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Feedforward-feedback control of dissolved oxygen concentration in a predenitrification system

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Abstract As the largest single energy-consuming component in most biological wastewater treatment systems, aeration control is of great interest from the point of view of saving energy and improving wastewater treatment plant efficiency. In this paper, three different strategies, including conventional constant dissolved oxygen (DO) set-point control, cascade DO set-point control, and feedforward-feedback DO set-point control were evaluated using the denitrification layout of the IWA simulation benchmark. Simulation studies showed that the feedforward-feedback DO set-point control strategy was better than the other control strategies at meeting the effluent standards and reducing operational costs. The control strategy works primarily by feedforward control based on an ammonium sensor located at the head of the aerobic process. It has an important advantage over effluent measurements in that there is no (or only a very short) time delay for information; feedforward control was combined with slow feedback control to compensate for model approximations. The feedforward-feedback DO control was implemented in a lab-scale wastewater treatment plant for a period of 60 days. Compared to operation with constant DO concentration, the required airflow could be reduced by up to 8–15% by employing the feedforward-feedback DO-control strategy, and the effluent ammonia concentration could be reduced by up to 15–25%. This control strategy can be expected to be accepted by the operating personnel in wastewater treatment plants.

Keywords Energy-saving · Feedforward-feedback control · DO control · Predenitrification

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Introduction

The growing reliance upon biological nitrogen removal to meet increasingly stringent effluent criteria, and increasing demands for process economy and performance highlight the need for new process monitoring and control strategies. This work investigates the control of one of the most important control handles in wastewater treatment plants: the aeration. Aeration is responsible for approximately 50% of the electrical power consumption and it is a key factor in maximizing the efficiency of biological treatment of wastewater [1]. In addition, the nitrification process (the biological transformation of ammonia to nitrate) is dependent on the availability of oxygen. A dissolved oxygen (DO) concentration that is too high will lead to unnecessary power consumption due to high aeration and may also affect anoxic processes. A DO concentration that is too low inhibits bacterial growth (especially nitrifying bacteria), and leads to both bad-quality sludge and less efficient pollutant removal [2]. Improving the control of DO could help us achieve improved process performances, and there is an economic incentive to minimize excess oxygenation by supplying only the air necessary to meet the time-varying oxygen demand of the mixed liquors. Therefore, the objective of this paper is to effectively evaluate and compare the DO control strategies under standardized conditions, the International Water Association (IWA) simulation benchmark, and to provide practical knowledge for applying those control strategies to wastewater treatment plants.

Materials and methods

Many control strategies have been proposed in the literature, but it is difficult to evaluate and compare them either practically or by simulation. To enhance the development and acceptance of innovative control

strategies, the evaluation procedure must be made easier and fairer. Therefore, a simulation benchmark of an activated sludge process was developed by the group of COST Action 624 and 682 in 1999. This benchmark model defines plant layout, influent loads, the modeling and test procedure, and evaluation criteria [3]. Figure 1 is a schematic representation of the plant layout, which is a standard activated sludge process including a bioreactor and a secondary settler. The bioreactor is composed of five compartments; the first two compartments are anoxic and the last three are aerated, and all five compartments are fully mixed. The IAWQ activated sludge model No1 (ASM1) was selected to model the biological processes in the bioreactor (a further description of ASM1 can be found in Henze et al [4]). The secondary settler is modeled as a series of ten layers, and the double exponential settling velocity model proposed by Takacs et al [5] is chosen to resemble the behavior of the settler. The full set of equations and all the parameter values are available on the COST 624 website (<http://www.ensic.u-nancy.fr/COSTWWTP/>). In this paper, the controllers are implemented in the benchmark, using Matlab/Simulink. The internal recycle flow was controlled to be proportion to influent flow rate by a factor of 2.5, and the sludge recycle flow was controlled to be proportional to influent flow rate by a factor of 0.75. Waste sludge flow was set to 300 m³/day. The performance of the plant was always evaluated for the last 7 days of simulation under dry weather influent, and the influent ammonia and total nitrogen concentrations used in the simulation are shown in Fig. 2.

Proposed DO-control strategies

Three different control strategies, including conventional constant DO controller, cascade DO controller, and feedforward-feedback DO controller were evaluated using the IWA simulation benchmark, and these are described in the following paragraphs.

Constant DO controller

This control system serves as the reference case. It is a classic DO controller, which controls the DO concentration at some prespecified level, where the DO controller directly changes the air flow valve to adjust the DO level to the desired value. In this study, the DO concentrations in aerobic zones are kept at 3.5 mg/l.

Fig. 1 Benchmark plant layout

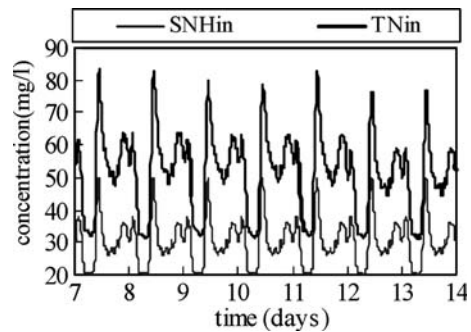
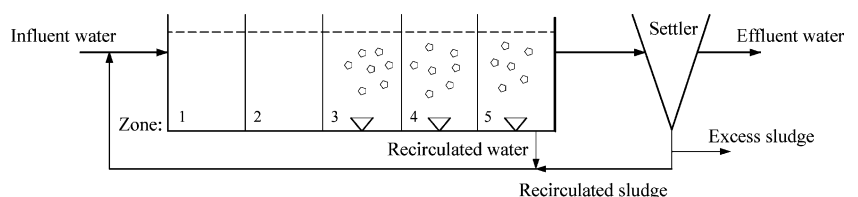


Fig. 2 Influent ammonia and total nitrogen concentrations

Cascade (feedback) DO controller

This 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 (with an ammonia set-point of 2.0 mg/l). A master control loop calculates the desired DO set-point for adjusting the effluent ammonia to a given set-point, and a slave controller is then used to adjust the air flow to get the desired DO set-point.

Feedforward-feedback DO controller

This controller is an extension of the cascade DO controller, described above, with the addition of a feedforward controller. The ammonia concentration in the influent and the influent flow are 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 Vrecco et al) [6]. If we assume that all three aerobic basins can be considered to be one aerobic basin, the following equation can be obtained approximately:

$$\frac{dS_{NH}}{dt} = \frac{Q(S_{NH,0} - S_{NH})}{V} - \frac{\mu_A X_{BA}}{Y_A} \frac{S_{NH}}{(S_{NH} + K_{NH})} \frac{S_O}{(S_O + K_{OA})}, \quad (1)$$

where Q is the total incoming flow (including influent, nitrate recirculation and sludge recycle flow), V the total volume of our aerobic basin, $S_{NH,0}$ the ammonia concentration in the total incoming flow, S_{NH} the ammonia concentration in the outlet of the aerobic basin, X_{BA} the concentration of the autotrophic biomass in the aerobic basin, μ_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 basin. By considering model (1) in the steady state, the following equation for the oxygen set-point is obtained:

$$S'_{O,set} = \frac{K_{OA}}{(X_{BA} V S_{NH,set} \mu_A / Q (S_{NH,0} - S_{NH,set}) (S_{NH,set} + K_{NH}) Y_A) - 1}, \quad (2)$$

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. 2 gives only an approximate oxygen set-point in the basin and hence feedback control should also be applied. The master controller for the oxygen set-point can be written as follows:

$$S_{O,set} = S'_{O,set} + K'_i \int (S_{NH,set} - S_{NH}) dt, \quad (3)$$

while the oxygen concentration is controlled by slave PI controllers manipulating KLa in each basin:

$$KLa_j = K_P (S_{O,set} - S_{O,j}) + K_i \int (S_{O,set} - S_{O,j}) dt, \quad j = 3, 4, 5 \quad (4)$$

In the feedforward term (2) 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 (μ_A , Y_A , K_{NH} and K_{OA}). By using the feedforward controller as described above, the oxygen set-point remains the same in all three aerobic basins. The integral gain of the master controllers ($K'_i = 5$) was the same in the cascade and feedforward-feedback DO controller, and the slave controllers were the same in three different DO controllers ($K_P = 100$ and $K_i = 10,000$).

Simulation results and discussion

Sample simulation results are shown in Table 1; the average and maximum effluent ammonia concentrations, average effluent total nitrogen, average DO concentration, and the aeration energy are calculated for the

different strategies. Simulation results from the constant DO controller are shown as the reference case. A steady state for the plant was used as a starting point for each simulation, as defined in the benchmark specification (long time dry weather conditions).

Cascade DO controller

A comparison between the cascade controller and the constant DO controller is shown in Fig. 3. Unlike operation with a constant oxygen concentration, the cascade controller can adjust the DO set-point according to the effluent ammonia concentration, resulting in better effluent concentrations, so that average effluent ammonia is reduced by up to 13.3%, energy consumption for aeration is reduced by up to 9.6%, and at the same time average total nitrogen concentration in the effluent is reduced by up to 4%. The ammonia peak was 6% lower than for the constant DO controller. Obviously, load increases are not detected quickly, and subsequently the aeration is sometimes increased when the ammonia concentration is already at a decreased level. However, in general it can be concluded that the cascade controller is more successful than the constant DO controller in meeting effluent standards and in reducing operational costs.

Feedforward-feedback DO controller

Analyzing the performance of the cascade controller, we noted that only a reduction in peak level could be achieved. This is related to the principal limitation of the use of feedback control to reject disturbances, especially for plug-flow type plants. The only way to improve the control behavior is to apply feedforward control. However, this is only possible when applying the new generation of sensors, as they can even be used in difficult locations such as in raw influent or in the effluent of the primary clarifier.

Figure 4 shows the effect of feedforward-feedback action, where the ammonia peaks are reduced by approximately 17.86% and denitrification is improved by 6.5% during the night compared to operation with constant DO controller. As this controller decreases the

Table 1 Sample simulation results for DO control strategies

Controller	Constant controller	Cascade controller	Feedforward-feedback controller
Max NH ₄ -N of effluent (mg/l)	8.40	7.85	6.89
Mean NH ₄ -N of effluent (mg/l)	2.79	2.40	2.11
Mean NH ₄ -N of the fifth zone (mg/l)	2.34	2.03	1.82
Mean TN of effluent (mg/l)	18.46	17.74	17.26
Mean DO of aerobic zone (mg/l)	3.50	3.15	2.96
Aeration energy (kW h/day)	15,569	14,074	14,121

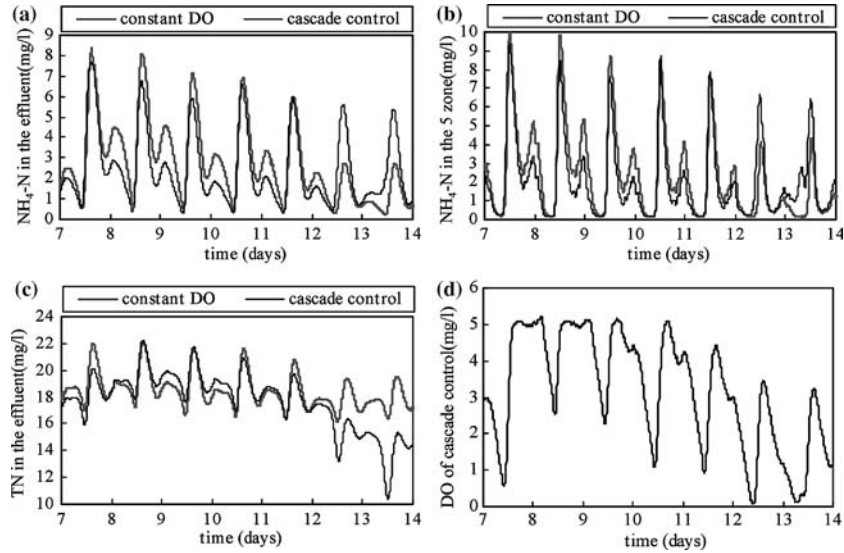


Fig. 3 Simulation results for the cascade controller compared to the constant DO controller

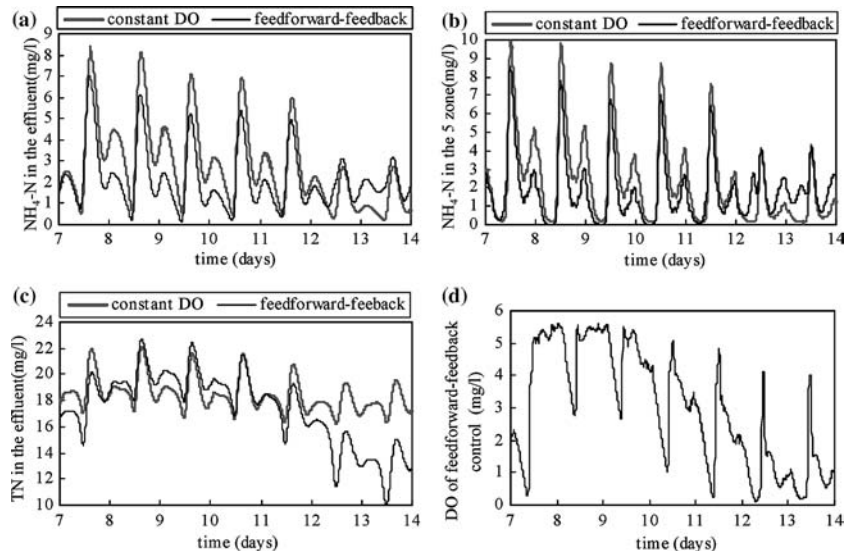
mean ammonia effluent concentration by approximately 9% compared to the cascade DO controller, slightly more aeration energy is needed (0.33%). Unlike operation with constant DO concentration or cascade DO control, by using the ammonia load in the influent as a feedforward signal, the feedforward-feedback controller can be used to adjust the DO set point according to the influent and effluent ammonia concentration, resulting in better effluent concentrations.

Strategy comparison and discussion

Based on the above results, we can see that constant DO-control strategy has a major drawback when a nitrifying aerobic process is used: neither feedback from effluent ammonia nor feedforward from influent

ammonia concentration is used. Since the load to a wastewater treatment plant may vary by a factor of six or more, this may cause large variations in ammonia concentration in the effluent [7]. 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, there are time delays that mean that the influent ammonia peaks are not inhibited quickly enough. 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 com-

Fig. 4 Simulation results for the feedforward-feedback controller and the constant DO controller



compensate for model approximations is the best DO-control strategy.

The results from the three tests indicated that the feedforward-feedback controller performed significantly better than the other controllers in terms of energy savings and fine control of the concentration of effluent ammonia. However, this control strategy may cause some problems. If the aerated volume is not sufficient, the airflow rate may saturate and the DO level may become too high. If a predenitrification process is used and the DO level in the internal recirculation is too high, this may inhibit the denitrification. On the other hand, a DO level that is too low may decrease the sludge quality and induce the formation of nitrous oxide. Also, mixers are generally needed when the DO level becomes too low. Controlling the aerobic volume can resolve the problem; maximum and a minimum DO set-points are fixed, and the aerobic volume is automatically increased when the DO set-point selected by the feedforward-feedback control strategy is larger than its maximum level, while the aerobic volume is reduced when the DO set-point selected by the control strategy is less than the minimum level.

Lab-scale experiments investigating the aeration control strategies

In order to validate the performance of the DO-control strategies practically, experiments were carried out in a lab-scale predenitrification plant (Fig. 5) for 60 days. During the experiment, two identical activated sludge lines were used. The feedforward-feedback controller was implemented in one line, while a constant DO set-point aeration strategy (using DO set-point of 2.5 mg/l) was used as a reference for comparison in the other line. The DO set-point was obtained using a PID ($K_p=1$, $K_i=5$, $K_d=0$) controller and the aeration valves were controlled with a computer. The inflow, nitrate recirculation flow and sludge recycle flow were controlled by a variable speed peristalsis pump, and the influent and effluent ammonia concentration were measured by ammonia on-line sensors. During the experiments, the influent flow, MLSS, SRT and sludge recycle ratio were maintained at 150 l/day, 2,200 mg/l, 10 days, and 0.75 respectively; the temperature in the mixed liquor was stable (20 °C). As shown in Fig. 6, the effluent ammonia concentration varied greatly due to the constant DO-control strategy. When the influent ammonia concentration was 22 mg/l, the effluent ammonia was 0 mg/l;

when the influent ammonia concentration was 85.6 mg/l, the effluent ammonia was 21.2 mg/l. The effluent ammonia concentration was basically kept at a pre-specified level (4 mg/l) using a feedforward-feedback control strategy, and the ammonia peaks in the effluent were reduced significantly, from 21.2 to 9.23 mg/l. Calculations indicated that the average effluent ammonia concentration was 4.11 mg/l for feedforward-feedback control, while it was 4.90 mg/l for constant DO control, so the effluent ammonia concentration reduced by 16.4%; at the same time the aeration energy was reduced up to 9.6%, while the nitrate nitrogen concentration in the effluent was basically equal. The results from the tests indicate that of feedforward-feedback control strategy performed significantly better than the constant DO set-point control strategy in terms of energy savings and fine control of the concentration of effluent ammonia.

Conclusions

Three different DO-control strategies, including constant DO, cascade control and feedforward-feedback control, were evaluated using the IWA simulation benchmark in order to improve effluent quality, and reduce energy costs. The simulation studies indicated that the constant DO-control strategy has a major drawback in that neither feedback from effluent ammonia nor feedforward from influent ammonia concentration are used.

Only approximately the same peak level can be achieved using the cascade controller. This is related to the principal limitation of the use of feedback control to reject disturbances, especially for plug-flow type plants.

By implementing the ammonia load in the influent as a feed-forward signal, a feedforward-feedback controller could be used to adjust the DO set point according to the influent and effluent ammonia concentrations. The feedforward-feedback controller performed significantly better than the other controllers in terms of saving energy and fine control of the concentration of effluent ammonia.

Using experimental investigations, we have also shown that the feedforward-feedback controller produces a large decrease in the DO concentration, leading to aeration energy savings in the region of 8–15%, while average effluent ammonia was reduced by up to 15–25% when compared with the constant DO set-point aeration control strategy.

Fig. 5 Lab-scale plant used for experimental validation of the DO control strategy

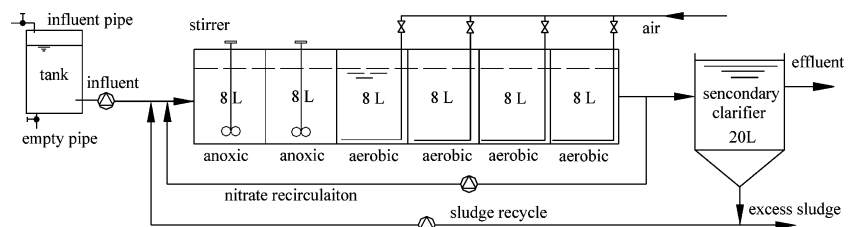
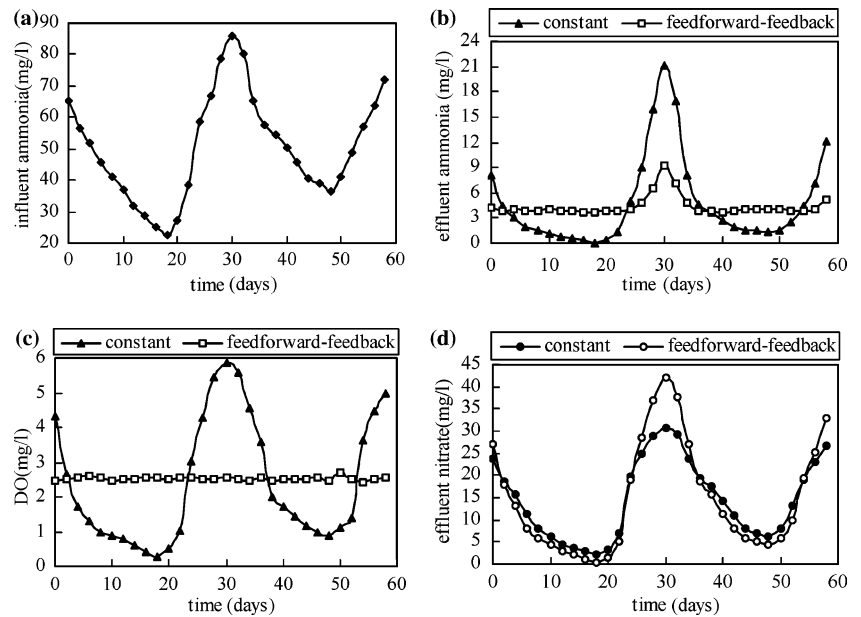


Fig. 6 Experimental results for effluent ammonia, total nitrogen, and DO concentration in the aerobic reactor with a constant DO controller and a feedforward-feedback controller



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