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*Review*

# Modeling of nitrogen removal and control strategy in continuous-flow-intermittent-aeration process

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**The continuous-flow-intermittent-aeration process was introduced to achieve nitrogen removal in a wastewater treatment plant (WWTP). Without structural readjustment of completed mixed activated-sludge treatment unit, operation scheme of intermittent aeration would be upgraded to promote the WWTP performance. As an aid of the implementation, mathematical simulation models were developed as an invaluable tool. Due to some uncertainties associated with the mechanisms and quantification of the process, some simplification in a reliable model should be addressed progressively by using the relevant information drawn from the existing models, the literature and the works on the experiments. An unsteady-state model for the upgrade of WWTP process was developed. The model predictions are coincident with the practical trends of the effluents, which the error percentages are about 10%. Moreover, the model facilitates the insight into nitrogen removal with the process operational conditions. The study could provide some valuable reference and recommendation on the design and operation of the municipal WWTP.**

**Key words:** Kinetic model, nitrification, denitrification, process control, continuous flow, intermittent aeration.

## INTRODUCTION

With increasingly stricter discharge standards, especially in environmentally sensitive areas, the wastewater treatment plant (WWTP) is facing challenges for nutrient (nitrogen and phosphorus) removal efficiencies (Wang et al., 2009). Undoubtedly, the biological nutrient removal (BNR) processes based on activated sludge are the best choices for their cost-effective and highly efficient characteristics (Eldyasti et al., 2012).

The BNR process can be classified into spatial phase and temporal phase separation (Wang et al., 2007). The sequencing batch reactor (SBR), as a temporal phase separated or a real-time control of the bioprocess (Zanetti et al., 2012), can create suitable conditions for simultaneous removal of nitrogen, phosphorus and organics in a single reactor (Huang et al., 2006; Dosta et al., 2007). The continuous flow and intermittent aeration process, just as a modified form of SBR (Cassidy et al., 2000; Moussavi et al., 2011), has the significant advantages of continuous flow and constant water level in a reactor. The continuous-flow-intermittent-aeration activated process showed potential superiority, such as operational flexibility, high stability, and minimal complexity (Einfeldt, 1992; Hong et al., 2008). Therefore, the process has been developed and implemented in full-scale WWTP extensively.

To be specific, the process means continuous flow (for keeping regular water level) and intermittent aeration (for periodically rotating aerobic and anoxic phases) in one reactor, which the operation allows for flexible adjustment of aerobic and anoxic times to meet the needs for BNR. Strongly, performance of the system depends on the flexible operational parameters such as the aeration time,

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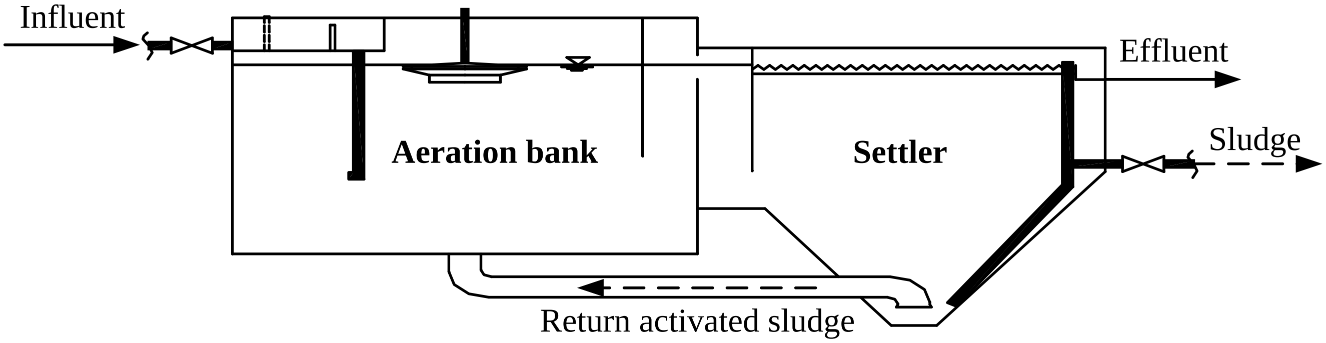

**Figure 1.** Schematic diagram of the WWTP unit.

cycle length, recycle ratio, hydraulic retention time (HRT), sludge retention time SRT, etc (Zeng et al., 2004; Irizar et al., 2004).

On the other hand, mathematical modeling would be invaluable as an aid of the design, operation, control and optimization of wastewater treatment processes; and it offer a beneficial approach for further research and development of WWTP. Accordingly, the mathematical simulation models of BNR have got more and more attention. The related research and development of the mechanism and modeling for BNR processes have achieved much progress in the last decade (Hu et al., 2003; Marazioti et al., 2003; Vandekerckhove et al., 2008).

Since the activated sludge models (ASMs) were developed by the International Water Association (IWA) task group, they were widely used for design and operation of biological wastewater treatment processes and have been paid much more attention by the researchers all around the world (Iacopozzi et al., 2007; Ekama et al., 2004; Ni and Yu, 2008; Sun et al., 2009). Among them, ASM1 and ASM3 were implemented primarily for biological nitrogen removal but AMSs are the complex system including many biological conversion and transportation processes and a large number of uncertainty of parameters are inevitably needed for the quantitative evaluation and validation. Furthermore, some steady-state simulation based on ASMs seemed as a reluctant choice (Lu et al., 2009; Koch et al., 2001; Ekama, 2009) and some simplified and calibration efforts become inevitable (Heinen, 2006).

This study was aimed at developing an unsteady-state process model for a full-scale WWTP. The model analyzes and evaluates the nitrogen removal performance of a continuous-flow-intermittent-aeration activated process. It facilitates a more obvious insight into the relationships between the nitrogen removal efficiency and the operation parameters. The control strategies were evaluated using the developed model and the mechanism and effectiveness have been considerably confirmed. As a result, the upgrade scheme of intermittent aeration was operated to promote the performance without the structural readjustment of the WWTP.

## DESCRIPTION OF THE WASTEWATER TREATMENT PLANT (WWTP) AND PREVIOUS STUDY

The WWTP using the continuous-flow-intermittent-aeration process for organics and nutrient removal in the municipal wastewater is located in Chongqing city, P.R. China. The designed capacity of the WWTP was 20,000 $m^3$/d (max. 30,000 $m^3$/d). The study was made in an experiment unit attached to the WWTP (capacity 1,200 $m^3$/d) from April to October in 1999 for the WWTP upgrade. Figure 1 shows a schematic diagram of the core faculty in the unit. According to 14 different conditions/operations, the experiments were operated on different aeration time and non-aeration time. The different working conditions were named by aeration and non-aeration time, such as 1 to 1 mode, and 2 to 1 mode, etc. The data from 12 working conditions were used to calculate the model parameter, and 2 working conditions (4 to 4 and 4 to 5 modes) were used to examine the predicting performance (Long et al., 2000).

## MODEL DEVELOPMENT

### Model flow scheme and assumptions

Based on many models containing complex structures and uncertain parameters, it is necessary for the model to be simplified. The simplification of the flow scheme is illustrated in Figure 2. The validity of the simplification is based on the fact that only the relatively short term process kinetics are concerned in the model; and the following assumptions basically reflect the process behaviors: (1) there is no microorganism in the influent; (2) the reactor is completely stirred and the sludge concentration in the reactor is maintained approximately constant; (3) there is no metabolic activity of microorganism in the settlement for precipitation; (4) there

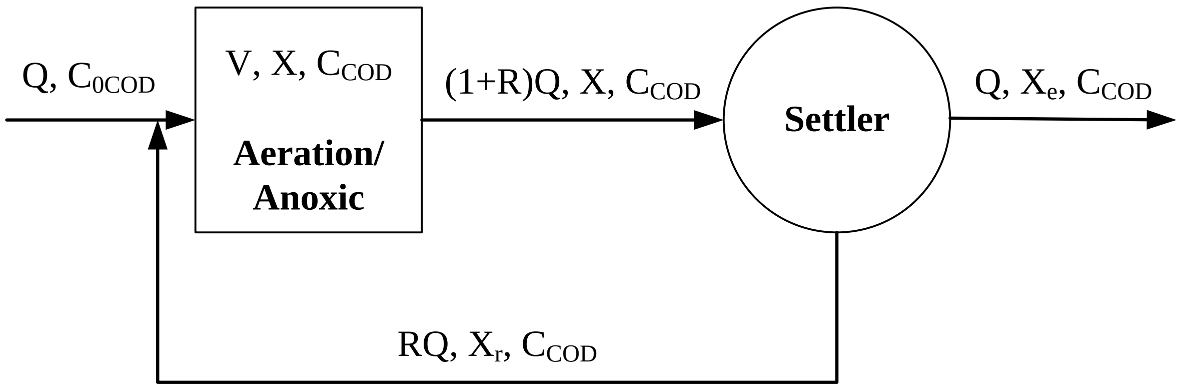

**Figure 2.** Flow scheme of the model.

is no sludge cumulated in the settler; and the solid separates from the mixed liquid easily.

### Nitrification models under aeration conditions

In the aeration phase, the concentration of $NO_3^-$-N increases with the oxidization of $NH_3$-N simultaneously. However, it is possible that denitrification occurs in the inner part of activated sludge due to its anoxic condition. So $NO_3^-$-N could be degraded even under aeration conditions. Therefore, $NO_3^-$-N degradation rate could be described as follows:

$$r = \left(\frac{\mathrm{d}C_{\mathrm{NO_3^-\text{-}N}}}{\mathrm{d}t}\right)_{\mathrm{nitri}} + \left(\frac{\mathrm{d}C_{\mathrm{NO_3^-\text{-}N}}}{\mathrm{d}t}\right)_{\mathrm{denitri}} \qquad (1)$$

By considering the change in $NO_3^-$-N concentration with first-order kinetic equation (Metcalf and Eddy, 2004), the following expression is derived:

$$\left(\frac{\mathrm{d}C_{\mathrm{NO_3^-\text{-}N}}}{\mathrm{d}t}\right)_{\mathrm{nitri}} = KX \qquad (2)$$

Considering first-order kinetic equation with reference to denitrification yields, the same method as above is that:

$$\left(\frac{\mathrm{d}C_{\mathrm{NO_3^-\text{-}N}}}{\mathrm{d}t}\right)_{\mathrm{denitri}} = -K^{'}X \qquad (3)$$

Substituting equation (2) and (3) into (1), the expression is presented:

$$r = KX - K^{'}X = -K_{\mathrm{N}}X \qquad (4)$$

Taking aeration and sedimentation basin as an example (Figure 2), the mass balance for the generation of $NO_3^-$-N is as follows:

$$QC_{0,\mathrm{NO_3^-\text{-}N}} + rV = QC_{\mathrm{NO_3^-\text{-}N}} + \left(\frac{\mathrm{d}C_{\mathrm{NO_3^-\text{-}N}}}{\mathrm{d}t}\right) \qquad (5)$$

Substituting equation (4) into (5), the expression is presented:

$$QC_{0,\mathrm{NO_3^-\text{-}N}} - VK_{\mathrm{N}}X = QC_{\mathrm{NO_3^-\text{-}N}} + \left(\frac{\mathrm{d}C_{\mathrm{NO_3^-\text{-}N}}}{\mathrm{d}t}\right) \qquad (6)$$

Rearranging and integrating from 0 to $t_{\mathrm{I}}$, the result is as follows:

$$\frac{C_{\mathrm{II,NO_3^-\text{-}N}} - (C_{0,\mathrm{NO_3^-\text{-}N}} - K_{\mathrm{N}}XH)}{C_{\mathrm{I,NO_3^-\text{-}N}} - (C_{0,\mathrm{NO_3^-\text{-}N}} - K_{\mathrm{N}}XH)} = e^{-\frac{t_{\mathrm{I}}}{H}} \qquad (7)$$

According to the data in aeration and non-aeration optimized tests (except Mode 4 to 4 and Mode 4 to 5), $NO_3^-$-N degradation rate constant $K_N$ could be obtained by Equation (7) under aeration conditions (Table 1).

From Table 1, $NO_3^-$-N degradation rate constant $K_N$ is stable under aeration conditions. To simplify, the average value of $K_N$ is about 0.127 h. Rearrange Equation (7) and integrate from 0 to $t$, the result is as follows:

$$C_{\mathrm{NO_3^-\text{-}N}} = \left[C_{\mathrm{I,NO_3^-\text{-}N}} - (C_{0,\mathrm{NO_3^-\text{-}N}} - K_{\mathrm{N}}XH)\right]\mathrm{e}^{-\frac{t}{H}} + (C_{0,\mathrm{NO_3^-\text{-}N}} - K_{\mathrm{N}}XH) \qquad (8)$$

### Denitrification models under aeration conditions

In the anoxic phase, considering first-order kinetic

**Table 1.** Calculation of $NO_3^-$-N degradation rate constant $K_N$ under aeration conditions.

| $C_{0,NO3^--N}$ (mg/L) | $C_{I,NO3^--N}$ (mg/L) | $C_{II,NO3^--N}$ (mg/L) | $X$ (g/L) | $H$ (h) | $t_I$ (h) | $t_{II}$ (h) | $T$ (°C) | $K_N$ ($h^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| 10.2 | 4.3 | 4.7 | 5.840 | 5.25 | 1 | 1 | 23.4 | 0.117 |
| 11.6 | 7 | 7.4 | 7.506 | 5.25 | 2 | 1 | 26.3 | 0.104 |
| 11.2 | 6 | 6.6 | 6.230 | 5.25 | 2 | 2 | 27.8 | 0.119 |
| 10.5 | 3 | 4 | 6.457 | 5.25 | 2 | 3 | 27.9 | 0.125 |
| 11.4 | 4.1 | 5 | 6.878 | 5.25 | 2 | 4 | 28.9 | 0.121 |
| 11.1 | 7.5 | 7.7 | 6.049 | 5.25 | 3 | 1 | 25.2 | 0.125 |
| 9.8 | 5.3 | 5.6 | 5.098 | 7.51 | 3 | 2 | 28.9 | 0.142 |
| 10.4 | 4 | 4.7 | 6.066 | 5.25 | 3 | 3 | 24.9 | 0.130 |
| 11.1 | 3 | 4.9 | 5.123 | 4.47 | 3 | 4 | 25.6 | 0.144 |
| 10.2 | 8.9 | 9.4 | 5.744 | 5.25 | 4 | 1 | 25.8 | 0.117 |
| 11.5 | 5 | 5.4 | 4.944 | 6.24 | 4 | 2 | 25.5 | 0.179 |
| 12.1 | 3.4 | 6 | 7.138 | 4.47 | 4 | 3 | 28.7 | 0.102 |
| Average | — | — | — | — | — | — | — | 0.127 |

**$C_{0,NO3^-N}$,** Influent $NO_3^-$-N concentration (mg/L); **$C_{I,NO3^-N}$,** $NO_3^-$-N concentration in the reactor at the beginning of the aeration phase (mg/L); **$C_{II,NO3^-N}$,** $NO_3^-$-N concentration in the reactor at the beginning of the anoxic phase (mg/L); **X,** sludge concentration in the reactor (mg/L); **H,** hydraulic retention time (h); **$t_I$,** aeration time (h); **$t_{II}$,** anoxic time (h); **T,** water temperature (°C); **$K_N$,** K' – K, also $NO_3^-$-N degradation rate constant $K_N$ under aeration conditions ($h^{-1}$).

equation with reference to denitrification, the following equation is derived:

$$r = -K_D X \quad (9)$$

Substituting equation (9) into (5), the expression is presented:

$$QC_{0,NO_3^- \text{-N}} - VK_D X = QC_{NO_3^- \text{-N}} + V\left(\frac{dC_{NO_3^- \text{-N}}}{dt}\right) \quad (10)$$

Rearranging and integrating from 0 to $t_{II}$, the result is as follows:

$$C_{I,NO_3^- \text{-N}} = (C_{II,NO_3^- \text{-N}} + K_D XH - C_{0,NO_3^- \text{-N}})e^{-\frac{t_{II}}{H}} - (K_D XH - C_{0,NO_3^- \text{-N}}) \quad (11)$$

According to the data in aeration and non-aeration optimized tests (except Mode 4 to 4 and Mode 4 to 5), $NO_3^-$-N degradation rate constant $K_D$ could be obtained by equation (7) under aeration conditions (Table 2).

From Table 2, $NO_3^-$-N degradation rate constant $K_D$ is stable under non-aeration conditions. To simplify, $K_D$ could be regarded as a constant and its value should be the average 0.291 L/h. Rearranging and integrating from 0 to $t$, the result is as follows:

$$C_{NO_3^- \text{-N}} = (C_{II,NO_3^- \text{-N}} + K_D XH - C_{0,NO_3^- \text{-N}})e^{-\frac{t}{H}} - (K_D XH - C_{0,NO_3^- \text{-N}}) \quad (12)$$

Combining equation (7) and (12), the expression is presented:

$$C_{I,NO_3^- \text{-N}} = \frac{b}{1-ab}\left[(D - C_{0,NO_3^- \text{-N}})ab - (D+N)a + (C_{0,NO_3^- \text{-N}} + N)\right] + (D - C_{0,NO_3^- \text{-N}})(b-1) \quad (13)$$

$$C_{II,NO_3^- \text{-N}} = \frac{b}{1-ab}\left[(D - C_{0,NO_3^- \text{-N}})ab - (D+N)a + (C_{0,NO_3^- \text{-N}} + N)\right] \quad (14)$$

Meanwhile, there is $a = e^{-\frac{t_I}{H}}$, $b = e^{-\frac{t_{II}}{H}}$.

Substituting equation (13) into (8), the following expression for the concentration of $NO_3^-$-N in the aeration phase could be obtained:

$$C_{NO_3^- \text{-N}} = \left\{\frac{b}{1-ab}\left[(D - C_{0,NO_3^- \text{-N}})ab - (D+N)a + (C_{0,NO_3^- \text{-N}} + N)\right] + (D - C_{0,NO_3^- \text{-N}})(b-1) - (C_{0,NO_3^- \text{-N}} + N)\right\}e^{-\frac{t}{H}} + (C_{0,NO_3^- \text{-N}} + N) \quad (15)$$

Substituting equation (14) into (12), the following expression for the concentration of $NO_3^-$-N in the anoxic phase could be obtained:

$$C_{NO_3^- \text{-N}} = \left\{\frac{1}{1-ab}\left[(D - C_{0,NO_3^- \text{-N}})ab - (D+N)a + (C_{0,NO_3^- \text{-N}} + N)\right] + (D - C_{0,NO_3^- \text{-N}})\right\}e^{-\frac{t}{H}} - (D - C_{0,NO_3^- \text{-N}}) \quad (16)$$

Meanwhile, there is $N = -K_N XH$, $D = K_D XH$.

## KINETIC MODEL EVALUATION AND PREDICTION

Based on analysis and deduction from previous model deductions, kinetic model of $NO_3^-$-N degradation could be obtained as follows:
In aeration phase:

$$C_{NO_3^- \text{-N}} = \left\{\frac{b}{1-ab}\left[(D - C_{0,NO_3^- \text{-N}})ab - (D+N)a + (C_{0,NO_3^- \text{-N}} + N)\right] + (D - C_{0,NO_3^- \text{-N}})(b-1) - (C_{0,NO_3^- \text{-N}} + N)\right\}e^{-\frac{t}{H}} + (C_{0,NO_3^- \text{-N}} + N) \quad (17)$$

**Table 2.** Calculation of $NO_3^-$-N denitrification rate constant $K_D$ under non-aeration conditions.

| $C_{0,NO3^--N}$ (mg/L) | $C_{I,NO3^--N}$ (mg/L) | $C_{II,NO3^--N}$ (mg/L) | $X$ (g/L) | $H$ (h) | $t_I$ (h) | $t_{II}$ (h) | $T$ (°C) | $K_D$ ($h^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| 10.2 | 5.1 | 4.3 | 5.840 | 5.25 | 1 | 1 | 23.4 | 0.316 |
| 11.6 | 8.6 | 7.0 | 7.506 | 5.25 | 2 | 1 | 26.3 | 0.310 |
| 11.2 | 6.6 | 5.0 | 6.230 | 5.25 | 2 | 2 | 27.8 | 0.294 |
| 10.5 | 4.0 | 2.5 | 6.457 | 5.25 | 2 | 3 | 27.9 | 0.293 |
| 11.4 | 5.0 | 2.3 | 6.878 | 5.25 | 2 | 4 | 28.9 | 0.317 |
| 11.1 | 7.7 | 7.2 | 6.049 | 5.25 | 3 | 1 | 25.2 | 0.249 |
| 9.8 | 6.0 | 5.3 | 5.098 | 7.51 | 3 | 2 | 28.9 | 0.278 |
| 10.4 | 6.0 | 4.0 | 6.066 | 5.25 | 3 | 3 | 24.9 | 0.283 |
| 11.1 | 6.0 | 3.0 | 5.123 | 4.47 | 3 | 4 | 25.6 | 0.315 |
| 10.2 | 9.4 | 8.5 | 5.744 | 5.25 | 4 | 1 | 25.8 | 0.293 |
| 11.5 | 5.4 | 4.8 | 4.944 | 6.24 | 4 | 2 | 25.5 | 0.268 |
| 12.1 | 6.0 | 3.1 | 7.138 | 4.47 | 4 | 3 | 28.7 | 0.278 |
| Average | — | — | — | — | — | — | — | 0.291 |

**Table 3.** The comparison of prediction on real results of $NO_3^-$-N degradation.

| Mode | $t$ | $NO_3$-N in effluent (mg/L) | Simulation (mg/L) | Absolute error (mg/L) | Relative error (%) |
|---|---|---|---|---|---|
| 4-4 | 0:00 | 4.5 | 3.6 | 0.9 | 19.92 |
| | 1:00 | 4.8 | 4.3 | 0.5 | 11.05 |
| | 2:00 | 5.1 | 4.8 | 0.3 | 5.50 |
| | 3:00 | 5.8 | 5.3 | 0.5 | 9.06 |
| | 4:00 | 6.1 | 5.7 | 0.4 | 7.37 |
| | 4:30 | 5.4 | 5.3 | 0.1 | 1.82 |
| | 5:00 | 4.8 | 5.0 | -0.2 | -3.85 |
| | 5:30 | 4.1 | 4.7 | -0.6 | -14.5 |
| | 6:00 | 3.9 | 4.4 | -0.5 | -13.7 |
| | 6:30 | 3.8 | 4.2 | -0.4 | -10.4 |
| | 7:00 | 3.6 | 4.0 | -0.4 | -10.5 |
| | 7:30 | 3.4 | 3.8 | -0.4 | -11.3 |
| | 8:00 | 3.2 | 3.6 | -0.4 | -12.6 |
| 4-5 | 0:00 | 8.6 | 8.0 | 0.6 | 7.06 |
| | 1:00 | 8.0 | 7.4 | 0.6 | 7.46 |
| | 2:00 | 7.9 | 6.9 | 1.0 | 12.26 |
| | 3:00 | 7.6 | 6.6 | 1.0 | 13.76 |
| | 4:00 | 7.4 | 6.3 | 1.1 | 15.51 |
| | 5:00 | 7.0 | 6.0 | 1.0 | 14.12 |
| | 6:00 | 7.2 | 6.7 | 0.5 | 7.18 |
| | 7:00 | 7.5 | 7.2 | 0.3 | 3.73 |
| | 8:00 | 8.0 | 7.6 | 0.4 | 4.38 |
| | 9:00 | 8.5 | 8.0 | 0.5 | 5.97 |

In anoxic phase:

$$C_{NO_3^--N} = \left\{ \frac{1}{1-ab} \left[ (D - C_{0,NO_3^--N})ab - (D+N)a + (C_{0,NO_3^--N} + N) \right] + (D - C_{0,NO_3^--N}) \right\} e^{-\frac{t}{H}} - (D - C_{0,NO_3^--N}) \tag{18}$$

Based on the data in aeration and non-aeration optimized tests (except Mode 4 to 4 and Mode 4 to 5), and combining equation (17) and (18), the model could predict the concentration of $NO_3^-$-N in effluent. The simulation results are shown in Table 3.

As in Table 3, the results predicted by this model were significantly correspondent with those of real effluents; and the errors were only around 10%. The results suggest that the prediction of kinetic model of $NO_3^-$-N degradation could well meet the needs of operation and optimization.

## Conclusion

The mechanic models describing organic degradation for the continuous-flow-intermittent-aeration process of the WWTP were developed. The models are appropriate to describing organic degradation in aerobic and anoxic processes, respectively. The models have the advantage based on the unsteady-state presumption. Kinetic constants were determined and found to be in good agreement with other research data. Moreover, the model predictions of COD conversions are coincident with the practical trends of the effluents, which the error percentages are less than 20%. The operation condition and the operation parameters in a WWTP unit could be adjusted according to the required effluent quality by using the models. Therefore, the models would provide a useful tool by which the designers and operators could investigate the performance of the continuous-flow-intermittent-aeration process under a variety of conditions. The study could provide some valuable reference and recommendation on the design and operation of the municipal WWTP for BNR.

## *Abbreviations*:

**Q,** Flow rate (L/h); **$C_{COD}$,** chemical oxygen demand (mg/L); **$C_{0,COD}$,** chemical oxygen demand of influent (mg/L); **$C_{0,NO3^{-}N}$,** influent $NO_3^-$-N concentration (mg/l); **$C_{NO3^{-}N}$,** $NO_3^-$-N concentration in the reactor (mg/l); **$C_{I,NO3^{-}N}$,** $NO_3^-$-N concentration in the reactor at the beginning of the aeration phase (mg/L); **$C_{II,NO3^{-}N}$,** $NO_3^-$-N concentration in the reactor at the beginning of the anoxic phase (mg/l); **V,** reactor volume (L); **K,** nitrification constant ($h^{-1}$); **K,** denitrification constant ($h^{-1}$); **$K_N$,** $K' - K$, also $NO_3^-$-N degradation rate constant $K_N$ under aeration conditions ($h^{-1}$); **$K_D$,** $NO_3^-$-N denitrification rate constant under non-aeration conditions ($h^{-1}$); **R,** recycle ratio; **X,** sludge concentration in the reactor (mg/l); **$X_r$,** return activated sludge concentration (mg/L); **$X_e$**, excess sludge concentration in settler (mg/l); **H,** hydraulic retention time (h); **t,** reaction time (h); **$t_I$,** aeration time (h); **$t_{II}$,** anoxic time (h); **T,** water temperature (°C).

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