Fuzzy-control for improved nitrogen removal and energy saving in WWT-plants with pre-denitrification

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Abstract In the last few years, numerous studies were carried out, dealing with the application of fuzzy-logic to improve the control of the activated sludge process. In this paper, fuzzy-logic based control strategies for wastewater treatment plants with pre-denitrification are presented that should lead to better effluent quality and, in parallel, to a reduction of energy consumption. Extensive experimental investigations on a large scale pilot plant as well as simulation studies (ASM1 with SIMBA®) were carried out in order to design, evaluate and compare different fuzzy-controllers with each other and with comparable conventional control systems. The fuzzy-controllers were designed as high-level controllers that determine the DO-setpoints in the aerated zones and the ratio between aerated and non-aerated zones. Conventional PI-controllers were used to maintain the DO-concentration at the set-point levels. The ammonia and nitrate concentration in the effluent and the ammonia load in the influent were considered as input variables for the different fuzzy-controllers. Compared to the operation with fixed nitrification/denitrification zones and constant DO concentrations, the required air-flow could be reduced up to 24% by using fuzzy-logic based control strategies. In comparison with a more advanced conventional control strategy (relay controller with two thresholds and the NH_4-N concentration in the effluent as single control variable) a reduction of air-flow-rate up to 14% could be achieved. At the same time, NH_4-N peaks in the effluent that are normally caused by peak flow conditions could be reduced significantly. The large scale experiments show that the fuzzy-controllers can be easily implemented in modern control and supervision systems and that the control characteristics can be followed and modified during operation. It therefore can be expected that the developed fuzzy-control systems will be accepted by the operating personnel in wastewater treatment plants.

Keywords Energy saving; fuzzy-control; nitrogen removal; process optimisation

Introduction

With the development of suitable on-line analysers for ammonia, nitrate and other parameters, control systems have been developed that consider not only a single variable (for example the dissolved oxygen concentration – DO concentration) but try to include and optimise the entire biological treatment step. For wastewater treatment plants with primary denitrification, these conventional control systems focus on the control of the ammonia and/or nitrate concentration in the effluent by adapting the nitrification/denitrification volume ratio, the DO concentration in the aerated zones and the internal recycle flow rate. The applied control strategies are mostly cascaded relay (or PI) controllers, switching the aeration in the facultative zones on and off or adjusting the DO setpoints and the recycle flow rate when defined ammonia or nitrate concentrations are reached. Examples are described e.g. by Ermel (1992) and Grünebaum and Schmitt (1994). Although these systems have some advantages, they did not find any widespread application in practice. In some cases, installed complex control-systems were even removed due to difficulties in understanding the control behaviour and in further tuning the systems.

In recent years, research has focused on the development of advanced control strategies such as Model-Based-Predictive-Control or Fuzzy-Control. Control strategies for pre-denitrification plants based on the estimation of the actual purification capacity through on-line modelling are described e.g. in Hoen *et al*. (1996). Fuzzy-control methods can be applied to almost all kinds of processes. They can be used to create transparent controllers that are easy to modify and extend because the rules are written in the language of process experts and plant operators. Recent studies regarding the application of fuzzy-logic for the control of aeration and nitrogen removal in WWTPs have mainly focused on systems with intermittent and simultaneous aeration (Aoi *et al*., 1992; Hansen, 1997; Kalker *et al*., 1999). For activated sludge plants with pre-denitrification only some very basic simulation studies are reported (Haupt *et al*., 1995).

In this study, fuzzy-systems for the control of aeration in wastewater treatment plants with pre-denitrification are developed. The fuzzy-controllers are tested in simulation studies and large scale experiments and compared with conventional controllers that are already used in practice.

Materials and methods

General procedure – development of fuzzy-controllers

The development and evaluation of the fuzzy-control-systems was performed in three steps. 1) Observation and evaluation of pilot plant operation with conventional control strategies. Implementation of gained expert knowledge in three fuzzy-controller-prototypes, each using different control variables. Off-line optimization of controllers. 2) Development and calibration of a dynamic model of the pilot plant. Implementation of the fuzzy-controllers and step-by-step optimization using different influent scenarios. First comparison of different fuzzy-control strategies. 3) Integration of selected fuzzy-controllers into the pilot plant control-hardware, further tuning and evaluation under operating conditions. The large scale pilot plant and the dynamic process model of the pilot plant are further described hereunder. A more detailed description of the development process is outlined in Meyer (2000).

Large scale pilot plant

A schematic of the large scale pilot plant is shown in Figure 1. In order to allow an estimation of the effects that can be achieved with the designed fuzzy-controllers with respect to effluent concentrations and energy consumption, two identical activated sludge pilot plants were operated in parallel. Each plant consists of a cascade reactor with 6 tanks in series and a total volume of 16 m^3. In the reference plant (Plant 1 in Figure 1) four tanks were aerated permanently and two tanks with a total volume of 5.7 m^3 were used for denitrification. Plant 2 was equipped with two tanks that could be operated under aerobic as well as under anoxic conditions (facultative zones D/N1; D/N2) which leads to a denitrification volume between 3.2 and 8.2 m^3. The internal recycle flow rate was at first not controlled in the present study. The plants were fed with pre-settled wastewater from a municipal wastewater treatment plant with a maximum inflow of 2 m^3/h. The inflow was controlled independently of the inflow of the municipal wastewater treatment plant which guaranteed a dynamic inflow including rain-weather and other peak-flow situations. The entire pilot plant was equipped with a control and supervision system as is frequently done in practice. Pumps and blowers were equipped with frequency inverters. All important parameters were measured on-line (see Figure 1) and transferred to a programmable logic controller (Bosch, CL 400) and a connected visualisation and process control system. In every phase of the experiments the reference plant (Plant 1) was operated with a constant DO-concentration (2 mg/l O_2) and a fixed nitrification volume. The more advanced conventional controllers and the developed fuzzy-controllers were tested in Plant 2.

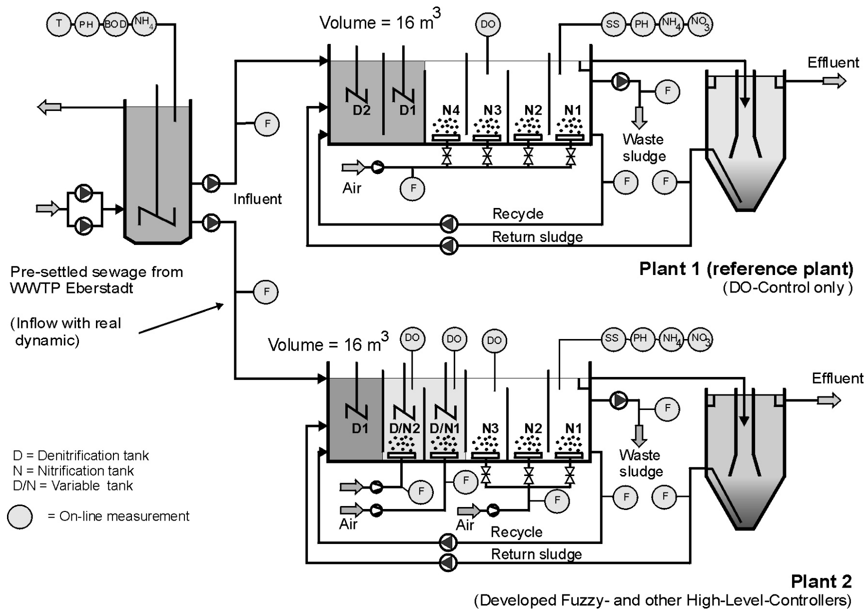

Figure 1 Schematic flow diagram of the wastewater treatment pilot plant

Process model and simulation studies

As a mathematical model of the biochemical process, the Activated Sludge Model No. 1 (ASM 1) was used. The model of the pilot plant was developed using the simulation platform *SIMBA 3.2*$^{+}$®, which is based on Matlab/Simulink®. Corresponding to the set up of the pilot plant, the bioreactor was described by six completely mixed reactors. The secondary clarifier was described with a simple storage model. Two sampling periods on the pilot plant of 14 days each were carried out in order to determine the stoichiometric and kinetic parameters of the model and to characterise the COD in the influent (Meyer, 2000). The developed fuzzy-control prototypes were programmed using the software Fuzzy-TECH®. Via a DDE-interface, this program could be linked with the simulation software which makes it possible to observe the control characteristics parallel to the simulations. The prototypes were step by step optimized through variation and/or extension of membership-functions and linguistic rules. The simulation studies were carried out using different influent scenarios that are based on measured data and that are representative different influent situations that had been observed during operation of the pilot plant.

Description of the developed fuzzy-controllers

The developed fuzzy-controllers are designed as high-level controllers, which means that the fuzzy-systems determine the DO setpoints in the permanent nitrification zone N1–N3 (0.5–2 mg/l O_2) and in the two facultative zones D/N1 and D/N2 (0;…0.5–2 mg/l O_2) and therefore also determine the denitrification/nitrification volume ratio. Conventional PI-controllers are then used to maintain the DO concentrations at the defined levels (Figure 2). One of the goals of control is to ensure a low concentration of total inorganic nitrogen in the effluent. Therefore, in all tested variants, the NH_4-N- *and* NO_3-N concentrations in the effluent are used as control variables. In addition, the NH_4-N load in the influent (feed-forward-signal) and the time variation of the NH_4-N concentration in the effluent (δ NH_4-N) were tested as input variables in order to overcome the problems that are related to the time-delay in cascaded pre-denitrification systems. Also, the actual operation modes of the two facultative zones (D/N1; D/N2) have to be considered as input variables in order to prevent an unstable control behaviour and a permanent turning on and shut-down of the blowers. Figure 2 shows the block diagrams of the tested high-level fuzzy-controllers. The fuzzy-controllers were compared with a conventional relay controller that is also shown in Figure 2.

Between two and seven linguistic terms had to be used to describe the input and output variables and between 37 and 51 linguistic rules in all had to be implemented in order to reach the envisaged control results. The considered input variables, the number of linguistic terms and the number of rules for the tested fuzzy-control variants are summarised in Table 1.

Only linear membership-functions are used to describe the input variables. Figure 3 illustrates the membership-functions for the input variables NH_4-N and NO_3-N. It is obvious that seven fuzzy-sets are required to describe the NH_4-N concentration, because all three output variables (DO setpoints) are influenced by this main control parameter and, furthermore, the membership-functions have to be very "dense" at low NH_4-N concentrations.

To give an idea about the implemented linguistic rules and the logic of the fuzzy-controllers, a section of the linguistic rule base for the fuzzy-control variant N1 is shown in Table 2. 13 linguistic rules define the operation mode and the DO concentration (DO-setpoint) of the zone D/N2 (see Figure 1). For NH_4-N concentrations between XS (very low) and M (medium), the zone is not aerated in any case and its volume is available for denitrification. For medium high (ML) and high (L) concentrations, also the NO_3-N concentration is considered. In the case of the NO_3-N concentration being medium (M) or high (L) (for example as a result of low COD in the influent), the zone will be used for denitrification in order to prevent a further increase of nitrate in the effluent. Only for very high NH_4-N concentrations (XL), both the facultative zones have to be aerated independently of the NO_3-N-concentration.

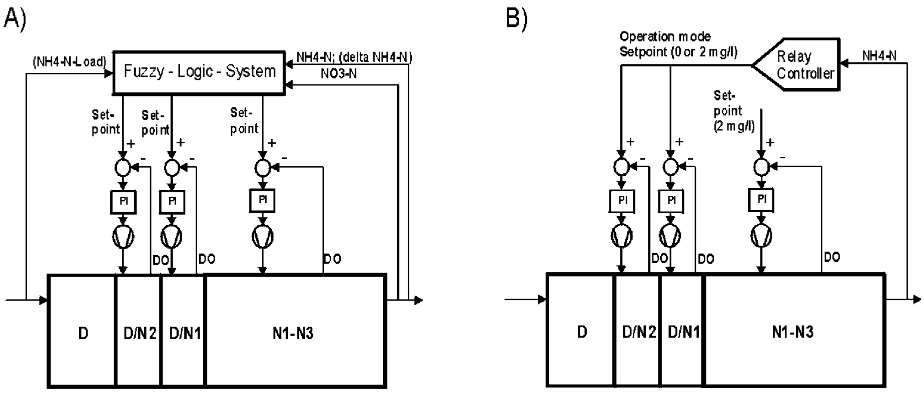

Figure 2 Block diagrams of high-level fuzzy-controllers (A) and conventional relay controller (B)

Table 1 Characterisation of developed high-level fuzzy-controllers

Characteristics	Variant N1		Variant N2		Variant N3	
Input Variables	NH_4-N_{Eff}	[7]	NH_4-N_{Eff}	[7]	NH_4-N_{Eff}	[7]
[ ] = number of linguistic terms	NO_3-N_{Eff}	[3]	NO_3-N_{Eff}	[3]	NO_3-N_{Eff}	[3]
			δNH_4-N_{Eff}	[3]	NH_4-N-$Load_{Inf}$	[3]
Number of linguistic rules	37		51		41	

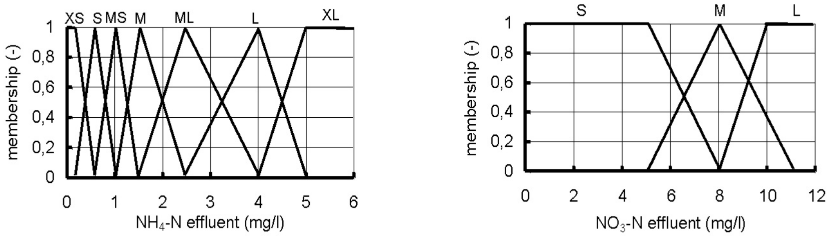

Figure 3 Membership-functions in the high-level fuzzy-controllers for the input variables NH_4-N- and NO_3-N-concentration in the effluent

Table 2 Section of the linguistic rule base applied in fuzzy-control-variant N1 (13 from 37 linguistic rules defining the DO-setpoint and operation mode in zone D/N2)

Rule Nr	Input variables				DOS	Output variables → (DO-setpoint in:		
	NH4-N	NO3-N	Mode D/N1	Mode D/N2		N1–N3	D/N 1	D/N2
25	XS				1.00			0
26	S				1.00			0
27	MS				1.00			0
28	M				1.00			0
29	ML	S		Off	0.40			M
30	ML	S		On	1.00			L
31	ML	M			1.00			0
32	ML	L			1.00			0
33	L	S		Off	1.00			M
34	L	S		On	1.00			L
35	L	M			1.00			0
36	L	L			1.00			0
37	XL				1.00			L

Results and discussion

Simulation studies

Exemplary simulation results are shown in Table 3. For an influent scenario with a duration of three days and one rain event, the average and maximum effluent concentrations and the total required air-flow are calculated for the different control strategies. Figure 4 shows the effluent concentrations for the relay controller and fuzzy-controller variant N3.

Compared to the operation with fixed aeration volume (D/N1 aerated) and constant oxygen concentration, the required airflow was reduced by all tested control variants (Table 3). In comparison to the conventional relay controller, the fuzzy-controllers lead to a further reduction of the airflow and with fuzzy-controller N3 the highest reduction could be achieved with 14% compared to the conventional control system and 25% compared to the operation with fixed nitrification/denitrification volume ratio. Regarding the effluent

Table 3 Exemplary simulation results for the fuzzy-controllers, the relay controller (NH_4-N thresholds at 0.7 and 1.2 mg/l) and the operation with fixed aeration volume

Control strategie	NH_4-N (mg/l) Aver.	NH_4-N (mg/l) Max	NO_3-N (mg/l) Aver.	NO_3-N (mg/l) Max	Total N (mg/l) Aver.	Total N (mg/l) Max	Air flow (m3/d)	Air flow %
Fixed aeration volume	0.52	3.09	9.06	12.18	9.58	13.78	322.56	100
Conventional relay controller	0.78	3.87	7.69	12.81	8.47	14.02	282.72	87.65
Fuzzy controller variant N1	0.97	4.42	7.16	12.50	8.13	13.98	262.32	81.32
Fuzzy controller variant N2	1.27	4.08	6.63	12.45	7.90	14.30	256.32	79.46
Fuzzy controller variant N3	0.85	1.72	5.71	12.36	6.56	13.21	243.36	75.45

concentrations, it is obvious that compared with the fuzzy controller N3 all control strategies lead to an increase of the NH_4-N concentration. This is mainly caused by the time delay in the system. For the simulation with a fixed aerated volume, the facultative zone D/N1 (see Figure 1) is aerated at any time, whereas for all control strategies, both facultative zones have to be activated depending on the actual effluent concentrations. The reaction of the system might be "too late" especially under rain weather conditions. Only with fuzzy controller variant N3 was it possible to overcome this problem. Through the implementation of the NH_4-N load in the influent as a feed-forward signal, a controller could be created that leads to an optimal use of the facultative zones, resulting in better effluent concentrations and at the same time in a reduction of energy consumption for aeration.

Large scale experiments

Fuzzy-controllers N1 and N3 and the relay controller have been tested in the pilot plant for a duration of several months each. The fuzzy-controllers could be easy implemented in the

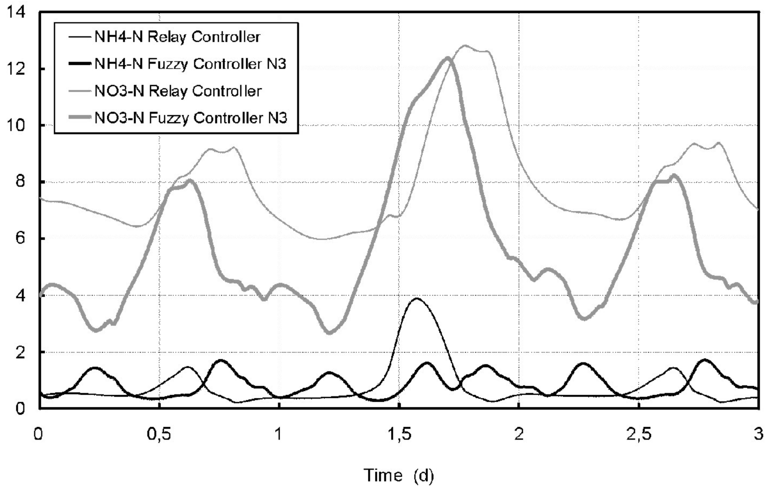

Figure 4 NH_4-N- and NO_3-N effluent concentrations for fuzzy-controller variant N3 and the conventional relay controller (simulation results)

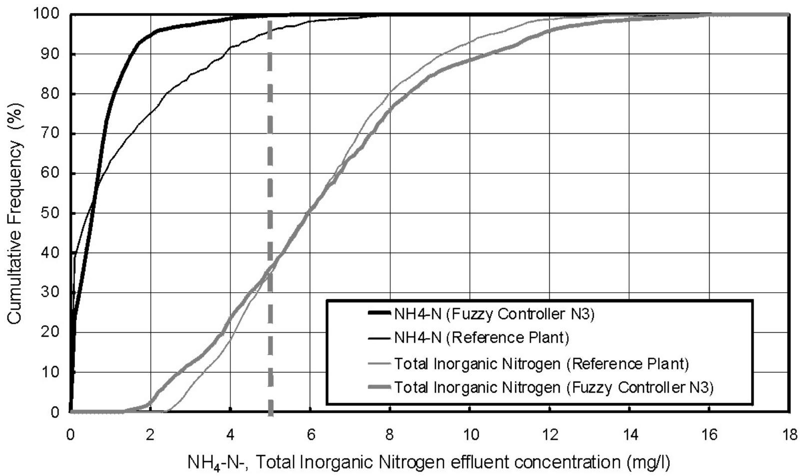

Figure 5 Cumultative frequency of NH_4-N- and total inorganic nitrogen effluent concentrations (experimental results)

control hardware of the pilot plant and the control characteristics could be observed during operation. Only few modifications were required during the tuning period of the controllers. Fuzzy-controller variant N1 was tuned in a way so that the facultative zones (especially zone D/N1) were aerated for lower NH_4-N concentrations in the effluent. This modification led to a reduction of NH_4-N peaks in the effluent but, of course, also to less energy savings. Figure 5 demonstrates the NH_4-N and Total Inorganic Nitrogen concentrations for the period when operating with fuzzy-controller variant N3. NH_4-N peaks could be reduced significantly (the 95%-value is 2 mg/l with fuzzy-control and 4.8 mg/l in the reference plant!). At the same time, a reduction of required air flow in the range of 23% was observed. The experimental results verified the good results from the simulation studies also under real operation conditions.

Conclusions

The results of the simulation studies and experimental investigations show that it is possible to design transparent fuzzy-controllers also for pre-denitrification plants and that these controllers can lead to an optimized aeration, saving energy during low-load periods and ensure sufficient aeration and extended aerated volume during peak-flow conditions. Based on the results and observations of the study, a general procedure for the step-by-step development of high level fuzzy-controllers for activated sludge plants with pre-denitrification is outlined (Meyer, 2000). It could be demonstrated that dynamic simulation is a useful tool for the design and first tuning of the fuzzy-systems. The fuzzy-controllers have to be implemented in modern control and supervision systems, as was tested successfully in the present study, so that the control characteristics can be followed and modified during operation. This will lead to an acceptance of fuzzy-control in practice.

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