Improvement of nitrogen removal and reduction of operating costs in an activated sludge process with feedforward–cascade control strategy

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A B S T R A C T

In this paper, a feedforward–cascade controller for dissolved oxygen concentration in an activated sludge process is designed in order to meet stricter effluent quality standards at a minimum cost. Conventional proportional and integral (PI) constant dissolved oxygen set-point control and feedforward–cascade dissolved oxygen set-point control are evaluated using the reduced model of activated sludge model no. 1 and reduced IWA simulation benchmark. The feedforward–cascade control has been based on a hierarchical structure where a high level or cascade control selects the set-point of the low level or conventional controller and low level directly control dissolved oxygen concentration. And feedforward control is introduced in the control system for preventing the influent loading from influencing the system. Simulation results show that feedforward–cascade control of the activated sludge process is more successful than conventional PI control in meeting the effluent standards and reducing operational costs. This control strategy can be expected to be accepted by the operating personnel in wastewater treatment plants.

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1. Introduction

The activated sludge is one of the most widely used biological wastewater treatment processes (WWTP). The dissolved oxygen (DO) concentration in WWTP has been recognized as an important variable to be controlled both for economical and process efficiency purposes. A proper DO concentration has to be maintained by proper aeration. And aeration consumption is very important since it is responsible for approximately 50% of electrical consumption of the plant [1]. The optimal DO control is that the effluent ammonia and chemical oxygen demand (COD) concentration are kept below the defined limit in spite of influent and weather condition changes at the lowest possible aeration consumption [2].

The control of DO concentration in the aerobic zone of an activated sludge process is usually performed by three ways: first way is feedback control based on oxygen and/or ammonia measurement in the last aerobic reactor [3,4]; second is model-based feedforward control strategy [1,5]; last one is time-varying DO set-point control [6–8]. For the first and second control ways, the set-point of the control loop is normally fixed at a constant value on the basis of theoretical and heuristic considerations concerning the different biological processes that take place in the aerobic zone. One problem with such control is that it acts on the process only when influent causes changes in the last aerobic zone, which is usually too late with respect to process time constants and influent disturbance dynamics. Another problem is that it will lead to unnecessary power consumption due to high aeration and may also affect anoxic processes.

Obviously the set-point value is chosen as a compromise among the various values that would be more suitable in different operational conditions. Moreover, it might be difficult to choose a suitable DO set-point because of the competing biological reactions and the economical causes. For the third control way, that is usually determined by a higher level controller driven by the ammonia concentration in the aerobic zone. Though it realized time-varying DO set-point control, a problem with such control is that it cannot overcome the influent disturbance dynamics. In this paper, a new strategy for DO control which combines cascade and feedforward control is developed and validated. In this control strategy, DO set-point is determined by cascade control and feedforward control is used to overcome influent disturbance dynamics. The control strategy presented in this paper is tested on a reduced activated sludge model no. 1 (ASM1) and benchmark developed within COST Action 624 and 682.
2. Wastewater treatment plant benchmark and reduced model

The comparison between different control strategies for a WWTP is often difficult due to the variable influent conditions and the high complexity of a WWTP. Therefore, to enable objective comparisons between different control strategies, a simulation WWTP benchmark has been developed by the COST 682 Working Group No. 2 [9]. In the WWTP benchmark, a typical WWTP with predenitrification is implemented. The plant composed of two anoxic zones, three aerobic zones and a secondary settler (see Fig. 1). Each of the zones of the bioreactor is assumed to have a constant volume (1000 m$^3$, 1000 m$^3$, 1333 m$^3$, 1333 m$^3$, and 1333 m$^3$, respectively) and to be ideally mixed, the secondary settler has a constant volume (6000 m$^3$). The model for each bioreactor zone is based on the IAWQ ASM1 [10]. The double exponential settling velocity model proposed by Takács et al. [11] was selected to describe the behavior of the settler. To get an objective view of the performance of the applied control strategy in different situations, simulated influent data are available in three two-week files derived from real operating data. These files are generated to simulate three different weather situations. The file dry-influent contains two weeks of dry weather. The file rain-influent contains one week of dry weather and a long rain event during the second week. The file storm-influent contains one week of dry weather and two storms during the second week.

The complete benchmark model is summarized by the following equations:

For $k = 1$ (zone 1):

$$\frac{dz_1}{dt} = \frac{1}{V_1}(Q_0Z_0 + Q_rZ_r + Q_0Z_0 + r_1V_1 - Q_1Z_1)$$  \hspace{1cm} (1)

where $Q_1 = Q_4 + Q_0$, $Q_0$ is the internal recycle flow rate, $Q_r$ is the external recycle flow rate, $Q_0$ is the influent flow rate, $Z_1$, $Z_5$, $Z_r$, $Z_0$ are, respectively, the component concentrations of zone 1, zone 5, external recycle and the initial concentration of influent, $V_1$ is the volume of zone 1, $r_1$ is the component reaction rate in zone 1.

For $k = 2–5$ (zone 2–5):

$$\frac{dz_k}{dt} = \frac{1}{V_k}(Q_kZ_k - r_kV_k - Q_kZ_k)$$  \hspace{1cm} (2)

where $Q_k = Q_{k-1}, Z_k$ is the component concentration of $k$th zone, $V_k$ is the volume of $k$th zone.

Special case of oxygen ($S_{O,k}$)

$$\frac{dS_{O,k}}{dt} = \frac{1}{V_k}(Q_{k-1}S_{O,k-1} + Q_kS_{O,k} + r_kV_k + (kla_k)V_k(K_{S_{O,sat}} - S_{O,k}))$$  \hspace{1cm} (3)

with $r_k = \sum_{j=1}^{8} v_{kj} \rho_j$ (observed conversion rates), $kla$ is the oxygen transfer coefficient, $S_{O,sat}$ is the concentration at saturation of oxygen.

$Z = [S_5, X_5, X_{BH}, X_{BA}, S_0, S_{NO}, S_{NH}, S_{ND}, X_{ND}]$.

Some state variables that are independent of the nitrogen removal phenomenon, i.e. the soluble and particulate inert organic matters and the alkalinity, have not been represented.

In the purpose of using this model for the design of the control strategy, the model has to describe some variables at specific loca-

<table>
<thead>
<tr>
<th>Table 1 Performances comparison of controllers</th>
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<tbody>
<tr>
<td>Feedforward–cascade controller</td>
</tr>
<tr>
<td>Feedforward controller</td>
</tr>
<tr>
<td>Aeration energy (kWh/d)</td>
</tr>
<tr>
<td>Average NH$_4$-N (mg/l)</td>
</tr>
<tr>
<td>Average NO$_3$-N (mg/l)</td>
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</tbody>
</table>
tions: the output of the anoxic zone, the input and the output of the aerobic zone. Therefore, the benchmark can be reduced using a system composed of two zones. So the benchmark is composed of only two units: the first two anoxic zones are lumped together as well as the last three aerobic zones are lumped together (see Fig. 2).

Though the ASM1 and benchmark model are simple through above reduced work, the dynamics of the ASM1 model are very complex and exhibit stiff dynamics with time scales ranging from seconds to weeks. The singular perturbation approach is well suited for this type of behavior. A singular perturbation system is a system for which the state equations rates can be written in the standard form (similar to Cadet et al. [12]):

\[
\frac{dx_1}{dt} = f_1(x_1, x_2, u, \varepsilon) \\
\frac{dx_2}{dt} = f_2(x_1, x_2, u, \varepsilon)
\]  \hspace{1cm} (4)

where \(x_1 \in \mathbb{R}^n, x_2 \in \mathbb{R}^n, f_1 \) and \(f_2 \) are regularly function vectors of \((x_1, x_2, u, \varepsilon)\), and \(\varepsilon\) is a parameter, positive and small.

Define \(\tau = t/\varepsilon\)

\[
\frac{dx_1}{d\tau} = \varepsilon f_1(x_1, x_2, u, \varepsilon) \\
\frac{dx_2}{d\tau} = f_2(x_1, x_2, u, \varepsilon)
\]  \hspace{1cm} (5)

In the limit of \(\varepsilon \to 0\) in Eq. (5), the fast dynamics system is:

\[
\frac{dx_1}{d\tau} = 0 \\
\frac{dx_2}{d\tau} = f_2(\hat{x}_1(t), \hat{x}_2(t) + x_2(\tau), u, 0)
\]  \hspace{1cm} (6)

In the limit of \(\varepsilon \to 0\) in Eq. (4), the slow dynamics system is:

\[
\frac{dx_1}{dt} = f_1(x_1, \phi(x_1, u), u, 0) \\
x_2 = \phi(x_1, u)
\]  \hspace{1cm} (7)

where \(\hat{x}_1(t), \hat{x}_2(t)\) are considered over the timescale \(\tau\). The reaction rates are chosen to be the \(\varepsilon\) parameter: \(\rho_1 \equiv \rho_2 \equiv \rho_7 \equiv 1/\varepsilon\).

Finally, after writing the ASM1 model in the standard form, the fast state variable are: \(Z_f = [S_S, S_X, S_{BH}, S_O, S_{NO}, S_{NH}]\) and the slow state variables are \(Z_S = [X_{BA}, S_{ND}, X_{ND}]\). To keep information on nitrogen removal, the system of fast dynamics is used. This leads to an algebraic–differential system of only six state variables for each zone. The model has now only 12 state variables (65 states in the initial model), and is much simpler.

3. Feedforward–cascade control strategy

The basic idea of the feedforward–cascade is to control the DO set-point from on-line measurements of the influent and effluent ammonia concentration. The aim of the control strategy is to better control the effluent ammonia concentration and save energy by applying a time-varying DO set-point. The control scheme of such DO set-point control is shown in Fig. 3.

Fig. 4. Relationship between influent ammonia and dissolved oxygen in aerobic zone.
This structure is referred to as cascade control, where the inner DO loop is much faster than outer the ammonia loop. To avoid the DO set-point becoming too high or too low coming of the influent disturbance dynamics, this controller makes an extension of the cascade DO controller, described above, with the addition of a feedforward controller. The ammonia concentration in the influent is measured continuously, and from this the ammonia influent load is calculated. In the paper, a simple model for the ammonia removal rate derived from ASM1 has been used (similar to Vrečko et al. [13]). According to the above reduced model, the following equation can be obtained approximately:

\[
\frac{dS_{NH}}{dt} = \frac{Q(S_{NH0} - S_{NH})}{V} - \frac{\mu_A X_{BA}}{Y_A} \frac{S_{NH}}{(S_{NH} + K_{NH})} S_O
\]

(8)

where \(Q\) is the total incoming flow (including influent, nitrate recirculation and sludge recycle flow), \(V\) the total volume of aerobic zone, \(S_{NH0}\) the ammonia concentration in the total incoming flow, \(S_{NH}\) the ammonia concentration in the outlet of the aerobic zone, \(X_{BA}\) the concentration of the autotrophic biomass in the aerobic zone, \(\mu_A\) the maximum specific growth rate of autotrophic biomass, \(Y_A\) the yield for autotrophic biomass, \(K_{NH}\) and \(K_{OA}\) the ammonia and oxygen half saturation constants, and \(S_O\) is the oxygen concentration in the aerobic zone. By considering model (8) in the steady state, the following equation for the oxygen set-point is obtained:

\[
S_{O,ref} = \frac{K_{OA}}{(X_{BA} V S_{NH, set} \mu_A) / Q (S_{NH0} - S_{NH, set}) (S_{NH, set} + K_{NH}) Y_A - 1}
\]

(9)

Fig. 5. DO set-point under different weather conditions.

Fig. 6. Effluent nitrate concentration in under different weather conditions.
where $S_{NH, set}$ is the desired set-point for the ammonia concentration in the outlet of the aerobic basin. Due to the model’s approximations, Eq. (9) gives only an approximate oxygen set-point in the zone and hence feedback control should also be applied. The master controller for the oxygen set-point can be written as follows:

$$S_{O, ref} = S_{O, ref} + K'_p (S_{NH, set} - S_{NH}) + K' \int (S_{NH, set} - S_{NH}) \, dt$$  \hspace{1cm} (10)

If $S_{O, ref}(k - 1) + \Delta S_{O, ref}(k) > S_{max, O, ref}$, Then $S_{O, ref}(k) = S_{max, O, ref}$

If $S_{min, O, ref} \leq S_{O, ref}(k - 1) + \Delta S_{O, ref}(k) \leq S_{max, O, ref}$, Then $S_{O, ref}(k) = S_{O, ref}(k - 1) + \Delta S_{O, ref}(k)$

If $S_{O, ref}(k - 1) + \Delta S_{O, ref}(k) < S_{min, O, ref}$, Then $S_{O, ref}(k) = S_{O, ref}(k - 1) + \Delta S_{O, ref}(k)$

Then $S_{O, ref}(k) = S_{O, ref}$, where $S_{O, ref}$ is the maximum DO set-point, $S_{O, ref}$ is the minimum DO set-point. The oxygen set-point is now changed according to the influent ammonia and the ammonia in the last aerobic zone. While the oxygen concentration is controlled by slave PI controllers manipulating $K_L a$ in aerobic zone:

$$K_L a(t) = K_P (S_{O, ref}(t) - S_o(t)) + \frac{1}{T} \int_0^t (S_{O, ref}(\tau) - S_o(\tau)) \, d\tau.$$  \hspace{1cm} (11)

In the feedforward term (9) of the oxygen set-point controller, the concentration of the autotrophic biomass is needed but it cannot be measured on line. Since this concentration is only changing slowly, it may be entered into the controller as a constant. In this paper, this concentration is known, whereas the default values in ASM1 were used for the other parameters ($\mu_A$, $Y_A$, $K_{NH}$ and $K_{OA}$).

By using the feedforward controller as described above, the oxygen set-point remains the same in aerobic zone.

### 4. Results and discussion

Simulation results are shown in Table 1. The average effluent ammonia concentrations, average effluent nitrate and the aeration energy were calculated for the different strategies under different weather conditions. Compared to the case of PI control, the average effluent nitrate was reduced by 3.9%, 13% and 5.2%, respectively, under dry, rain and storm weather. The aeration energy was reduced by 4.7%, 7.9% and 3.7%, respectively, under the three weather conditions. The average effluent ammonia was reduced by 2.5% and 1.6%, respectively, under dry and storm weather. Under the rain weather condition, the average effluent ammonia was increased slightly.

Fig. 4 shows the relationship between influent ammonia and DO concentration in aerobic zone, real line is influent ammonia and dash line is DO concentration. Compared to the operation with PI controller, through the implementation of the ammonia load in the influent as a feedforward signal, the feedforward–cascade controller could adjust the DO set-point according to the influent and effluent ammonia concentration. Fig. 5 shows the time-varying DO set-point. According to the results, we can see that DO set-point has been changed with time under different weather conditions. So it realized time-varying DO set-point control.

Figs. 6 and 7 show the effluent ammonia and nitrate under different weather conditions with feedforward–cascade controller and PI controller, real line represents the results with

![Fig. 7. Effluent ammonia concentration under different weather conditions.](image-url)
feedforward–cascade controller and dash line represents the results with PI controller.

Based on the above results, we can see that PI constant DO set-point control strategy has a major drawback: neither feedback from effluent ammonia nor feedforward from influent ammonia concentration is used. The problem can be partly solved using a cascade DO-control strategy, which is achieved by implementing a control law that adjusts the set-point of the DO so that the ammonia concentration in the effluent is kept at some prespecified level. However, it cannot overcome the influent disturbance dynamics. The feedforward control is an efficient strategy to use in the activated sludge process because of the high hydraulic delays, which can attenuate disturbances relatively quickly. The idea of feedforward control is to reduce the influent disturbance before it causes major changes in the effluent. In the feedforward parts of the controllers, static physical models based on a simplification of the ASM1 model are applied. So, feedforward control combined with slow feedback control to compensate for model approximations is the best DO-control strategy. The results from the test indicated that the feedforward–cascade controller performed significantly better than the PI controller in terms of energy savings and fine control of the concentration of effluent ammonia and nitrate.

5. Conclusions

In this paper, a new control strategy for improving nitrogen removal and operating costs in an activated sludge process has been discussed. The basic idea of the control strategy was to control the DO set-point according to the influent and effluent ammonia concentration. The main objective was to reject changes in influent load variations quickly. The control strategy has been validated using the reduced ASM1 and benchmark model. Simulation results showed that, by using this controller not only energy could be saved due to a lower DO set-point, but also the effluent nitrate and ammonia concentration could be improved.

References