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REDUCED ENERGY CONSUMPTION AND IMPROVED NITROGEN REMOVAL BY USING MORE EFFECTIVE AERATION

Minskad energiförbrukning och bättre kväverening genom effektivare luftning

by MATS EKMAN[1] *and BERNDT BJÖRLENIUS*[2]
1 Dep. of Information Technology, Uppsala University, Box 337, S-751 05, Uppsala, Sweden
e-mail: mats.ekman@it.uu.se
2 Stockholm water Co. S-106 36, Stockholm, Sweden
e-mail: Berndt.Bjorlenius@stockholmvatten.se

Abstract

In this study, an aeration volume control strategy for an activated sludge process is evaluated in a pilot plant at Hammarby Sjöstad in Stockholm, Sweden. The main idea has been to let the DO concentration in some of the aerated compartments be determined by the DO concentration in other compartments. In this way only sensors for measuring the DO concentrations are needed for the decision of time varying DO set-points. The high reliability of such sensors implies robust input values for the proposed control strategy. The suggested manipulations of the DO set-points are indirectly determined by the current load into the plant. Compared to constant DO control, the suggested aeration volume control strategies could reduce the effluent nitrate and ammonium concentrations significantly without increasing the aeration energy. A simulation study including an evaluation of different controller design parameters has also been performed.

Key words – automatic control, activated sludge process, aeration, volume control, cascade control, DO set-points, nitrogen removal, energy consumption.

Sammanfattning

I denna studie utvärderas en överordnad reglerstrategi, där luftningsvolymerna i den aeroba delen av en aktivslamprocess styrs för att åstadkomma en optimering av kvävereduktionen och luftförbrukningen. Den överordnade reglerstrategin baseras på mätningar av syrehalter i bassängerna vilket medför att inga andra givare än syregivare är nödvändiga för att strategin ska fungera. Syrebörvärden för de olika luftade bassängerna beräknas av den överordnade reglerstrategin och kommer därför också att indirekt bestämmas av belastningen in till verket. Styrstrategin har testats i ett småskaligt avloppsreningsverk, och i jämförelse med en klassisk syrereglering med konstanta börvärden visar den föreslagna överordnade reglerstrategin att både nitrat- och ammoniumhalter kan minskas utan att luftningsenergiförbrukningen behöver ökas. I denna studie utvärderas även hur olika designparametrar i den föreslagna reglerstrategin påverkar resultaten.

Introduction

A common concept for biological wastewater treatment is the activated sludge process (ASP). Nitrogen removal in an ASP is governed by the two biological processes, nitrification and de-nitrification. To obtain a satisfying nitrification it is necessary in the aerobic environment to have an adequately large aeration volume together with a sufficiently high concentration of dissolved oxygen (DO) to cover the oxygen demand of the microorganisms. On the other hand, aeration causes high energy costs and constitutes the major expenditure of an ASP plant. Moreover, a too high DO level may unfavorably influence the de-nitrification rate in the anoxic compartments (Olsson and Newell, 1999). Therefore, controlling the DO level and limit the aeration as much as possible, is very important for process reasons as well as on economical grounds.

Today, the most common way of controlling the aeration in an ASP is to keep the DO concentration at some pre-specified level. However, it is often difficult to know the DO concentration needed to achieve a satisfactory ammonium reduction. Moreover, it might be difficult to choose a suitable DO set-point because of the competing biological reactions and the economical causes mentioned above. One way to overcome these difficulties is to use a time varying DO set-point, which is determined supervisory by the ammonium concentration in the last aerobic compartment, (Nielsen and Lyngaard, 1993), (Lindberg, 1997), and (Carlsson and Rhenström, 2002). Multivariable approaches for controlling the nitrification and denitrification simultaneously have also been a subject for investigation, (Lindberg, 1998) and (Ekman, 2005b). In order to achieve a satisfactory nitrification it is important that the aerated volume is sufficiently large when DO control is used. Attempts to use the aeration volume as an extra control variable have been made. A model based feedforward control strategy of the aeration volume was evaluated in a pilot plant (Brouwer et al., 1998). The strategy is based on a simplified ASP model. A related model based approach is presented in Samuelsson and Carlsson, (2002), where feedforward information together with a traditional feedback is used for controlling the aeration volume. Other related approaches, where feedback control is combined with feedforward information have been studied by Alex et al. (2002) and Samuelsson (2005). Some rule based strategies for manipulating the aerobic volume can for example be found in Hoen et al. (1996) and Krause et al. (2001), and a volume control strategy using oxygen uptake monitoring is presented in Svardal et al. (2003).

In this paper, a strategy where the DO concentration in some of the compartments is determined by a higher level controller driven the DO concentration in other compartments is studied. In this way, only sensors for measuring the DO concentrations are needed for the decision of the time varying DO set-points. The oxygen consumption is affected by the content of substrate and nitrogen in the compartments. Therefore, the suggested manipulations of the DO set-points are indirectly determined by the current load into the plant. By using threshold values the DO concentration in the compartments with time varying set-points can for some periods be very low, hence, the suggested strategy may be regarded as a control of the aeration volume. Nevertheless, it is not obvious how to choose the design parameters associated with the threshold values. The suggested strategy was first described in (Ekman, 2005a). However, in this paper a more detailed investigation of the design parameters and their influence on the controller behaviour is performed.

The aeration volume control strategy was tested and evaluated in a pilot wastewater treatment plant situated at the Hammarby Sjöstadsverket in Stockholm, Sweden. The investigated strategy was run and compared with a standard constant DO set-point control in the pilot plant for more than one month with satisfactory result. The suggested strategy is also tested on a wastewater treatment simulation benchmark developed within the COST Action 624 and 682.

The pilot plant in Hammarby Sjöstad

The practical test of the suggested control strategy was carried out in the existing pilot plant in Hammarby Sjöstad, Stockholm, Sweden. Hammarby Sjöstad is the largest urban development project in Stockholm for many years. When Hammarby Sjöstad is fully developed, in 2016, it will include 9.000 apartments for around 22.000 residents, and altogether 30.000 people are expected to live and work in the area.

The new area has its own environmental programme as well as a special eco-cycle model and an environment information center. One essential part of the technical infrastructure and eco-cycle model is the experimental on-site sewage facility, officially opened in 2003. New treatment technologies, at least for Nordic conditions, are used to treat and extract nutrients from sewage for use on farmland. Storm water is treated locally to avoid overloading and contamination of the sewage facility. The research program will continue until 2007. The results will be used to design a full scale treatment plant for Hammarby Sjöstad but can also be employed for novel developments in existing sewage works.

The pilot plant consists of four treatment lines including sludge treatment (anaerobic digestion and dewatering). Line 1 and 2 have aerobic processes as the main biological treatment: activated sludge and membrane bio reactor (MBR), respectively. Line 3 and 4 use anaerobic processes as principal biological treatment: fluidized bed respectively up-flow anaerobic sludge blanket (UASB).

Line 1 is characterized by the same process layout as the existing main central sewage works in Henriksdal WWTP in Stockholm, i.e. chemical pre-precipitation, pre-denitrification and sand filtration. Line 1 is equipped with a primary sedimentation including a separate hydrolysis tank, three anoxic compartments with mixers, three aerated reactors, secondary sedimentation and a dual media down-stream sand filter, see Figure 1. The biological reactors all have membrane diffusers so the air flow can be controlled or be completely shut off or, alternatively, fully on. The primary and excess sludge are thickened by a gravity thickener, digested in a mesophilic digester, and finally dewatered in a centrifuge. Line 1 has a design inflow of 1.2 m^3/h. Design data for line 1 are shown in Table 1.

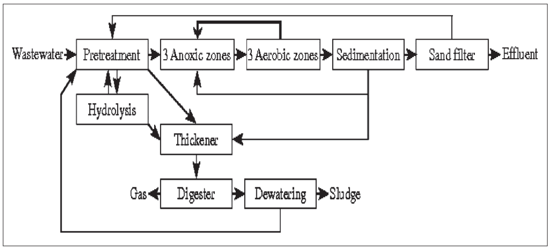

Figure 1. *Schematic outline of line 1.*

The aeration volume control strategy

The main idea behind the suggested aeration volume control strategy is as follows:

1. During periods when the influent load into the plant is low, a relatively low number of compartments are aerated using controllers with pre-specified DO set-points.
2. When the influent load is increasing, some additional compartments are as well aerated using a cascade control strategy. Depending on the plant layout, the additionally aerated compartments may be located before and/or after the compartments which are aerated also during low load periods.

The suggested aeration volume controller is based on reliable DO measurements in a cascade strategy. The idea is to utilize the fact that during closed loop DO control, the aeration flow in the aerobic compartments reflects the dynamics of the influent load into the plant. Thus, a feasible strategy is to use a larger aeration volume during high load conditions than during low load conditions. Such a strategy has the potential to save aeration energy.

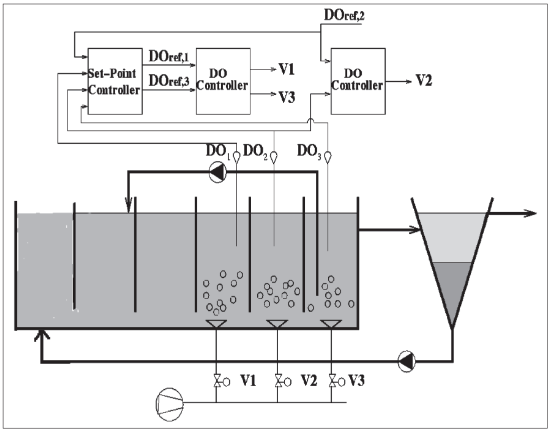

Figure 2. *The pilot plant with DO sensors together with the supervisory volume control strategy.*

Table 1. *Design data for line 1.*

Parameter in Line 1	Volume [m^3]	Horisontal Surface [m^2]
Pre-sedimentation	2.5	1.1
Biological reactors 1–6	6 * 5	6 * 1.4
Second sedimentation	5.4	2.5
Sand Filter	0.85	0.28
Hydrolysis	0.77	0.40
Thickener	0.30	0.44
Digester	12	31

The strategy is illustrated in Figure 2. It can be seen in the figure that the DO set-points for the first and the last aerobic compartments, $DO_{ref,1}$ and $DO_{ref,3}$, are determined by an outer control loop. The inner DO controllers regulate the DO level in the first and last aerobic compartments by adjusting the valve openings V1 and V3, respectively. The set-point for the DO controller of the second compartment, controlling the valve opening V2, is though not determined by the outer control loop. Instead, the set-point $DO_{ref,2}$ is fixed or decided by another outer control loop (the set-point, $DO_{ref,2}$, may, for instance, be determined supervisory by the ammonium concentration in the last aerobic compartment). The set-point for the second compartment $DO_{ref,2}$ is also used as an input for the set-point controller.

The suggested set-point controller is displayed in more detail in Figure 3. The supervisory volume control strategy is based on the concept that the DO level in the

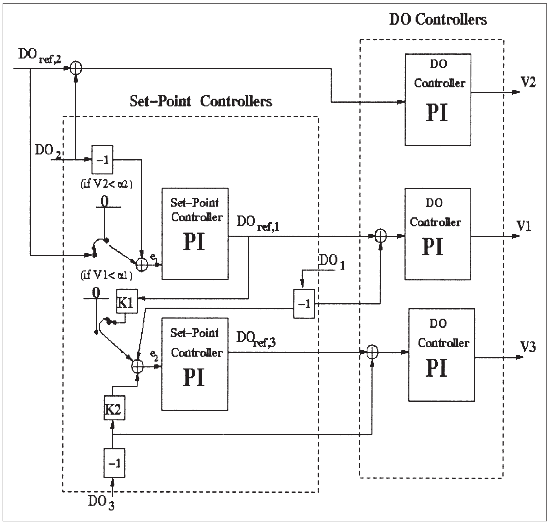

Figure 3. *Block diagram of the supervisory set-point controller.*

second compartment has to be kept at its pre-specified set-point, $DO_{ref,2}$, despite external disturbances like time-varying influent load. The other two compartments act as complements and are made aerobically active when needed, i.e. when the load into the plant is sufficiently high. Since the DO concentration in the second aerobic compartment is directly and highly affected by the DO concentration in the first aerobic compartment, a standard cascade control strategy for the first aerobic compartment is possible. In the controller, there are also switching functions which are triggered by the degree of opening of the valves. The openings of the air valves are graded from 0 to 100 %. The reason for introducing switching functions is to permit a more on-off like behaviour of the controller.

The control error for the DO set-point controller, with $DO_{ref,1}$ as output, is given by:

$$e_1 = \begin{cases} -DO_2 \text{ if } V2 < \alpha_2 \\ DO_{ref,2} - DO_2 \text{ if } V2 \geq \alpha_2 \end{cases} \quad (1)$$

where the parameter α_2 is the chosen limit value for the valve opening V2, i.e. the set-point for the outer DO set-point controller is 0 when the valve opening is below α_2. Choosing low values for α_2 will lead to longer periods with anoxic conditions in the first compartment. The DO level in the first aerobic compartment is settled by the control error e_1. Now, the idea is that when the DO level in the first aerobic compartment is too low, then the aeration in the last aerobic compartment is triggered.

Considering the inner control loop in Figure 3 for the last aerobic zone, it can be seen that the DO set-point, $DO_{ref,3}$, is determined by the magnitude of the variable:

$$e_2 = \begin{cases} -(DO_1 + K2 \cdot DO_3) \text{ if } V1 < \alpha_1 \\ K1 \cdot DO_{ref,1} - (DO_1 + K2 \cdot DO_3) \text{ if } V1 \geq \alpha_1 \end{cases} \quad (2)$$

The parameter α_1 is the chosen limit for V1 in the controller which is controlling the valve opening for the last compartment. Thus, the set-point for the DO set-point controller is 0 when the valve opening, V1, is below α_1. The variable e_2 may be considered as a control error, although selected in a rather ad hoc manner. The configuration of this second cascade strategy, which is controlling the valve opening, V3, for the last compartment, is not as obvious as for the first aerobic compartment. However, the motivation for reducing the DO concentration in the last aerobic compartment is quite clear. Allowing the DO level in the last aerobic compartment to be low or even zero will not only save aeration energy but also improve the denitrification rate, since less oxygen is recirculated to the first anoxic compartment. One may also consider this as an enlargement of the deoxic compartment. Thus, the main idea for the cascade control for the last aerobic compartment is the same as for the first aerobic compartment, i.e. to aerate the compartment only when necessary. Moreover, in the cascade control strategy for the last compartment it might be convenient to include an extra parameter which makes the control more flexible. This is illustrated in Figure 3 by addition of the parameters *K1* and *K2*. Those positive parameters can be regarded as design variables, which decide how much air to add in the last compartment, depending on the DO concentrations in the first and last aerobic compartments. Since the DO concentration in the first aerobic compartment is indirectly affected by the influent load, the last aerobic compartment will be aerated when the influent load is high. How the design parameters *K1* and *K2* will affect the aeration in the last aerobic zone will be illustrated in the next section.

One way to overcome a possible situation where the switch functions are triggered too frequently might be to introduce a hysteresis switching function. It is also important that the inner control loop is much faster than the outer control. The supervisory control strategy described in this chapter can be regarded as a control of the aeration volume, because the DO concentrations in the first and last compartments for some periods can be chosen very low or even zero.

Parameter values for the controllers

When traditional PID controllers are used for controlling a process, there are three design parameters (the proportional gain, K_p, the integral time constant, T_i, and the derivative time constant, T_D) that have to be tuned in a proper way in order to achieve a satisfactory control behaviour. There exist several methods and rules of thumb for tuning the design parameters in PID controllers. This issue will not be treated here, instead the interested readers are referred to the large number of literature available on the subject. However, for the controllers suggested in this paper there are four additional parameters, *K1*, *K2*, α_1 and α_2, which also can be considered as design parameters and, thus, have to be chosen in a proper way. Suggestion on how to choose the parameters *K1*, *K2*, α_1 and α_2 is explained in this section.

Values of the design parameters K1, K2, α_1 and α_2

The positive constant parameters *K1* and *K2* (see Figure 3) can be considered as design variables, and the choice of parameter values will affect the behaviour of the aeration in the last aerobic compartment. The reason for introducing the constants $K1$ and $K2$ is to make the control of the last aerobic volumes more flexible. It is not obvious how to decide the values of $K1$ and $K2$, and it might seem that those parameters only can be chosen in an ad hoc manner. However, there are some guidelines which can give some help before choosing the parameter values. First, by defining the upper bound of the reference value $DO_{ref,1}$ and the DO concentrations DO_1 and DO_3 as $DO_{ref,1max}$, DO_{1max} and DO_{3max}, respectively, we can write the control error (2) as:

$$e_2 = K1 \cdot DO_{ref,1max} - (K2 \cdot DO_{3max} + DO_{1max}) \qquad (3)$$

In order to avoid windup in the integration part of a PI controller the set-point should be less than the maximum value of the controlled signal. Thus, in (3) a weak requirement is to have $e_2=0$ at steady-state when $DO_3 = DO_{3max}$. Therefore, putting the control error equal to zero and using (3) we can write $K2$ as a function of $K1$:

$$K2 = (K1 \cdot DO_{ref,1max} - DO_{1max})/DO_{3max} \qquad (4)$$

Assuming that $DO_{ref,1max} \leq DO_{1max}$, then the nominator in (4) implies the inequality, $1 \leq K1$, in order to avoid that $K2 \leq 0$. One may notice that DO_{1max} and DO_{3max} are not constants. On the contrary, they are very much dependent on process and influent load conditions. Choosing a large $K1$, such that $K1 > \frac{(K2 \cdot DO_3 + DO_1)}{DO_{ref,1}}$, will have the effect that when the outer supervisory PI controller for the last aerobic compartment is triggered by the valve opening V1, then the value of e_2 will also be large. Thus, initially the supervisory PI controller will provide large DO set-points and the DO concentration in the first aerobic compartment is increasing relatively fast, giving a sharper transition between anoxic conditions and aerobic conditions in the compartment. On the other hand, a relatively large $K2$ value will result in that the control error, e_2, is reaching zero relative rapidly, giving small DO concentrations in the compartment. By changing the values of $K1$ and/or $K2$, the aeration in the last compartment may be adapted for slowly time varying process conditions. For example, if DO_{3max} is increasing for some periods, one may decrease $K2$ in order to utilize more of the aeration capacity. In other words, the parameters $K1$ and $K2$ may also be tuned such that appropriate aeration operation points in the last aerobic compartment for different incoming loads are achieved. Moreover, since the aeration in the last aerobic compartment is affected, the parameters α_1 and α_2 can be regarded as threshold values which decide when the outer supervisory controllers are triggered depending on the valve openings V1 and V3, respectively. Choosing large values of α_1 or α_2 will give relatively longer periods with anoxic conditions. This is also the motivation for having switching functions, i.e. we want to achieve an on/off control in order to obtain a more strict volume control, i.e. longer periods with clear anoxic conditions, and thereby save some aeration energy. On the other hand, this might complicate the overall control performance and the limiting value should be chosen with care. Some illustration on how α_1 influence the anoxic/aerobic condition in the first aerated compartment is given in the next section.

Results and discussions

In this section the influence of the parameters K1, K2 and α_1 in the proposed control strategy is investigated. The fourth parameter, α_2, is assumed to have the same affect on the controller as α_1, and is therefore excluded in the investigation. Moreover, the suggested volume control strategy is also tested on a pilot wastewater treatment plant.

Evaluation of the design parameters

Simulation set-up

In the simulations in this paper the default benchmark configuration is used with the corresponding model parameters plant volumes and flows. The benchmark plant is designed as a pre-denitrifying activated sludge process with two anoxic and three aerobic compartments and a secondary settler. All five compartments are fully mixed and the aerated compartments have a maximum KLa of 10 h^{-1}. For more information about default values of model parameters and volumes etc. for the original benchmark configuration it is referred to the benchmark homepage at: http: www.ensic.u-nancy.fr/COSTWWTP and (Alex et al., 1999). During the simulations the dry weather data file was used and the parameter values, $\alpha_1 = 0\,\%$ and $\alpha_2 = 70\,\%$.

Simulation results

In Figure 4 one can observe how different values of $K1$ affect the DO concentration in the last aerated compartment. The figure shows that the larger values of $K1$, the larger levels of DO concentration in the compartment. The values of $K1$ in Figure 4 are valid for $K2 = 0.7$.

Figure 5 illustrates how different values of $K2$ influence the DO concentration in the last aerated compartment. $K2$ has the reversed affect on the DO concentration as $K1$. Small values of $K2$ will entail larger levels of DO concentration in the compartment. By choosing proper values of $K1$ and $K2$ (and also α_2) one might tune

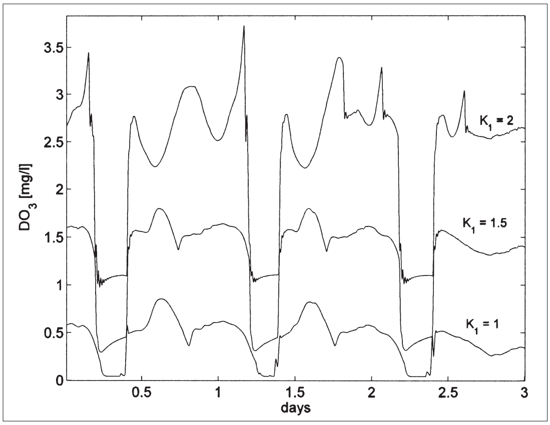

Figure 4. *The lines illustrate the DO concentration in the last compartment for different values of K1, using a fixed K2.*

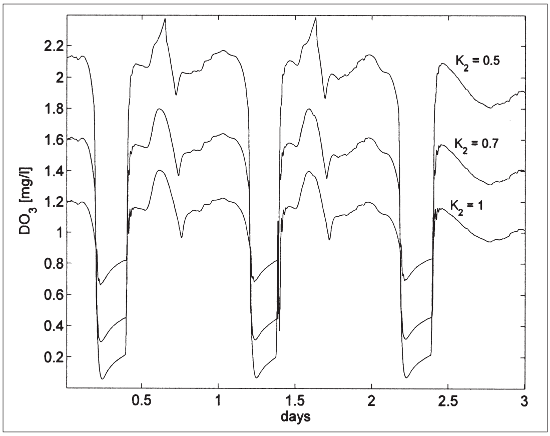

Figure 5. *The lines illustrate the DO concentration in the last compartment for different values of K2, using a fixed K1.*

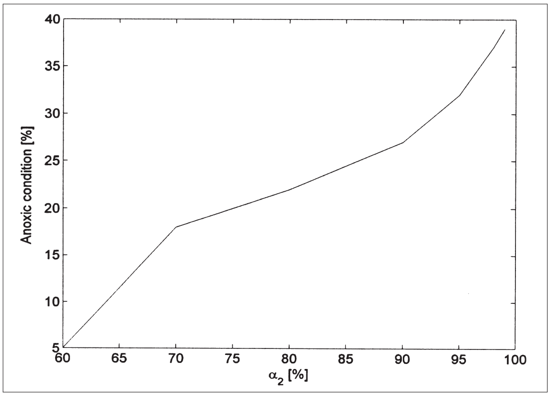

Figure 6. *The time period of anoxic conditions (as percentage of the total simulation time) in the first aerated compartment as a function of the parameter* α_2.

the controller so that a good ratio between anoxic and aerobic conditions in the last compartment is achieved. The values of *K1* in Figure 5 are valid for *K1* = 1.5.

The behaviour of the DO concentration in the first aerated compartment using different values of α_2 is illustrated in Figure 6. In the figure one can see that large values of α_2 give longer periods of anoxic conditions, as percentage of the total simulation time. Here, anoxic condition is defined as periods when the DO concentration in the compartment is below 0.1 mg/l.

Evaluation in the pilot plant

Pilot plant set-up

The control parameters of the PI controllers in the pilot-plant at Hammarby Sjöstad were tuned to make the controllers as fast as possible without creating an oscillating behaviour. The same parameter values for the PI controllers, which are controlling the valve openings for the aerated compartments, were used during the entire evaluation period. Therefore, we concentrate on the chosen values of the controller parameters *K1, K2*, α_1 and α_2. The design parameters were tuned during periods not included in the evaluation periods. The chosen parameter values were, *K1* = 1.7, *K2* = 0.83 and $\alpha_1 = \alpha_2 = 95\,\%$.

Experimental results

The results in this section were first presented in (Ekman, 2005a). The aeration volume control strategy, denoted $DOC_{v,2,v}$, was evaluated at the Hammarby Sjöstad pilot plant during the period 2004-07-01 to 2004-08-08. Table 2 shows the average concentration of effluent ammonium and nitrate and the average airflow consumption for the aeration volume control strategy during the period of six weeks. In the table the same variables are displayed for the period from 2004-01-01 to 2004-06-30, where a constant DO control strategy, denoted $DOC_{r1,r2,r3}$, with manually changed set-points was used

Table 2. *Average effluent ammonium and nitrate concentrations and airflow.*

Control strategy	S_{NO} [mg/l]	S_{NH} [mg/l]	totN [mg/l]	Airflow [m^3/h]	Temp. [°C]
$DOC_{v,2,v}$	2.8 (2.2)	1.9 (4.5)	(6.7)	9.2	22.1
$DOC_{r1,r2,r3}$	5.82 (6.7)	4.94 (6.7)	(13.0)	14.5	19.7

in the pilot plant. The values put in brackets illustrates the average concentrations obtained from laboratory measurements during the same period, i.e. the other values are collected from on-line measurements. Note that total nitrogen is not measured on-line. The results presented in Table 2 indicate that the aeration volume control strategy suggested in this paper results in lower effluent concentrations and less aeration energy consumption compared to a traditional constant DO control. However, one important factor to consider when evaluating the results in Table 2 is that the average water temperature was higher during the (summer) period when the aeration volume control strategy was tested. The table shows that the difference in temperature between the two periods was 2.4°C.

Conclusions

A volume control strategy for an ASP is suggested and has been evaluated in a pilot plant. The control strategy is of a cascade type and only requires on-line measurements of the DO concentration in the aerated compartments. The control structure also involves that, besides the ordinary PI controller parameters, some extra control parameters have to be tuned. The reason for introducing the extra parameters is to achieve a more distinct control action. The introduction of the extra parameters allows the operator to control the relative time of anoxic or aerobic conditions in especially the last compartment in a more flexible way. The influence of the extra design parameters on the control performance was investigated in a simulation study. The control strategy worked well for the pilot plant, and the results indicate that the suggested strategy has the potential to decrease the effluent concentrations as well as the aeration energy consumption compared to a traditional constant DO control. It should be mentioned that tuning of the aeration volume controller must be done with care to avoid oscillations.

As a topic for further research it would be of great interest to investigate the practical use of the suggested volume control strategy, i.e. to test the approach on a full-scale wastewater treatment plant.

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