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# Study of control strategy and simulation in anoxic-oxic nitrogen removal process

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**Abstract**: The control strategy and simulation of external carbon addition were specially studied in an anoxic-oxic(A/O) process with low carbon: nitrogen(C/N) domestic wastewater. The control strategy aimed to adjust the flow rate of external carbon dosage to the anoxic zone, thus the concentration of nitrate plus nitrite($NO_x^-$-N) in the anoxic zone was kept closed to the set point. The relationship was studied between the $NO_x^-$-N concentration in the anoxic zone($S_{NO}$) and the dosage of external carbon, and the results showed that the removal efficiency of the total nitrogen(TN) could not be largely improved by double dosage of carbon source when $S_{NO}$ reached about 2 mg/L. Through keeping $S_{NO}$ at the level of about 2 mg/L, the demand of effluent quality could be met and the carbon dosage could be optimized. Based on the Activated Sludge Model No.1(ASM No.1), a simplified mathematical model of external carbon dosage was developed. Simulation results showed that PI controller and feed-forward PI controller both had good dynamic response and steady precision. And feed-forward PI controller had better control effects due to its consideration of influent disturbances.

**Keywords**: ASM No.1; biological nitrogen removal; external carbon addition; feed-forward PI control

## Introduction

Nitrogen compound is the principal nutrient concerned in the treated wastewater, which is one of the reasons causing eutrophication of the water body. Increasing effluent quality demands imposing the need for the implementation of nitrogen removal processes in activated sludge wastewater treatment plants. The A/O process is an economical configuration for nitrogen removal, which can make full use of the organic matter in the influent wastewater. But if the treated wastewater does not contain enough organic carbon, denitrification may be impaired and an external carbon source is required(Samuelsson, 2001).

External carbon addition is of considerable importance for the A/O process treating domestic wastewater with low C/N. Dosing insufficient amount will result in high effluent nitrate and TN concentration. Dosing too much will increase the costs considerably due to a higher external carbon use, a higher sludge production, and an increased oxygen demand (Cho, 2002). Together with the strong variations of the influent flow and composition, a demand for on-line control of nitrogen removal process is initiated to guarantee a sufficiently low effluent nitrogen concentration, optimal dosage of external carbon, and minimum operational costs of the treatment system. Many researchers have studied the problem of determining appropriate amount of carbon sources (Barros, 1998; Lindberg, 1996; Cho, 2002).

In this paper, a simplified mathematical model of external carbon addition was developed based on the ASM No.1(IWA task group, 2002). The main objective was to adjust the flow rate of the external carbon dosage to the anoxic zone to keep $S_{NO}$ at the set point level and to quickly remove the disturbances of the influent quality and quantity.

## 1 Control strategy study

### 1.1 Experimental equipment

A bench-scale treatment system consisted of a plug flow A/O reactor and a settling tank. The volume of the A/O reactor was 57 L, 22% was anoxic zone and 78% was oxic zone. The settling tank was 23 L. The plug flow was simulated with 10 compartments in series: 2 for the anoxic zone, 8 for the oxic zone.

The domestic wastewater used is from the community of Beijing University of Technology. The composition of the treated wastewater was as follows: COD was about 280—400 mg/L, TN was about 90—110 mg/L, ammonia nitrogen ($NH_3$-N) was about 85—105 mg/L and pH was about 7.1—7.8.

Methanol was added into the anoxic zone to improve the denitrifying capacity for the low C/N(about 3.5—4) of the treated wastewater and its dosage was converted into the equivalent of the influent COD concentration. The influent flow, the nitrate recycle flow and the sludge recycle flow were measured by peristaltic pumps. Dissolved oxygen concentration(DO), pH, and oxidation-reduction potential (ORP) were measured by the WTW on-line measuring equipment. The variations of COD, mixed liquor suspended solids(MLSS), TN, $NH_3$-N, nitrite ($NO_2^-$-N), nitrate ($NO_3^-$-N) were analyzed according to the standard methods (APHA, 1995).

### 1.2 Experimental process analysis of the external carbon addition

In order to analyze the relationship between the external carbon dosage and $S_{NO}$, we tuned the total recycling rate (defined as the ratio of the internal recirculation flow plus the return sludge flow to the influent flow) and the additional carbon dosage during the experimental period. The system reached steady state via numbers of periods, and then the steady-state results were analyzed.

It is difficult to provide an illustrative description of the relationship among the additional carbon dosage, the total recycling rate and the effluent TN concentration with only tens of the experimental data. So the approaching ability and the data inserting ability of neural network was used to predict data at points which had not been measured in the experiment. Fig.1 shows that the effluent TN concentration decreased under different total recycling rate with the carbon dosage increasing from 0 to 697 mg/L; when $S_{NO}$ reached to some value, the effluent TN concentration tended to become stable in spite of continuously increasing the external carbon

Foundation item: Beijing Science and Technology Commission(No. H020620010120), the Significant International Projects of the National Natural Science Foundation of China(No. 50521140075), Beijing Municipal Education Commission(No. KZ200310005003) and Beijing Key Laboratories; * Corresponding author dosage. There existed critical scope for $S_{NO}$. When $S_{NO}$ was more than the critical scope, the effluent TN concentration decreased largely with the increasing carbon dosage and the external carbon using efficiency was high. When $S_{NO}$ was less than the critical scope, the effluent TN concentration decreased little or did not decrease with the increasing carbon dosage and the external carbon using efficiency was low. If the external carbon dosage was continuously increased, the COD load in the oxic zone would be increased, and the nitrification ability in the oxic zone would be impaired.

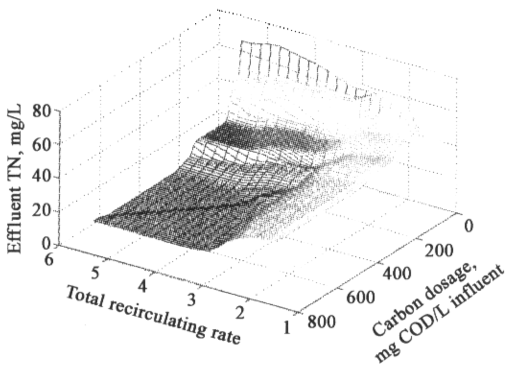


Fig.1 Three-dimensional simulation results of BP neural network

Fig.2 shows that the effect of carbon dosage on the effluent COD and $NOx^-$-N concentration and TN removal efficiency in the anoxic zone under total recirculating rate of 2.97. When carbon dosage varied from 0 mg/L to 221.58 mg/L, $S_{NO}$ decreased from 30.51 mg/L to 1.92 mg/L, the COD concentration increased from 66.22 mg/L to 82.78 mg/L, the TN removal efficiency improved from 45.2% to 73.1%. Continuously increasing carbon dosage to 697 mg/L, $S_{NO}$ decreased to 0 mg/L, but the TN removal efficiency only improved 3.27% with double dosage of the external carbon source. With the carbon dosage increasing, COD concentration in the anoxic zone increased from 82.78 mg/L to 185.12 mg/L which added burden to the oxic zone.

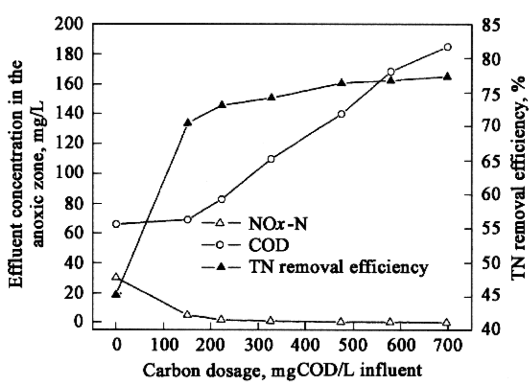


Fig.2 Effect of carbon dosage on the effluent COD, $NOx^-$-N and TN removal efficiency in anoxic zone with constant total recirculating rate

Under the constant total recirculating rate, $S_{NO}$ decreased with the carbon dosage increasing. When $S_{NO}$ reached to about 2 mg/L, even through the carbon dosage increased twice as much, $S_{NO}$ decreased little and the TN removal efficiency improved little. And dosing too much external carbon would increasing the effluent COD of the anoxic zone, the COD load of the oxic zone, and the operating costs. So it is important to choose the $S_{NO}$ set point for the performance of the controller since it will determine the consumption of the external carbon. According to the analysis above, this study determined that the $S_{NO}$ set point was 2.0 mg/L in the following simulation.

### 1.3 Determination of the nitrate recycle flow and the sludge recycle flow

In the A/O process, $NOx^-$-N produced by nitrification would be recycled to the anoxic zone through the nitrate recycle flow and finally be reduced by denitrification. In order to simplify the control strategy, it was supposed that all the incoming $NH_3$-N was either transformed into $NOx^-$-N or directly consumed by the biomass growth. Therefore the nitrate recycle flow could be expressed by the following equation:

$$Q_{int} = (1 - r) Q_{in} S_{NH,in} / (S_{NO,AE} - S_{NO}) - Q_{in} - Q_r. \quad (1)$$

In which, $S_{NO,AE}$ represents the effluent $NOx^-$-N concentration in the oxic zone (mg/L); $S_{NO}$ represents the $NOx^-$-N concentration in the anoxic zone (mg/L); $r$ represents the $NH_3$-N utilized by the biomass growth; $S_{NH,in}$ represents the influent $NH_3$-N concentration (mg/L); $Q_{in}$, $Q_{int}$, $Q_r$ represent the influent flow, the nitrate recycle flow, and the sludge recycle flow ($m^3/d$) respectively.

The nitrate recycle flow can be controlled according to the Equation (1). The sludge recycle flow was controlled the same as the influent flow.

## 2 Controller design and simulation analysis

The IAWQ ASM No.1 is a widely used model for simulation of biological nitrogen removal in wastewater treatment plants (Aspegren, 1992; Lukasse, 1998). Due to its complexity it is difficult to use the ASM No.1 directly for controller design. In order to design the controller of the flow rate of external carbon addition, a simplified model was derived with the following assumptions according to the understanding and analysis of the A/O process. The assumptions were: (1) the anoxic zone was completely mixed; (2) there was no denitrification in the settling tank; (3) the $NOx^-$-N concentration in the nitrate recycle and the sludge recycle was equal to the effluent $NOx^-$-N concentration; (4) the oxygen in the anoxic zone was always zero; (5) the oxygen that enters the anoxic zone via the influent, the nitrate recycle and the sludge recycle was not considered. Based on these hypotheses a model of external carbon addition was developed.

According to the mass balance theory (input-output + reaction = accumulation) of denitrification, the variations of the $NOx^-$-N and the biodegradable COD could be expressed by the following equations:

$$\frac{dS_s}{dt} = \frac{Q_{in}}{V} S_{S,in} - \frac{Q}{V} S_S - \frac{1}{Y_H} \mu_{H,max} \times \left(\frac{S_S}{K_S + S_S}\right)\left(\frac{S_{NO}}{K_{NO} + S_{NO}}\right) \eta_g X_{B,H} + \frac{1}{V} U, \quad (2)$$

$$\frac{dS_{NO}}{dt} = \frac{Q_r + Q_{int}}{V} S_{NO,in} - \frac{Q}{V} S_{NO} - \frac{1 - Y_H}{2.86 Y_H} \mu_{H,max} \times \left(\frac{S_S}{K_S + S_S}\right)\left(\frac{S_{NO}}{K_{NO} + S_{NO}}\right) \eta_g X_{B,H}, \quad (3)$$

$$Q = Q_{in} + Q_r + Q_{int}, \quad (4)$$

$$U = Q_C S_C. \quad (5)$$

In which, $S_S$ represents the biodegradable COD concentration in the anoxic zone, including the external carbon(mg/L); $S_{S,in}$ represents the influent biodegradable COD concentration (mg/L); $S_{NO}$ represents the $NOx^-$-N concentration in the anoxic zone(mg/L); $S_{NO,in}$ represents the recycle $NOx^-$-N concentration to the anoxic zone(mg/L); $X_{B,H}$ represents heterotrophic biomass concentration in the A/O reactor(mg/L); $Q_C$ represents the external carbon dosage flow rate ($m^3/d$); $S_C$ represents the concentration of the external carbon(mg/L); $U$ represents the carbon dosage per day(g/d); $V$ represents the volume of the anoxic zone($m^3$); $\mu_{H,max}$ represents the maximum specific growth of the heterotrophic biomass ($d^{-1}$); $Y_H$ represents the yield for heterotrophic biomass; and $K_S$ represents the saturation constant for biodegradable COD(mg/L).

## 2.1 Controller design

Variations of the influent flow and composition were the disturbances to the control system. Fig.3 shows the control structure of the external carbon addition.

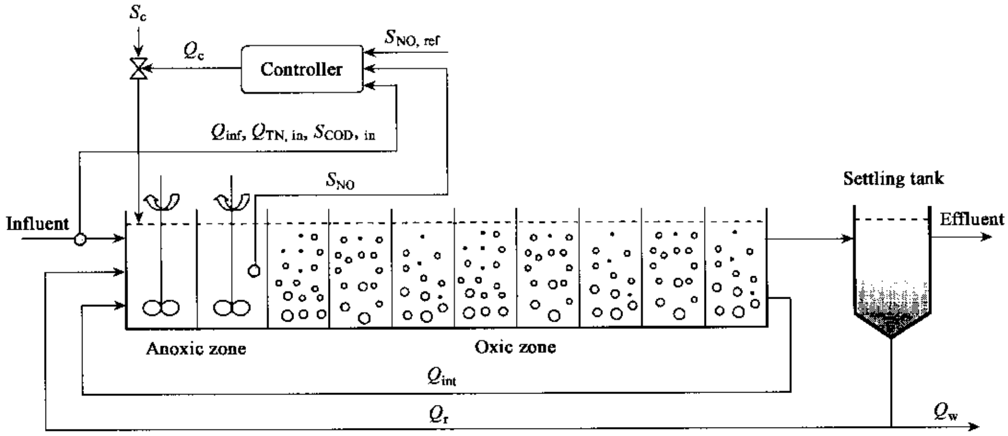


Fig.3 Schematic of the control structure of external carbon addition in the A/O process

PI controller was used. Let $S_{NO,ref}$ be the $S_{NO}$ set point, $K_p$ be the proportion factor, $K_I$ be the integrating factor, and the control rule could be expressed by Equation (6).

$$U(t) = K_P(S_{NO}(t) - S_{NO,ref}(t)) + K_I\int_0^t (S_{NO}(\tau) - S_{NO,ref}(\tau))d t. \quad (6)$$

In order to quickly eliminating the effect of the influent variations, a feed-forward part was added to the PI controller, then we get the feed-forward PI controller. The control rule could be expressed by Equation (7).

$$U(t) = \frac{1}{1-Y_H}((Q_r(t) + Q_{int}(t))S_{NO} - Q(t)S_{NO,ref}(t)) - Q_{in}(t)S_{S,in}(t) + Q(t)S_S(t) + K_p(S_{NO}(t) - S_{NO,ref}(t)) + K_I\int_0^t (S_{NO}(\tau) - S_{NO,ref}(\tau))d\tau. \quad (7)$$

## 2.2 Simulation analysis

The control objective was to keep $S_{NO}$ at the set point of 2 mg/L. A sin wave disturbance was input with a 50% swing of the reference to the influent flow, 25% swing of the reference to the influent biodegradable COD and 11% swing to the influent ammonia nitrogen. At the same time, a cycle-varied set point was given in order to verify the dynamic response and steady precision of the two controllers in the simulation: the set point was 2.0 mg/L at the first two days, and was adjusted to 2.5 mg/L at the second two days, and was adjusted to 1.5 mg/L at the third two days, and came back to 2.0 mg/L at the last two days.

The simulation results(Fig.4 and Fig.5) show that the two controllers both could reach the control objective and the feed-forward PI controller had better control effects than the PI controller for the consideration of the disturbances of the influent(including the influent flow and composition). The two controllers both could trace the variations of the set point with small error, and had the good tracing ability, but PI controller has bigger overshooting with a slight surge. About the control effects of the external carbon addition, when the set point changed, PI controller can give a fast response with large extent of change, so it is difficult to realize because of the limitation of executer. But the feed-forward PI controller has the same response speed with small extent of change, it was easy to be realized for the executer.

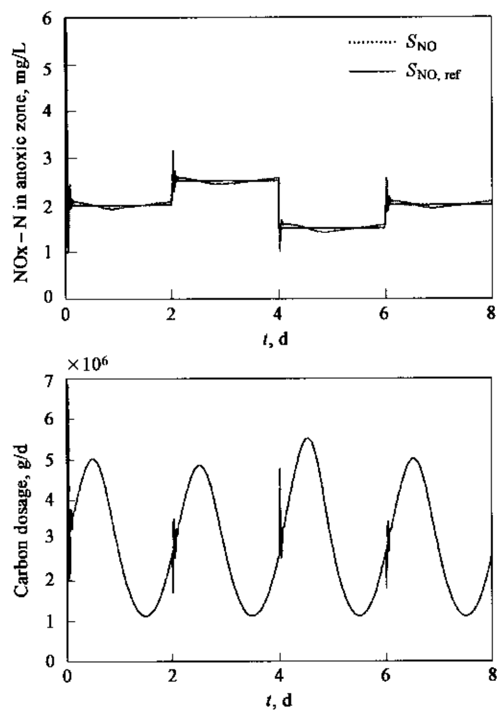


Fig.4 The simulation results of the PI controller

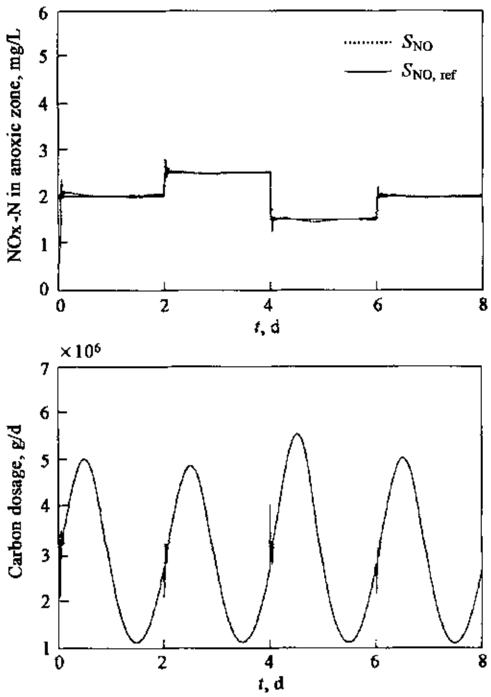


Fig.5 The simulation results of the feed-forward PI controller

## 3 Conclusions

In this paper, a control strategy to control $S_{NO}$ of the A/O process was determined by adjusting the flow rate of the external carbon dosage to the anoxic zone. Through the analysis of the experimental data, the demand of the effluent quality could bemet and the carbon dosage could be optimized by keeping $S_{NO}$ at the level of about 2 mg/L. Based on ASM No.1, a simplified mathematical model of external carbon dosage was developed and two controllers of PI and feed forward PI were designed. Simulation results showed that feed-forward PI controller had better dynamic response and steady precision due to its consideration of influent disturbances.

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