,j}(t)\).

In the ASM1 model, the reaction rate, \(R_{SNH}(t)\), in (2) is a highly nonlinear term, described by Henze et al. (1987):

\[
R_{SNH} = \left(-i_{XB} - \frac{1}{Y_A} \hat{\mu}_A \frac{S_{NH}}{K_{NH} + S_{NH}} \left( \frac{S_O}{K_{O,A} + S_O} \right) X_{BA} \right) \\
- \frac{i_{XB} K_{S}}{K_S + S} \left( \frac{K_{O,H}}{S_O} \right) X_{BH,H} + k_a S_{NO} X_{BH,H}
\]

where \(S_{NO}\) is the concentration of soluble biodegradable organic nitrogen, \(X_{BA}\) is the autotrophic biomass, \(X_{BH,H}\) is the heterotrophic biomass, \(S_S\) is the readily biodegradable substrate and \(S_{NO}\) is the nitrate nitrogen. The time index has here been omitted for convenience. See Henze et al. (1987) for a detailed discussion of the involved parameters in the reaction rate.

**Derivation of the controller**

Since major process disturbances such as time varying flow rates and influent concentrations affect the process, a control strategy that combines feedforward knowledge and traditional feedback could be of use. This could be achieved by exact linearization via feedback (see for instance Khalil (1996) for a general description, and Bastin and Dochain (1990) for...
applications in control of bioreactors). In the controller derivation in this paper, the output is chosen as the ammonium concentration in a totally mixed aerated compartment, and the control signal is chosen as the volume \( V(t) \). It is seen from (2) (when the last term is neglected) that a linearizing control law is given by:

\[
\dot{V}(t) = \frac{Q(t)(S_{\text{NH, in}}(t) - S_{\text{NH}}(t))}{u_{\text{lin}}(t) - R_{\text{S,NH}}(t)} \tag{4}
\]

yielding

\[
\frac{dS_{\text{NH}}}{dt} = u_{\text{lin}}(t) \tag{5}
\]

Theoretically, the problem is thus reduced to control an integrator with the control signal \( u_{\text{lin}}(t) \). There are many possible ways to choose the remaining control signal \( u_{\text{lin}}(t) \) in (5). In this paper a simple PI controller is chosen:

\[
\dot{u}_{\text{lin}}(t) = Ke(t) + K_I \int_{t_0}^{t} e(\tau) d\tau \tag{6}
\]

where

\[
e(t) = S_{\text{NH}}^{\text{sp}}(t) - S_{\text{NH}}(t) \tag{7}
\]

Here, \( S_{\text{NH}}^{\text{sp}}(t) \) is the ammonium set-point.

**Practical implementation**

When implementing the control law in practice, some modifications of (4) have to be made.

1. The reaction rate \( R_{\text{S,NH}}(t) \) first has to be estimated.
2. In a typical ASP, a fixed number of compartments can be aerated or non-aerated. Hence, only discrete volume changes can be utilized, i.e. the realizable volume \( V \) belongs to a set \( V = \{ V_1, V_2, \ldots, V_n \} \), where \( V_1 \) corresponds to the minimum aeration volume and \( V_n \) to the maximum aeration volume.
3. The control law has to be discretized with respect to time, and anti-windup should be implemented. This is standard procedure and is not discussed further.

**Estimation of the reaction rate**

A simple approach to estimate \( R_{\text{S,NH}}(t) \) is to use (2), neglecting the last term. It is then clear that:

\[
R_{\text{S,NH}}(t) = \frac{dS_{\text{NH}}}{dt} = \frac{Q(t)(S_{\text{NH, in}}(t) - S_{\text{NH}}(t))}{V(t)(S_{\text{NH, in}}(t) - S_{\text{NH}}(t))} \tag{8}
\]

Using the backward difference method to approximate the derivative in (8), an estimate of \( R_{\text{S,NH}}(t) \) is given by:

\[
\hat{R}_{\text{S,NH}}(t) = \frac{S_{\text{NH}}(t) - S_{\text{NH}}(t - h)}{h} \frac{Q(t)}{V(t)}(S_{\text{NH, in}}(t) - S_{\text{NH}}(t)) \tag{9}
\]

Here \( h \) denotes the sampling interval, the index \( t \) denotes the current sample and the index \( t - h \) denotes the previous sample. In practice, \( V(t) \) is replaced with \( V(t - h) \) in (9), which is reasonable if the volume changes are small. Since the estimate of the derivative in (9) may be affected by measurement noise and other fast transients, \( \hat{R}_{\text{S,NH}}(t) \) should be low pass filtered before being used in the controller. A suitable choice may be a first order low pass filter with the transfer function
\[ H(q) = \frac{\alpha q}{q + \alpha - 1} \]  \hspace{1cm} (10)

where \( q \) is the forward shift operator.

**Discrete changes of the aerobic volume**

As mentioned, the nature of the possible volume changes is discrete, since the plant is divided into compartments. Thus, to implement the control law (4), it has to be combined with some form of logical programming that takes this into account. The suggestion is therefore to control the ammonium in the last aerated compartment, by using (4) to calculate the desired aeration volume. The nearest larger volume \( V_j \) in the possible set \( V = [V_1, V_2, \ldots, V_n] \) should then be aerated. The rationale for this is to keep a low DO level by using a larger volume. In case the total aeration volume becomes too large and the non-aerated volume too small, it is possible to instead select the nearest smaller volume in the set.

To achieve the ammonium set-point, and to avoid fluctuations in the ammonium concentration this strategy needs to be combined with a slow supervisory DO controller that adjusts the set-point of the DO controllers in the aerated compartments. One possibility is to use the same DO set-point in all aerated compartments and let the supervisory DO controller used for calculating the DO set-point be:

\[ DO_{sp}(t) = -Ke(t) - K\int_{t_0}^{t} e(\tau)d\tau \]  \hspace{1cm} (11)

where \( e(t) \) is the control error of ammonium in the last aerated compartment, see (7). To prevent the DO concentration taking too high or too low values, \( DO_{sp}(t) \) should be given both an upper and a lower bound.

**Summary of the control strategy**

Below, a short summary of the control strategy is given:
1. Estimate \( R_{SNH}(t) \) according to (9).
2. Calculate the desired aeration volume (4), using the estimated reaction rate (9).
3. Aerate the nearest larger volume, \( V_j \), in the realizable set \( V = [V_1, V_2, \ldots, V_n] \).
4. Use (11) to adjust the DO set-point.

**A simulation study**

**Simulation setup**

The suggested control law was evaluated in a simulation study. A post-denitrifying ASM1 model with ten compartments was implemented and used in the study. Each compartment had a volume of 235 m³. MATLAB was used to implement the model. The model parameters were in both cases the default values reported in Henze et al. (1987). Some additional data regarding default flow rates and influent concentrations can be found in Samuelsson (2001). The layout of the simulated plant is shown in Figure 2.

![Figure 2](https://iwaponline.com/wst/article-pdf/45/4-5/45/425331/45.pdf)  
*Figure 2* The layout of the simulated ASP. The first four compartments are always aerated. The shaded compartments are allowed to be aerated when needed.
Simulations

Influent load variations according to Figure 3 was used. The superscript * in the figure denotes that these are influent flow rates and concentrations, not to be mixed up with the total influent to the controlled aerobic part. After 15 hours the ammonium concentration in the influent water is increased from 24 to 32 mg/l. After 65 hours the influent flow rate is changed from 250 to 300 m³/h.

This influent scenario was used first when simulating ordinary supervisory DO control with a PI controller, see (11). The sampling interval was 0.001 h. The parameters of the supervisory PI controller were chosen as $K = 0.0012$ and $K_i = 0.08$. The set-point of ammonium, $S^*_{NH}$, was chosen to be 2.5 mg/l. The constant total volume of the aerobic compartments was 1,175 m³. In Figure 4 the simulation results for this experiment is shown. It is clearly seen that the disturbance rejection, especially for the second disturbance, is poor and that the DO concentration takes very high values. This is caused by a too small aeration volume. The suggested volume controller was then simulated in combination with the supervisory DO controller, (11). In the simulations, the volume of the aerated compartment was allowed to take the discrete values $V = [940, 1175, \ldots, 1880]$ m³. The maximum allowed value of $DO^*(t)$ was 5 mg/l and the minimum value was 1.5 mg/l. The influent characteristics and the set-point of ammonium in the last aerated compartment were the same as in the simulation where only the supervisory DO controller was used. The PI parameters of the supervisory DO controller were the same, as well as the sampling rate. The volume control loop was sampled with the interval 0.1 h, and the PI parameters in (4) were chosen as $K = 0.000001$ and $K_i = 0.0000001$. The estimation of the reaction rate $R^*_{NH}(t)$ in (9) was performed over only the first four compartments to avoid fast transients, since these compartments were always assumed to be aerobic. The parameter in the low pass filter, (10), was chosen as $\alpha = 0.07$. Compared to when only the supervisory DO controller is used, it is seen that the disturbance rejection is significantly faster and that the required DO level for this control strategy is much lower, see Figure 4.

Conclusions

In this paper, a method based on linearization via feedback for controlling the aeration volume in an activated sludge process has been developed. The main objective was to reject
Changes in influent load variations quickly. Simulations suggest that the aeration volume could be an efficient control variable, and that feedforward methods could give a good result when controlling the aeration volume. It is also suggested how to implement the control law in practice, i.e., when the control variable is discrete. It should be mentioned that the tuning of the aeration controller must be done with care to avoid oscillations. Also, more advanced logics for handling the discrete volume changes could be incorporated. For example, the impact on the denitrification in the remaining anoxic compartments could be considered. An interesting step after performing more complete analysis and simulation experiments would be to evaluate the suggested strategy in a pilot plant.

References


