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PREDICTIVE CONTROL OF NITROGEN REMOVAL IN WWTPS USING PARSIMONIOUS MODELS

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Abstract: In the paper, control possibilities for the nitrogen removal process within activated sludge wastewater treatment plants are discussed. A predictive controller is introduced which aims to reduce the peaks in effluent concentration for ammonia nitrogen. Additionally, the controller improves the overall nitrogen removal using less aeration energy. A parsimonious deterministic model is used for the prediction of the effluent ammonia concentration. The main parameter of the model is used for the model adaptation. The performance of the developed controller is evaluated using a benchmark simulation model of a treatment plant introduced by an international work group. *Copyright © 2002 IFAC*

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1 INTRODUCTION

Most wastewater treatment plants (WWTPs) are operated in a fixed operation mode which is adapted to the summer/winter seasons only. Automatic control of WWTPs is seldomly installed in a way that the possible treatment capacity is used all the time as well as possible. Furthermore, an adaptation of the operation to the permanent changing load situation is rarely performed. One possible reason for non-optimal controller performance is that during the design phase of a treatment plant, the basic function of the control system is determined using a set of rules describing control actions. These control actions are based on threshold values for measured concentrations, where the set points and threshold values are related to the assumed 100% load situation. The actual load situation during the start-up phase of the new or upgraded plant is generally a different one. In addition, it must be noted that a number of conditions must be fulfilled in order for an automatic control system to achieve improvements in the plant's performance. The potential of improvements of a WWTP's performance by control actions is considerably limited. Thus, it depends on careful tuning and adaptation of the controller to use the existing potential. The reliable functioning of online measurements and the existence of an appropriate safety concept of the control system in the case of measurement failures are important preconditions.

The intention of the presented predictive controller is to use the available control handles to adapt the plant operation to the dynamic load of wastewater treatment plants.

2 CONTROL OF NITROGEN REMOVAL

2.1 WWTP with pre-denitrification

Wastewater treatment with extended nutrient removal is usually performed in activated sludge systems. The wastewater polluted with organic material containing carbon compounds - expressed by COD (chemical oxygen demand) – nitrogen N_{org} and phosphorous P_{org} and nutrients such as Ammonia (NH_4-N) and Ortho-Phosphates (PO_4-P), is mixed in activated sludge tanks with biomass. The process is designed and operated by a combination of reactors, aeration and wastewater influent distribution in a manner where suitable living conditions of up to three different functional groups of micro-organisms are maintained.

In municipal WWTPs with nitrogen removal, often a plant layout with a series of pre-denitrification and nitrification tanks, as presented in Figure 1, is used (Olsson and Newell, 1999).

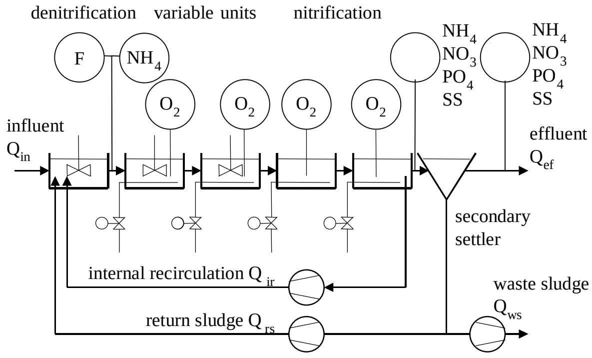

Fig. 1 Plant layout of a WWTP with pre-denitrification

The given plant layout contains 5 activated sludge tanks in series where the first compartment can not be aerated, the last two compartments are aerated mandatory and the second and third compartment can be aerated optionally. Figure 1 shows possible locations and types of online measurements, however only a sub-set of this configuration would be realistic for practical applications.

2.2 Control depending on load

In most WWTPs, the DO concentration in aerated tanks is controlled. However, only at a few treatment plants will one find more advanced controllers based on measurements of nutrient concentrations to adapt the operation to changing load. This can be stated although the measurements which would be necessary for these controllers are frequently available (Yuan et al., 2001). Additionally, in many cases appropriate control inputs are available such as optionally aerated activated sludge tanks. However, in general this control option is only used for an occasional adaptation to seasonal or long term changes in load or plant performance.

This paper utilises a dynamic simulation model for the development and evaluation of a predictive controller for nitrogen removal. The simulation system SIMBA used is based on the well-known MATLAB/SIMULINK software. SIMBA implements the Activated Sludge Model No. 1 (ASM 1, Henze et al., 1987), the same as most software systems for the dynamic simulation of wastewater treatment plants. This model sufficiently describes the degradation of organic load (described in COD – chemical oxygen demand) and the removal of nitrogen by micro-organisms in an activated sludge system.

The controller introduced below can be classified as a model based predictive controller (e.g. Morari and Lee, 1999). This classification assumes that model based predictive control can be seen as a general class of control algorithms with the following characteristics:

- explicit use of process models for the prediction of the controlled output variables of the process
- calculation of a sequence of controller output values minimising an objective function
- repeating calculation of the optimal control sequence in each sample time and use of the first value of the sequence.

If the process can be described by a linear model, the implementation of the predictive controller becomes very simple. In this case, it is possible to formulate an explicit control algorithm based on the process model. For the considered WWTP application, linear models are only possible in exceptional cases. However, if it is accepted that no explicit algorithm can be formulated, the concept of predictive control can be easily applied to non-linear systems. In this case, only the existence of an explicit process model is necessary, the type of which is irrelevant. For the evaluation of the optimal sequence of controller outputs, it becomes necessary to solve a numerical parameter optimisation problem in each sample step. Any kind of objective function can be applied. This provides a high degree of flexibility to adapt the controller to the specialities of the process, to include empirical modifications and to incorporate existing process knowledge.

3 DESIGN OF A PREDICTIVE CONTROLLER

3.1 Feedforward vs. feedback control

In treatment plants with pre-denitrification, often optionally aerated activated sludge tanks are available where the aeration can be switched on and off. The operation of these tanks or zones provides a valuable control handle.

A plant with pre-denitrification is formed by a number of tanks in series (cascade) or by one tank with a high length to width ratio. The hydraulics of such plants can be characterised more as a plug-flow reactor than a completely stirred tank reactor (CSTR). Due to this hydraulic behaviour, it can be stated that the position of the control action (optionally aerated zone) is located far in front of the usual location of effluent measurements. For this reason, any control based on effluent measurements and using the optionally aerated zones as control inputs is not well suited to deal with dynamic load disturbances. Simply, if a disturbance leads to changes in the effluent concentration it is too late for appropriate measures.

A proper use of this control option requires a feedforward control strategy. To measure the main disturbance for the nitrogen removal process, an online measurement of ammonia nitrogen is assumed. This measurement can be located directly in the influent of the activated sludge system or somewhere in the denitrification zone in front of the facultative zone. This additional ammonia online analyser causes higher costs for instrumentation and maintenance, which have to be related to the benefits expected from the proposed feedforward control.

With regard to ammonia analysers and the costs, some promising developments (simplified sample technology, inline analysers, inline sensors, see e.g. (Rieger et al., 2001)) can be observed.

3.2 *First principle model*

Predictive control requires a model of the process. In principle, any kind of model can be used which allows the numerical calculation of the controlled variable for a given control sequence and assumptions for the disturbances. In this application, a deterministic process model based on mass balances of NH_4-N is applied. Similar ideas were reported e.g. by (Hoen et al., 1996). Experiences made by the authors on the evaluation of different predictive controllers for wastewater treatment plants support the thesis that deterministic models based on very simple mass balances are preferable compared to black box models as ANN. Deterministic models are simple to understand for operators of WWTPs, they are characterised by a high robustness and provide good extrapolation capabilities.

For a high prediction quality, the appropriate modelling of the hydraulic behaviour from the measurement point for ammonia in the denitrification zone to the effluent of the nitrification zone turns out to be very important. A series of CSTRs is used to approximate the hydraulic behaviour. The size and number of these CSTRs are the tuning parameters to calibrate the retention time behaviour. The flow rate through this cascade can be assumed as shown below:

$$Q = Qin + Qrs + Qir$$

with

Q	flow rate through the tank cascade	$[m^3/d]$
Qin	influent flow rate of the WWTP	$[m^3/d]$
Qrs	return sludge flow rate	$[m^3/d]$
Qir	internal recycle flow rate	$[m^3/d]$

The influent flow rate is a standard measurement and the flow rates of return sludge and internal recycle are typically measured or implicitly known from the characteristics of the pumps. For the degradation of ammonia nitrogen, the following process rate is assumed:

$$R_{NH4-N}(t) = R_{NH4-N\,max} \frac{SO(t)}{SO(t) + KOA} \frac{SNH(t)}{SNH(t) + KN}$$

with

R_{NH4-N}	nitrification process rate (volume specific)	$[g\ N/\ m^3d]$
$R_{NH4-N\ max}$	maximum nitrification rate (volume specific)	$[g\ N/\ m^3d]$
SO	dissolved oxygen concentration	$[g\ DO/m^3]$
SNH	ammonia nitrogen concentration	$[g\ N/m^3]$
KOA	half saturation constant for SO	$[g\ O2/m^3]$
KN	half saturation constant for SNH	$[g\ N/m^3]$

The notation as well as the general model structure is inspired by the state-of-the-art models of the IWA (e.g. ASM1, Henze et al., 1987). The limitation of the nitrification rate with respect to the availability of substrate (ammonia nitrogen) and dissolved oxygen is expressed by monod kinetics. The typical identifiability problems for these kinetic parameters (KOA, KN) are not important as it is possible to use default values from literature without any significant loss of prediction quality. The maximum nitrification rate $R_{NH4-N\ max}$ can not be determined a-priori. It strongly depends on the special plant and is affected by temperature, average nitrogen load, sludge age and plant operation. For this reason, an estimation algorithm for this parameter has to be applied. This estimation has to be performed frequently in order to follow the expected time variant drift of this parameter.

The ammonia nitrogen balance for a tank section no. i with the volume V_i leads to

$$V_i \frac{d\ SNH_i(i)}{dt} = \left(SNH_{i-1}(t) - SNH_i(t)\right)Q(t) - R_{NH4-N}\ V_i$$

which is formulated for each compartment. The number of compartments was chosen in correspondence to the structure of the benchmark plant (4 tanks). This assumption gives an ideal situation for the model structure.

3.3 Controller structure

One instance of this model is used as an observer model in order to estimate the current ammonia profile along the tank cascade. In this observer model, the parameter $R_{NH4\text{-}N\ max}$ is assumed as the cause for any measured difference between the ammonia concentration in the effluent of the nitrification zone and the corresponding value of the observer model. An optimisation algorithm is applied in each sample step to calculate a value for this parameter which will avoid any difference between the measurement and the model output. The resulting ammonia profile is used as a reliable start state to predict future ammonia concentrations in the effluent of the nitrification zone (see Figure 2).

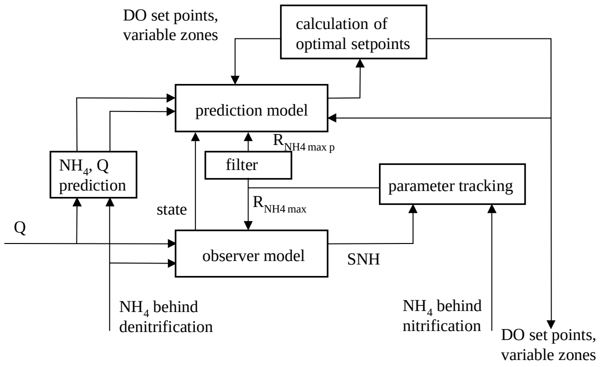

Fig. 2. Structure of the predictive controller

In addition, an estimation of the a-priori unknown and time variant parameter $R_{NH4\text{-}N\ max}$ is calculated by the optimisation algorithm. In this case, a simple linear search algorithm can be used to find a value for the parameter $R_{NH4\text{-}N\ max,}$ minimising the difference between the measured and simulated ammonia effluent concentration of the nitrification zone. Optimisation applied in each sample step avoids stabilisation or design problems which could occur when a classical feedback structure is utilised to implement the observer. To limit the calculation time in each sample step, a fixed number of steps for the linear search is introduced. The calculation time to sample time ratio will be very low in practice, thus this is not a strong limitation. But possible problems using a unpredictable termination condition can be avoided. Lower and upper saturation values of the optimisation parameter $R_{NH4\text{-}N\ max}$ are used to avoid extreme adaptation responses in the case of measurement problems. The value for $R_{NH4\text{-}N\ max}$ can not be seen as a good estimation for the recent value of the kinetic parameter maximum nitrification rate, instead it should be considered as an “artificial” measure to keep the observer model in track with the measurements and to compensate all effects which are the real cause of observed differences. For this reason, a derived parameter $R_{NH4\text{-}N\ max\ p}$, generated by first order low pass filtering of the value applied to the observer model is used instead of $R_{NH4\text{-}N\ max}$. Besides the start state and the current value of the maximum nitrification rate, assumptions with respect to the model input variables (flow rate and ammonia concentration in the effluent of the denitrification zone) are necessary. For the used prediction horizon, constant values for these input variables can be assumed.

The DO set points of the variable zones (optionally aerated) are the control inputs. In principle, only two discrete values for these control inputs are useful: a set point of zero to force a non-aerated operation of the selected unit (denitrification) and a sufficiently high value to ensure unlimited nitrification (e.g. 2 g/m^3). This results in a discrete number of control options: n+1 if n is the number of variable zones. These control variants can be simulated in each sample step using the prediction model. The optimisation task is simplified by the step input policy applied to the predictive controller.

Based on the results of the prediction for the possible control variants, a set of rules can be used to select a suitable configuration. The use of these rules provides a very transparent design approach. These rules can be easily explained to plant operators. The input information of the described predictive controller comprises of a measurement of the main disturbance as well as the controlled variable (ammonia concentration in the effluent of the nitrification zone). Consequently, this controller must be characterised as combined feedback and feedforward.

4 SIMULATION BASED EVALUATION

4.1 Control of a benchmark example

The function of the proposed predictive controller was evaluated for a test case. The test case is based on a numerical simulation model (Alex et al., 1999) which was designed by a European expert group within the COST framework as a benchmark. The plant corresponds to the layout with pre-denitrification shown in Figure 1.

The benchmark example was complemented with a number of basic controllers. For each permanently or optionally aerated tank compartment (tank 2 to 5), a DO control loop was installed. For each of the tanks an individual DO measurement was assumed. An appropriate air flow rate to establish the given DO set point is ensured by a PI controller. The first tank is permanently non-aerated and only used for denitrification. For the last two tanks, which are aerated permanently, a constant set point of 2 g/m^3

was applied. The benchmark (Alex et al. 1999) specifies three different influent situations. All investigations of this paper are based on the default dry weather influent situation, given over a 14 day period. The influent files for stormy weather defined into the benchmark specifications, will not create more critical load as the dry weather situation, thus the detailed discussion of these results are omitted in this paper.

The proposed parsimonious observer model was adapted to the benchmark. The model describes transport and nitrification within the last 4 compartments of the plant. The NH_4-N concentration in the effluent of the first tank (denitrification zone) and the known flow rate at this location (Q = Qin + Qrs + Qir) are the input information. Using a numerical optimisation (linear search), an appropriate value for $R_{NH4\text{-}N\ max}$ was calculated. By simulation of the "observer" model with a constant value of this parameter applied, it was possible to prove that the proposed parsimonious model was more or less perfectly able to calculate similar ammonia effluent concentrations as the complex ASM 1.

The DO set points of tanks number 2 and 3 (SOv1S and SOv2S) were used as control handles of the predictive controller. The following combinations of set points are reasonable:

Table 1 Control option

required nitrification performance	SOv1S	Sov2S
low load	0	0
default load	0	2
high load	2	2

Based on the assumptions of nearly constant influent concentration and flow rate of the model (location effluent denitrification), the ammonia effluent of the nitrification zone can be calculated for all three control variants. The prediction is performed for a horizon of 2 h at each sample step (T_0 = 15 min) of the controller. Given this prediction, a suitable variant is selected using simple rules. The presented predictive controller is mainly designed to reduce the height of peaks of the ammonia effluent concentrations. To achieve this, the following rules were applied:

- selection of the high load configuration if the prediction based on the default load configuration will lead to a violation of a maximum threshold value of the effluent ammonia concentration
- selection of the low load configuration if the prediction of the default load configuration will stay below a lower threshold value for NH_4-N
- in all other cases, the default configuration is selected

This set of rules only requires the prediction of the default load situation.

4.2 *Comparison of results*

To evaluate the controller performance, the following control variants were simulated:

1) *Constant operation*: The optionally aerated zones are operated with the default configuration (tank 2 non-aerated, tank 3 aerated) using constant DO set points.
2) *NH_4-N-relay control*: Conventional relay control based on the ammonia effluent concentration of the nitrification tank is used.
3) *Predictive control*: Predictive control is applied as presented above.

For all three variants, the DO set points of the permanently aerated tanks 4 and 5 were operated at constant values. In addition, the internal recycle was kept constant. Figure 3 shows simulated NH_4-N effluent concentrations of the nitrification tank for the three control variants considered.

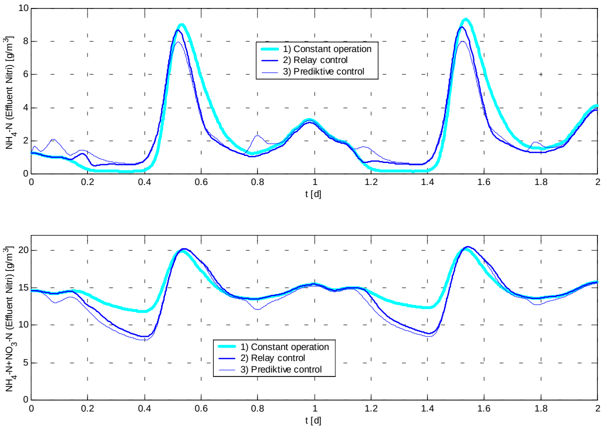

Fig. 3 NH_4-N effluent concentrations of the nitrification tank, Sum of NH_4-N and NO_3-N

To start the discussion it should be noted that in the case of constant operation (variant 1), high effluent peaks at around 9 g/m^3 for NH_4-N occur. On the other hand, during the night hours very low values are observed.

Using a conventional relay control, based on the measured effluent concentration (feedback control, variant 2), it must be noticed that only minor reductions of the NH_4-N effluent peeks are achieved. The first peak was reduced by only 0.35 g/m^3 (4%). The reason for this unsatisfactory result is related to the plug-flow characteristics of the plant. If the relay controller switches the aeration in the optionally aerated zones on, a significant effect to the effluent concentration at the end of the nitrification tank can not be expected before the end of the travel time between the location where the control action takes place to the measurement location. The control action for rapid changes of disturbances (influent nitrogen load) comes too late. The adaptation of the operation of the plant using the conventional relay control to low load situations works relatively well. In these situations, the focus is not on a quick response from the controller, but on a moderate adaptation to the low load situation in order to finally increase the plant's overall nitrogen removal efficiency by increasing the denitrification capacity.

The predictive control (variant 3) is able to achieve a significant reduction of the NH_4-N effluent peaks. The maximum effluent concentration of the second peak in Figure 3 is reduced by approx. 15%, from 9.4 g/m3 to 8 g/m3 without a reduction of the overall nitrogen removal efficiency.

This example shows that even advanced control can not overcome the fact of insufficient controllability of WWTPs with respect to dynamic load changes – effluent peaks are still inevitable - however significant improvements are possible. The same reduction of the effluent peaks using constant operation would require a significant increased tank volume. Both control variants 2 and 3 keep or increase the nitrification capacity of the plant compared to the constant operation case in the long term view. This is because approximately the same nitrogen load is nitrified. Along with the reduction of the NH_4-N effluent peaks, it is possible to increase the eliminated nitrogen load on an average basis. The overall nitrogen removal efficiency (mean values) is improved by both control options, by approx. 8% using relay-control and by approx. 10% using predictive feed-forward / feed-back control. This improvement is the result of the increased denitrification during low-load situations.

5 CONCLUSION

The presented evaluation of the predictive controller illustrates the existence of an interesting potential of improvements by automatic WWTP control within the principal limitations caused by the process characteristics. This potential can be used in high loaded plants to reduce effluent peaks, or for medium and low loaded plants to increase the average removal efficiency together with a lower energy consumption. However, even in high loaded plants, low load situations occur periodically, where appropriate control can be used to increase the nitrogen elimination rate and to save energy. Optionally aerated zones should be used for this purpose. Simple feedback control can be used to achieve improvements during low load periods.

To handle highly dynamic load situations, leading to high effluent concentration peaks, feedback control is not appropriate. For this task, feedforward control is required. This paper introduces a very simple and robust model for the nitrification which is well suited to predict the NH_4-N effluent concentration. A model-based controller is able to activate the potential of the used control handles to a high extent.

Although the controller was designed and tested by simulation, future practical application will be possible without any further simulation studies.

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