

# Comparison between Model- and pH/ORP- Based Process Control for an AAA System

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## Abstract

Model-based and on-line sensor control schemes in an alternating aerobic/anoxic system for nitrogen removal were applied and compared for system performance. A linear model was developed by simplifying the well known Activated Sludge Model No. 1 and incorporated into an optimization scheme. A program was developed to detect control points on the pH and ORP profiles to control aeration duration in an alternating system. Both systems demonstrate good COD (85%) and nitrogen (76-80%) removal efficiencies, with a range of the aeration ratio (aeration cycle time/total cycle time) 0.23 to 0.3. Both systems could save significant aeration energy, in addition to handling the variation of influent nitrogen loading. The model-based optimization approach has some advantages over the pH and ORP sensor control scheme, since the effluent ammonia level can be set by an operator according to the effluent regulation. Conversely, the on-line sensor based control scheme can be easily applied into a real system, since it does not require calibration or measurements of influent compositions.

**Key Words:** nitrogen removal, process control, pH/ORP, model

## 1. Introduction

To remove wastewater nitrogen and phosphorus, spatially or temporally activated sludge systems can be used. For example, a spatially alternating system for nitrogen removal consists of different tanks for different microbial reactions (Fig.1): ammonia in the influent is oxidized in the aerobic tank ( ② in Fig. 1) and nitrate recycled from the aerobic tank is denitrified with organic carbon present in the influent in the pre-denitrification tank ( ① in Fig. 1). In the third tank (post-denitrification, ③ in Fig. 1), the nitrate from the aerobic tank is denitrified via nitrate endogenous respiration. Finally, in the fourth tank ( ④ in Fig. 1), remnant ammonia is oxidized and the DO (dissolved oxygen) of the wastewater is

increased for better sludge settling. However, the spatial system usually requires large tankage and high energy associated with the large quantity of mixed liquor recycle.

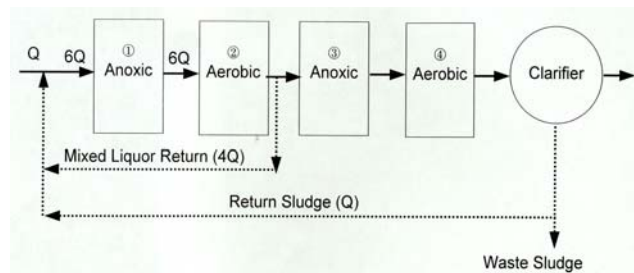


Figure 1. Schematic Diagram of a Spatially Alternating System

Temporally alternating systems, such as AAA (alternating aerobic and anoxic) systems,

create different environments for different reactions simply by turning aeration on or off. During A air-on periods, influent ammonia is oxidized to nitrate by autotrophs. During the subsequent A air-off periods, the nitrate produced is denitrified to nitrogen gas in the presence of the influent organic carbon. However, these systems are commonly operated with fixed cycle time scenarios, e.g., 1.5 h A air-on and 1.5 h A air-off, and do not take advantage of their flexible operation due to the lack of process control in this field. In other words, the duration of each aerobic and anoxic phase should be adjusted by turning aeration on/off to accommodate the variation of influent carbon/nitrogen loading conditions. For example, if the influent TKN (total Kjeldahl nitrogen) level is high, the aerobic phase should be enlarged to complete nitrification. On the other hand, if the influent TKN concentration is low, the aerobic phase needs to be shortened to save unnecessary aeration energy.

Recently, the adjustment of the duration of aerobic or anoxic cycles in an alternating system based on the model prediction [9] and the control points on the pH and ORP profiles [8] have been presented. The model-based control scheme consists of a simplified linear model and an optimization routine to optimize the aeration cycle, while meeting the effluent ammonia permit requirement. For the sensor-based control system, the aerobic phase is terminated with the identification of the so-called “ammonia valley” on the pH profiles, which indicates the end of nitrification. The anoxic cycle is terminated and the aeration initiated with the aid of the “nitrate knee” on the ORP profiles, which demonstrates the end of denitrification.

Since the trend in the wastewater treatment process is moving from design and operation to process control because of the stricter effluent regulations and increasing concern on energy consumption, the above process control approaches appear promising. In this paper, the results of model and pH/ORP sensor based control schemes applied for nitrogen removal are compared with respect to energy saving and ease of application. A brief description of each control strategy is reviewed for readers to familiarize themselves with this subject.

## 2. Background

### 2.1 Model-based optimization scheme

Various models have been proposed for process design [6], performance evaluation [10], and control [4] of activated sludge systems for nitrogen removal. Since models for biological processes are usually highly dimensional and need considerable computational resources for calibration and simulation, their application to on-line control has been rare. For example, the industry standard ASM1 (Activated Sludge Model No. 1) developed by IAWPRC (International Association on Water Pollution Research & Control, now IAW, International Association of Water) can adequately describe and predict biological organic carbon oxidation, nitrification and denitrification [7]. Unfortunately, it has rarely been applied for on-line process control because ASM1 is highly complex in model structure, consisting of 8 rate equations, 13 state variables, and 17 stoichiometric and kinetic parameters. Therefore, a simplified model is needed for computational purposes while maintaining the fundamentals in describing all biological reactions. This section briefly describes the development of a simplified linear model and an optimization scheme for controlling aeration duration. The details can be found elsewhere [1,2,9].

A linear model incorporated into the optimization scheme can be developed by simplifying ASM1. First, first-order rate expressions are used which best approximate each rate expressions. Five state variables [i.e.,  $S_I$  (inert soluble COD),  $X_I$  (inert particulate COD),  $X_P$  (inter product),  $S_O$  (dissolved oxygen), and  $S_{Alk}$  (alkalinity)] are excluded from the model. The first three terms,  $S_I$ ,  $X_I$ , and  $X_P$ , are neglected since they are inert material and do not participate in biological reactions significantly. Since high DO concentration is normally maintained during the aeration cycle, the DO is assumed to be a non-limiting factor for nitrification. Also, since alkalinity consumed during nitrification can be partially recovered during the subsequent denitrification, it can be maintained at a certain level. The alkalinity term, thus, is also excluded. Therefore, only eight state variables are predicted by the linear model, including soluble and particulate COD ( $S_S$  and  $X_S$ ), denitrifying and nitrifying bacteria concentration ( $X_{BH}$  and  $X_{BA}$ ), and effluent concentration of the four nitrogen species [ammonia ( $S_{NH}$ ), nitrate ( $S_{NO}$ ), soluble organic ( $S_{ND}$ ), and particulate organic ( $X_{ND}$ )].

Linearization of the ASM1 is achieved by substituting the non-linear Monod hyperbolic terms with “ $J$  correction factors” (rate equations in the last two columns of Table 1). In any AAA systems,

linear models for each aerobic and anoxic phase overall can be developed separately to provide an

Table 1. Process Kinetics and Stoichiometry in the Linear Model [1]

Component		$l \rightarrow$	1	2	3	4	5	6	7	8	ProcessRate, $\rho_i [ML^{-3}T^{-1}]$	
$j$	Process $j \downarrow$		$S_S$	$X_S$	$X_{B,H}$	$X_{B,A}$	$S_{NH}$	$S_{NO}$	$S_{ND}$	$X_{ND}$	Aerobic cycle	Anoxic cycle
1	Aerobic growth of heterotrophs	$-1/Y_H$			1						$\mu_H J_1 S_S$	0
2	Anoxic growth of heterotrophs	$-1/Y_H$			1						0	$\mu_H \eta_g J_2 S_S$
3	Aerobic growth of autotrophs					1	$i_{XB} - 1/Y_A$	$1/Y_A$			$\mu_A J_3 S_{NH}$	0
4	Decay of heterotrophs			$1 - f_P$	-1					$i_{XB} - f_P i_{XP}$	$b_H X_{B,H}$	$b_H X_{B,H}$
5	Decay of autotrophs			$1 - f_P$		-1				$i_{XB} - f_P i_{XP}$	$b_A X_{B,A}$	$b_A X_{B,A}$
6	Ammonification of soluble organic nitrogen						1		-1		$k_a J_4 S_{ND}$	$k_a J_4 S_{ND}$
7	Hydrolysis of entrapped organics	1	-1								$k_h J_6 X_S$	$k_h \eta_h J_5 X_S$
8	Hydrolysis of entrapped organic nitrogen								1	-1	$k_h J_6 X_{ND}$	$k_h \eta_h J_5 X_{ND}$
Observed Conversion Rate $[ML^{-3}T^{-1}]$		$r_i = \sum_j v_{ij} \rho_j$										

performance of the system. The developed linear model is then calibrated and eventually validated for its utilization.

Before proceeding with optimization, it is assumed that the plant operator would have the laboratory results of the previous day's influent compositions and the effluent quality. The optimization routine intends to set the two control variables at fixed values for the current day's operation: (1) total cycle time ( $t_c$ ) and (2) aeration ratio ( $f_a$ ). The measured parameters are COD ( $S_S$  and  $X_S$ ) and different nitrogen species ( $S_{ND}$ ,  $X_{ND}$ ,  $S_{NH}$ , and  $S_{NO}$ ).

After model calibration and incorporation into an optimization scheme, the optimizer is run to predict the values of eight state variables for the day ahead, starting from their initial values, and eventually providing the optimal values of  $f_a$  and  $t_c$ .

The predictions of the linearized model are used in the optimization scheme in the following way. For controlling plant effluent ammonia concentration, the two control variables,  $t_c$  and  $f_a$ , are manipulated in order to minimize energy costs, subject to meeting effluent permit restriction as:

$$\begin{aligned} & \text{Min } \{\text{cost}\} \\ & t_c, f_a \\ & \text{Subject to} \\ & NH_4^+ - N_{\text{predicted}} \leq NH_4^+ - N_{\text{max}} \end{aligned}$$

$$\begin{aligned} f_a \times t_c & \geq t_1 \\ (1 - f_a)t_c & \geq t_2 \\ f_a \times t_c & \leq t_3 \\ (1 - f_a)t_c & \leq t_4 \end{aligned} \tag{1}$$

where  $NH_4^+ - N_{\text{max}}$  in the first constraint is the maximum allowable value of the average daily  $NH_4^+ - N$  concentration in the effluent. The second and third constraints deal with the minimum air-on and air-off cycle time (e.g.,  $t_1 = 0.5$  hr and  $t_2 = 0.5$  hr). If there were no constraints on the air-on time, the optimizer would tend to drive  $f_a$  toward 0, resulting in an eventual washout of the  $X_{BA}$  bacteria. The fourth and fifth constraints deal with the maximum air-on and air-off cycle time (e.g.,  $t_3$  and  $t_4 = 4$  hr).

The linear model presented in Table 1 can be used to solve the optimization problem given by Eqn (1). In Fig. 2, the optimization scheme is schematically illustrated. The approach shown in Fig. 2 may not meet the  $NH_4^+$  constraint precisely, because there will certainly be some inaccuracy in the predictions of the linear model due to unmeasured disturbances in the system as well as the assumptions and simplifications involved in its development. This inaccuracy is referred to as model mismatch, which is described as:  $\Delta NH_4^+ - N = NH_4^+ - N_{\text{real}} - NH_4^+ - N_{\text{prediction}}$ .

To overcome the model mismatch, feedback of

information can be used as follows. On the first day of the AAA operation, the solution of Eqn. (1) provides the estimated  $t_{c1}$  and  $f_{a1}$ . When these values are implemented in the system, the actual  $\text{NH}_4^+$  measured at the end of the first day differs from that predicted by the linear model. To counteract the model mismatch, one can subtract  $\Delta \text{NH}_4^+-\text{N}$  from the value of  $\text{NH}_4^+-\text{N}_{\max}$  to bring the actual effluent  $\text{NH}_4^+-\text{N}$  closer to the constraint. For example, if  $\text{NH}_4^+-\text{N}_{\text{prediction}}$  is 1 mg/L, and the actual  $\text{NH}_4^+-\text{N}$  is 0.8 mg/L, then the  $\text{NH}_4^+-\text{N}$  constraint can be lowered to 1 mg/L minus the difference of -0.2 mg/L, and set at 1.2 mg/L. This method of overcoming model mismatch is essentially the same as that used in a commercially successful dynamic matrix control [5]. To make this feedback robust, and to avoid responding too sharply to daily fluctuations, another  $\delta$  correction can be implemented as an exponentially weighted moving average of the current value and yesterday's value as:

$$\delta \text{NH}_4^+-\text{N}|_t = \alpha \times \Delta \text{NH}_4^+-\text{N}|_t + \beta \times \delta \text{NH}_4^+-\text{N}|_{t-1} \quad (\alpha + \beta = 1) \quad (2)$$

where  $\delta \text{NH}_4^+-\text{N}|_{t-1}$  is the prior day's  $\delta$  correction, and  $\alpha$  and  $\beta$  are weighting factors. If  $\alpha$  is higher than  $\beta$ , the system relies more on the current data, and vice versa. As shown below, this approach controls an AAA system quite well.

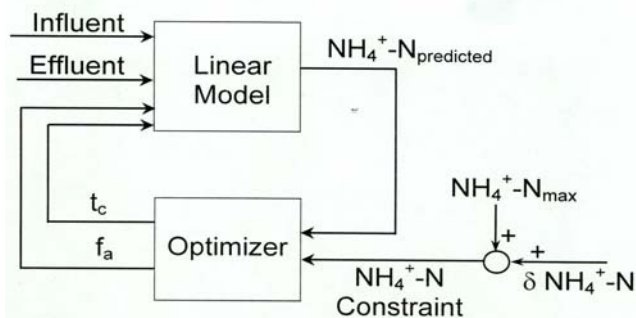


Figure 2. Schematic Diagram of the Model-Based Optimization

## 2.2 pH/ORP-based control scheme

During air-on periods of an AAA system, nitrification, a process which consumes alkalinity and lowers pH, takes place. Once nitrification is complete, the system pH increases due to ammonification, thus making a local minimum on the pH profile, the so-called “ammonia valley” (Fig. 3). Once the aeration is off, the system ORP value drops rapidly due to the change from the aerobic to

anoxic state (Fig. 4). When denitrification is complete, the ORP value further plunges rapidly due to the change of the reduced status from the anoxic to the fermentation stage. This results in a control point, termed the “nitrate knee” on the ORP profiles (Fig. 4), for indicating the termination of the anoxic period and the initiation of aeration. Consequently, the duration of the aerobic/anoxic cycle can be easily adjusted with these two control points: ammonia valley (pH profiles) for terminating aeration and nitrate knee (ORP profiles) for initiating aeration.

The identification of these two control points is straightforward, using the first derivative of the pH (local minimum) values and the second derivatives of the ORP (inflection point) profiles. Figure 5 shows a typical pH profile and corresponding  $\text{dpH}/\text{dt}$  changes from a negative to positive value near the ammonia valley (Fig. 5b). The “exact” point of the ammonia valley can be identified by locating a narrow  $\text{dpH}/\text{dt}$  band [from -0.001 (point A) to 0.001 (point B), Fig. 5b]. To provide better sludge settling, additional aeration (e.g., 10 min) can be employed after the detection of the “ammonia valley.”

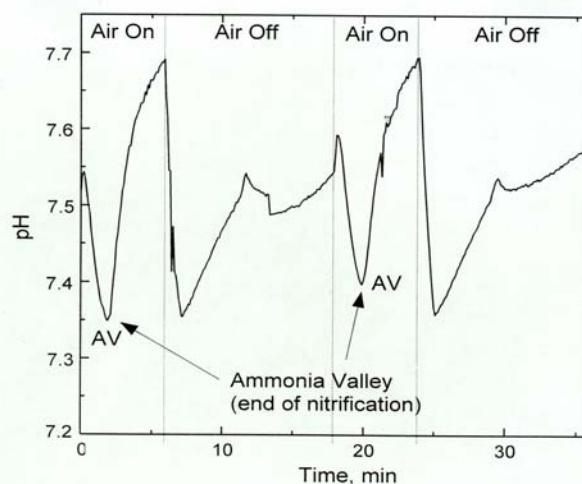


Figure 3. Typical pH Profile in an AAA System

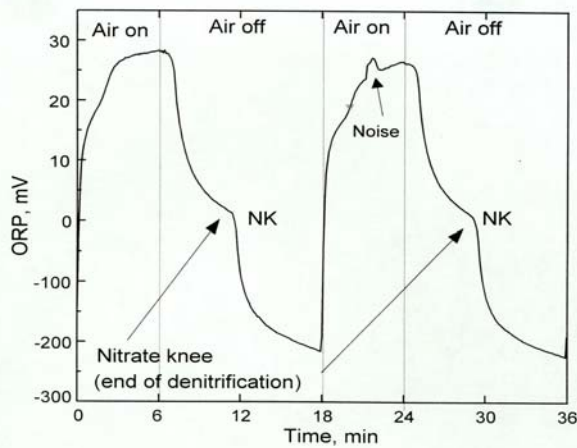


Figure 4. Typical ORP Profile in an AAA System

A similar approach can be easily implemented for the detection of the nitrate knee on the ORP profiles. As shown in the second derivative plot in Fig. 6 during air-off periods, the “nitrate knee” can be easily located.

### 3. Experiments

A bench scale AAA system (5 L) with MCRT (mean cell residence time) at 12 d, and HRT (hydraulic retention time) at 12 h was used. The switches for turning the air or mixer on or off were connected to a DAC (data acquisition and control) system. pH and ORP sensors were immersed directly into the reactor, and their readings were continuously stored on a computer via the DAC system. During the air-on period, the DO concentration of the reactor was maintained above 5 mg/L.

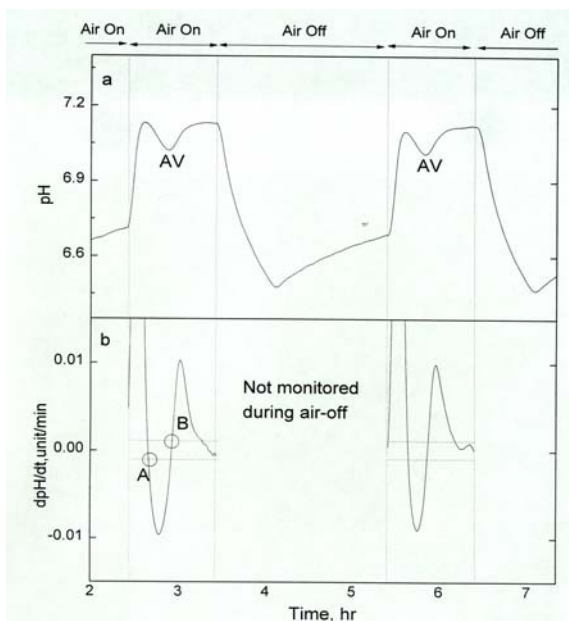


Figure 5. pH and dpH/dt Profiles for Detection of Ammonia Valley

Wastewater was collected from a local wastewater treatment plant, with typical compositions of chemical oxygen demand (COD) of 150-350 mg/L, TKN of 25-35 mg/L, and  $\text{NH}_4^+$ -N of 13-25 mg/L. Additional organic carbon (mixture of sodium acetate, methanol and ethanol) equivalent to 60 mg/L of COD was added into the reactor to provide an adequate COD/N ratio. The detailed description is shown elsewhere [8, 9]. The sample analyses followed the procedures in the Standard Methods [3].

## 4. Results

Prior to control application, the AAA system was operated with fixed cycle time ratios at air-on/off 1/1 h and 1/2 h (aeration ratio 0.33-0.5). The summary of the system performance is provided in Table 2. Overall, the system demonstrates good performance with 82% and 72% of COD and TN removal efficiencies, respectively.

### 4.1 Model based optimization

After operating the AAA system with the fixed cycle ratios, the system was then operated with the model-based control scheme described above. The calibration of the linear model is shown in Fig. 7; prediction of  $\text{NH}_4^+$  and  $\text{NO}_3^-$  concentrations with a full ASM1 is also included for comparison. In general, both ASM1 and the linear model predict the system dynamic concentrations of  $\text{NH}_4^+$  and  $\text{NO}_3^-$  reasonably well. However, the time for calibration of the linear model was much less than that for the ASM1, since the former has fewer state variables and model parameters.

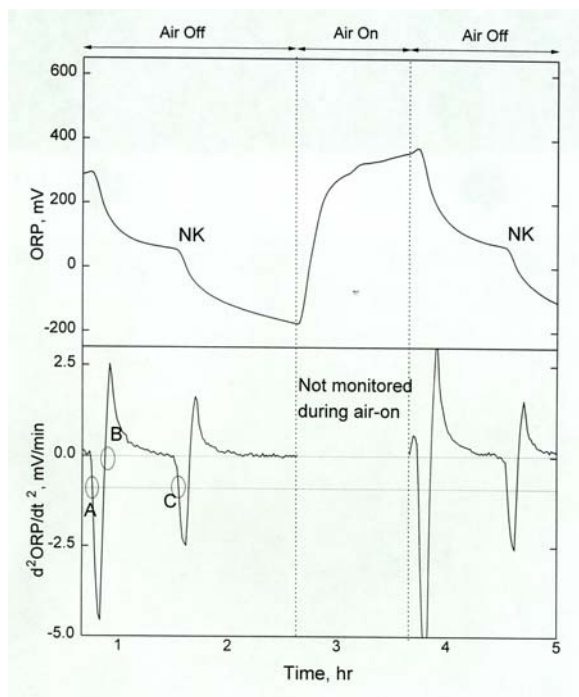


Figure 6. ORP and  $d^2\text{ORP}/dt^2$  Profiles for Detection of Nitrate Knee

After the linear model was calibrated and validated with several sets of parameter concentration profiles [1], it was incorporated into the optimization scheme described in Fig. 2. Again, the objective of the optimization was to minimize  $f_a$  while meeting the effluent ammonia permit requirement, which was set at 1 mg N/L. The results are provided in Fig. 8. The optimizer was able to control the system quite well by enlarging  $f_a$  when the influent TKN concentration was high, and by reducing  $f_a$  when the influent TKN level was low. The overall performance of the model-based optimization scheme is summarized in Table 2. The system could achieve 86% and 76% of COD and TN (total nitrogen) removal efficiencies, respectively, with an average  $f_a$  of 0.3. It is noticeable that without any constraint about effluent  $\text{NO}_3^-$ , the system could still achieve some degree of denitrification (Table 2).

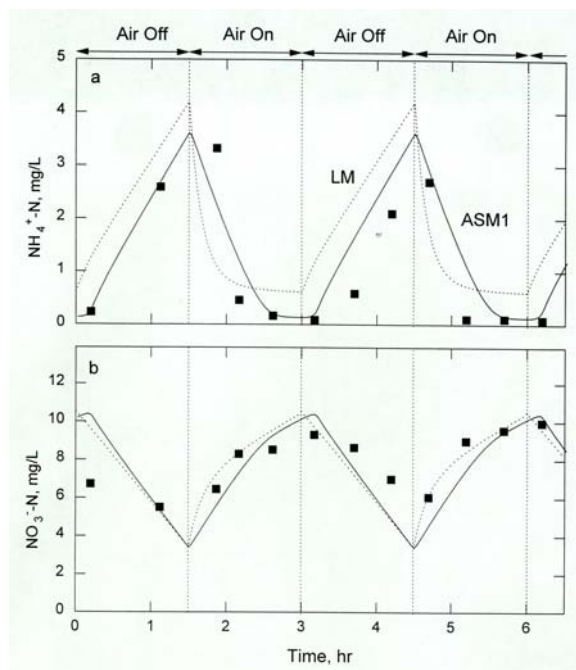


Figure 7. Comparison of Model Prediction with Experimental Data

#### 4.2 pH/ORP-based control

The control scheme based on pH/ORP readings described earlier was applied to the same AAA system for nitrogen removal. Typical ammonia and nitrate concentrations and the corresponding pH/ORP profiles are shown in Fig. 9. The aeration was turned off about 10 min after the ammonia valley (pH profile) was detected, and turned on when the nitrate knee on the ORP profile was detected. Figure 10 demonstrates the stability of the control system. The ability of the system in handling an influent TKN shock loading is illustrated in Fig. 11. After the influent TKN was raised from 35 to 50 mg/L, the duration of the aeration cycle was enlarged to complete nitrification, adjusted by the delayed occurrence of the ammonia valley on the pH profiles. By the same token, the system was able to prolong the air-off cycle to complete denitrification due to the presence of high nitrate concentration. Once the shock loading was removed, the system was able to retrieve its normal conditions. In short, the AAA system could be operated based on pH/ORP-based control to accommodate the influent flux. The summary of the results based on the pH/ORP profiles are also provided in Table 2.

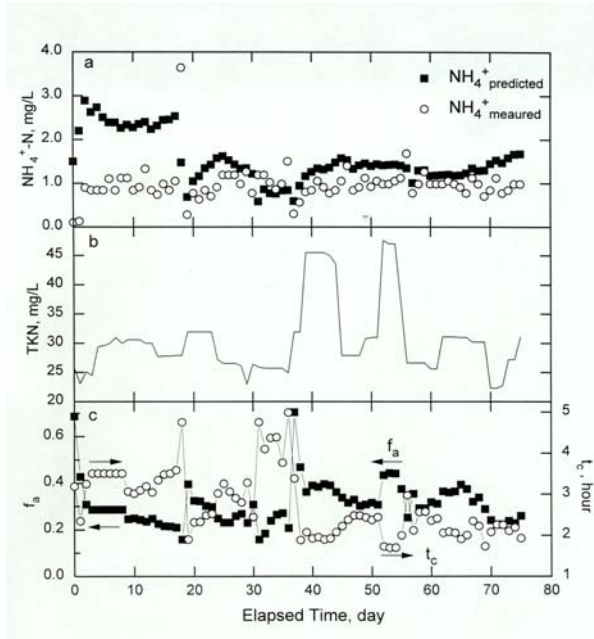


Figure 8. Optimization Results Based on Model-Based Scheme

### 5. Discussion

In this paper, both the model and on-line sensor (pH and ORP) based control approaches to adjust the duration of air-on and air-off cycles in an AAA system for nitrogen removal are presented. The parameter (COD and TN) removal efficiencies are similar, as also in the case of fixed-cycle conditions. In addition to energy saving, both process control systems are able to accommodate the variation of the influent TKN loading.

Table 2. Summary of AAA System Operation Based on Different Control Schemes

	Fixed Cycle			Model Base			Sensor Base		
	Influent, mg/L	Effluent, mg/L	% Removal	Influent, mg/L	Effluent, mg/L	% Removal	Influent, mg/L	Effluent, mg/L	% Removal
COD	300	53	82	388	56	86	360	52	84
TN	30.0	8.2	72	30.4	7.2	76	31.4	6.4	80
NH <sub>4</sub> <sup>+</sup> -N	18.1	0.6	97	21.8	1.0	96	21.1	1.6	92
NO <sub>3</sub> <sup>-</sup> -N		5.6			4.6			3.6	
Org N	11.9	2.0	82	8.6	1.6	81	10.3	1.2	88
f <sub>a</sub>		0.33-0.5			0.3			0.23	
t <sub>c</sub> , hr		2-3			2.7			2.9	

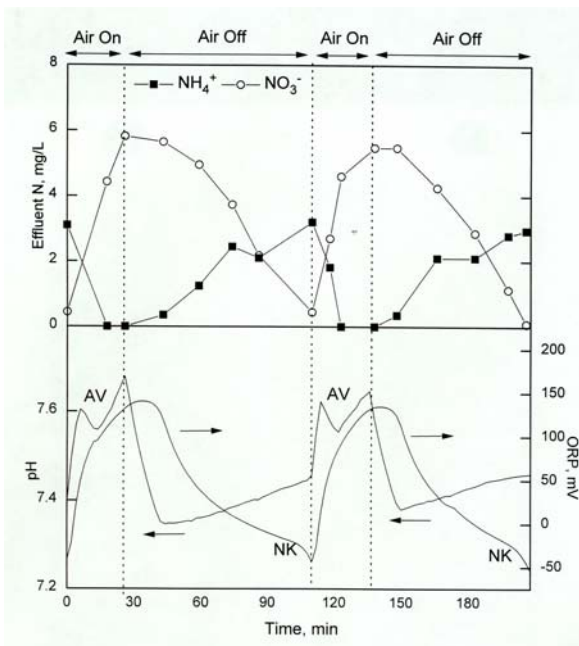


Figure 9. Typical Parameter Profiles with on line Sensor Control Scheme

The advantage of the model-based optimization over the pH/ORP-based control scheme is that the effluent ammonia level can be adjusted by an operator according to the permit requirement. In other words, one needs to operate and achieve an effluent concentration of, say, 3 mg/L to meet a permit requirement of 4 mg/L. With the control scheme based on pH and ORP profiles, however, it is possible to removal all ammonia during the air-on period and nitrate during the air-off period, regardless of the permit requirements. From an energy point of view, the passive approach of the former may be justified. A higher removal efficiency of contaminants in the latter case, however, is a necessity for public relation.

The model-based control approach needs the measurements of daily influent ammonia and other compositions; this may present a problem for small plants due to the lack of resources. Also, the model should be calibrated periodically to render the model prediction more reliable. The calibration of the model certainly requires the plant personnel to better understand the fundamentals of the model. The pH/ORP-based control scheme does not require information about the influent compositions. The control system does not require any model calibration, albeit it requires some maintenance on the probes. It is recommended that the pH/ORP scheme be employed in smaller plants with the placement of sensors at the end of aeration tanks.

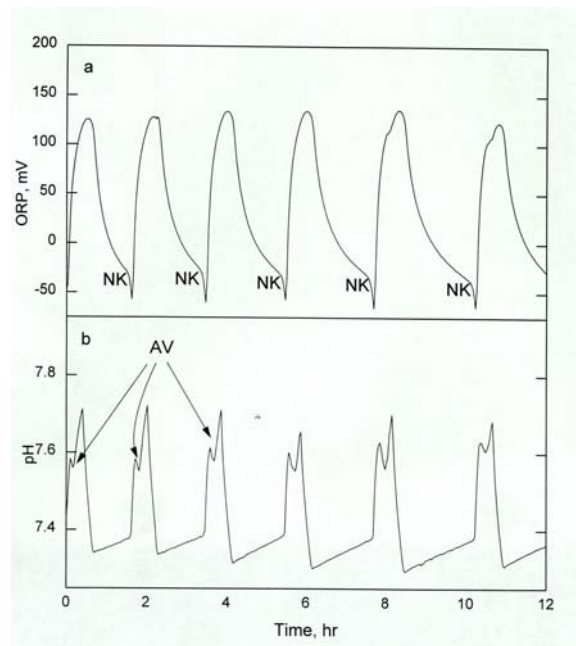


Figure 10. Six Cycles of pH and ORP Profiles with Constant Influent Compositions

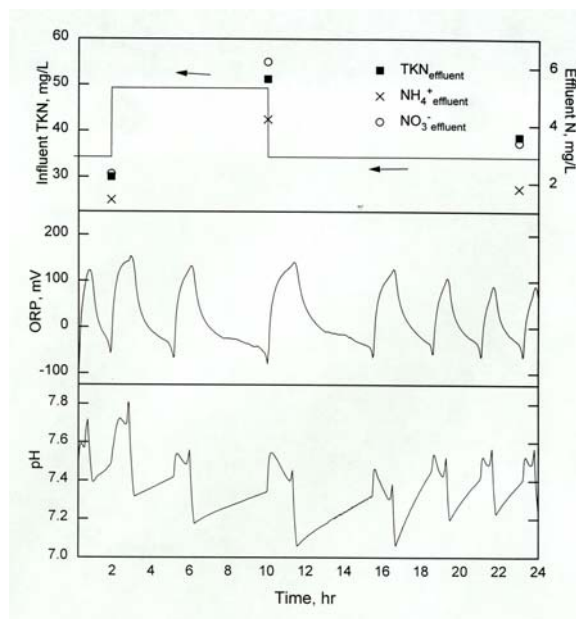


Figure 11. Response of the Online Sensor Control scheme against the Nitrogen Shock Loading

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