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Use of nitrate-nitrogen concentration for controlling source, cellular matter production and oxygen consumption for sewage treatment

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Abstract−Carbon saving, oxygen consumption reduction and cellular matter production reduction of Modified University of Cape Town (MUCT) process under different nitrate-nitrogen concentration in the main anoxic section was studied. This was investigated by material balance analysis, biochemical reaction process and its metrology of ordinary heterotrophic bacteria, denitrifying bacteria, nitrifying bacteria and phosphorus-accumulating bacteria. The flow and distribution of carbon, nitrogen, and oxygen in the MUCT, and the influence of the regulation of the $c(NO_3)$ on the carbon source, cellular matter production, and oxygen consumption of the process were explained in detail. In the programmable logic controller (PLC) automatic control system, the circulating flow rate of nitrate was set as the controlled variable. Adopting the feedback control structure, $c(NO_3)$ was altered at 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5 and 4.0 $mg \cdot L^{-1}$, respectively. In this experimental study, the quality of influent and other operation design parameters remained unchanged. The results showed that the effluent quality was at its best when $c(NO_3)$ was controlled at 2.0-4.0 mg/L. Again, the distribution of chemical oxygen demand (COD) in the anaerobic section was between phosphorus-accumulating bacteria, common heterotrophic bacteria and denitrifying bacteria, and the distribution was related to $c(NO_3)$. Due to this phenomenon, the distribution of nitrate-nitrogen between denitrifying bacteria and denitrifying phosphorus-accumulating bacteria, and poly-hydroxy alkanoates (PHA) between denitrifying phosphorus-accumulating bacteria and aerobic phosphorus-accumulating bacteria was changed. Carbon source of 110.0 kg acetic acid/10^3 m^3 sewage was saved, while the cell material output was reduced by 37.5%, and the oxygen consumption of 51.1 kg O_2/10^3 m^3 sewage was reduced. In the MUCT process, the regulation of $c(NO_3)$ enhanced the denitrifying phosphorus uptake performance of the main anoxic section and obtained good carbon source savings, reduction of cellular matter production, and reduction of oxygen consumption.

Keywords: Denitrifying Phosphorus Uptake, Biochemical Reaction Process, Carbon Saving, Cellular Matter Production, Oxygen Consumption

INTRODUCTION

River basin pollution source control is the most important treatment strategy for water pollution control, among which the treatment of urban sewage, one of the main pollution sources, is key, especially nitrogen and phosphorus (main nutrients causing water pollution), which are the components that must be controlled. However, the process of biological nitrogen and phosphorus removal in wastewater is relatively complex, as it involves the growth and reproduction of heterotrophic bacteria, denitrifying bacteria, nitrifying bacteria, phosphorus-accumulating bacteria and other microorganisms [1,2]. Due to the difference in the living environment of each strain, there are many factors that affect the removal of nitrogen and phosphorus, especially the competition of carbon source, nitrate-nitrogen in anaerobic zone and sludge age [3]. Among all kinds of biological nutrient removal (BNR), the MUCT process is widely used. It has been proved by many years of operation that the MUCT process not only eliminates the effect of nitrate-nitrogen on the phosphorus release process but also denitrifies and absorbs phosphorus in the anoxic zone. The results of batch tests also proved that there are denitrifying phosphorus-accumulating bacteria in the activated sludge [4-6].

The mechanism of denitrifying phosphorus is similar to that of traditional biological phosphorus removal. The phosphorus release process of the anaerobic section is also consistent with traditional processes. In the anoxic section, denitrifying phosphorus-accumulating bacteria degrade PHA by using nitrate as the electron acceptor. While the energy adenosine triphophate (ATP) produced during the process is partly supplied to the synthesis of cells (glycogen synthesis), life-sustaining activities and partly used for excessive intake of inorganic phosphate and stored in the form of polyphosphate [7-19]. Therefore, when denitrifying phosphorus is present, the carbon source in the sewage can be "one-carbon dual-use," which reduces the carbon source demand of the simultaneous nitrogen and phosphorus removal system. It fundamentally solves the contradiction and shortcomings of carbon source competition in the

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process of nitrogen removal and phosphorus removal in traditional processes, which is crucial for sewage treatment with low carbon source content. At the same time, the results showed that denitrification and phosphorus removal can take place in the wastewater treatment process, but the contribution to phosphorus removal in wastewater treatment plant is quite different. The contribution rate is affected by many factors such as water quality and operation parameters [6].

In recent years, the statistical analytical results of the characteristics of the inflow and outflow water quality of sewage plants show that the concentration of COD and biochemical oxygen demand (BOD_5) in the influent has decreased year by year, while the concentration of total Kjeldahl nitrogen (TKN) and total phosphorus (TP) has increased year by year. This has resulted in the increase of the frequency of BOD_5/TKN less than 4 and BOD_5/TP less than 20 in the influent, and the problem of insufficient carbon sources for denitrification and phosphorus release became more prominent. Also, the daily, weekly and monthly changes of COD, total nitrogen (TN), TP and NH_4^+-N in various water quality indexes are large, and the law is not obvious, which results in the insensitivity of the operation parameters of the sewage plant to the fluctuation of water quality [20-26]. Therefore, in order to respond to the change of water quality in time and maintain the high contribution rate of denitrifying phosphorus absorption, it is very important to develop control parameters and establish a process control system. Some researchers have determined that the main factor affecting the anoxic phosphorus absorption performance in the MUCT process is the concentration of nitrate-nitrogen in the second anoxic stage. Thus, when the nitrate load in this stage is large enough or exceeds the denitrification capacity of ordinary heterotrophic bacteria, it will promote the accumulation and growth of denitrifying polyphosphate-accumulating organisms (DPAOs) [27,28].

Therefore, in the preliminary research work, researchers studied the feasibility of the mass concentration of nitrate-nitrogen in the main anoxic section as the operating control parameter of the MUCT process. From the perspective of PHA and TP metabolism, the mechanism of $c(NO_3)$ as a control parameter to enhance the function of denitrifying phosphorus-accumulating bacteria was revealed [29-34]. To evaluate the effect of resource-saving and energy consumption reduction when $c(NO_3)$ was used as operation control parameter, based on the material balance principle, we analyzed the reaction amount of each material in the MUCT process under different $c(NO_3)$, combined with the biochemical reaction process and metrology of ordinary heterotrophic bacteria, denitrifying bacteria, nitrifying bacteria, and phosphate-accumulating bacteria. The flow and distribution of carbon, nitrogen, and oxygen were tracked to explain the reducing effects of denitrifying phosphorus uptake process of phosphorus-accumulating bacteria under different $c(NO_3)$ conditions on carbon source, cellular matter production, and oxygen consumption in the process.

EXPERIMENTAL MATERIALS AND METHODS

1. Sewage Water Quality Characteristics

The wastewater used for MUCT process in this study was artificially simulated wastewater in the laboratory. The pollutant composition and its index mass concentration of the wastewater were according to the effluent quality of the primary treatment system

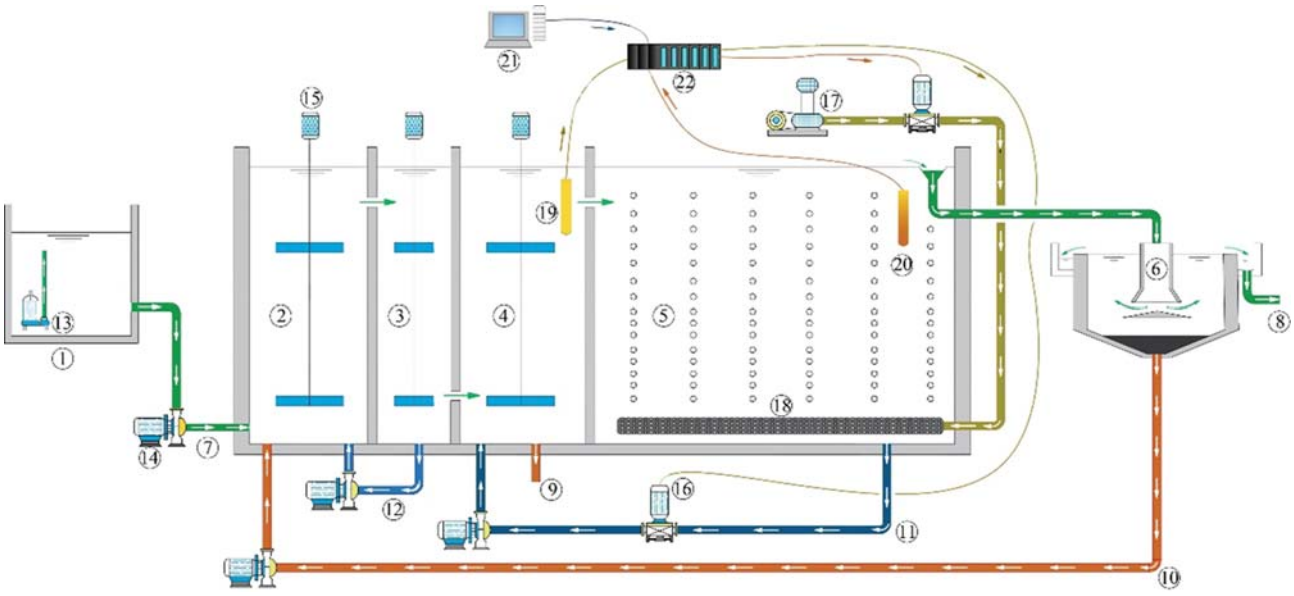

Fig. 1. Flow diagram of the test system.

1. Sewage tank
2. Anaerobic section
3. Pre-anoxic section
4. Main anoxic section
5. Aerobic section
6. Clarifier
7. Influent water
8. Effluent water
9. Excess sludge
10. Sludge reflux
11. Aerobic/main anoxic nitrifying fluid circulation
12. Pre-anoxic/anaerobic mixture circulation
13. Submersible pump
14. Peristaltic pump
15. Electric magnetic stirrer
16. Electric control valve
17. Air compressor
18. Air diffuser
19. Nitrate-nitrogen on-line analyzer
20. DO online tester
21. Computer
22. Programmable logic controller

Table 1. Sewage flow and design operating parameters

Item	Value	Item	Value
Sewage flow rate	10 $L \cdot h^{-1}$	Sludge reflux ratio	0.5
COD sludge load	(0.25±0.07) $kg \cdot (kg \cdot d)^{-1}$	Mixed reflux ratio	1
Aerobic section TN load	(0.049±0.006) $kg \cdot (kg \cdot d)^{-1}$	Sludge age	12 d
Anaerobic section TP load	(0.006±0.001) $kg \cdot (kg \cdot d)^{-1}$	Aerobic DO concentration	2 $mg \cdot L^{-1}$
Total hydraulic retention time	9 h	Clarifier surface load	0.14 $m^3 \cdot (m^2 \cdot h)^{-1}$

of China municipal sewage treatment plant [20,21,35-37]. The carbon source was whole milk powder (about 30% of the total COD of sewage) at a dosage of 50 $mg \cdot L^{-1}$, and the other carbon source was brewery wastewater (about 70% of the total COD of sewage) at a dosage of 0.5 $mg \cdot L^{-1}$. The source of nitrogen was ammonium chloride at a dosage of 50 $mg \cdot L^{-1}$ while the source of phosphorus was potassium dihydrogen phosphate at a dosage of 3.1 $mg \cdot L^{-1}$. Alkalinity was provided by sodium bicarbonate at a dosage of 0.4 $mg \cdot L^{-1}$. To meet the metabolic requirements of the phosphorus absorption process of microorganisms, 10 $mg \cdot L^{-1}$ of calcium chloride and 50 $mg \cdot L^{-1}$ of magnesium sulfate were added. Again, a micronutrient solution, with concentration 0.6 $mL \cdot L^{-1}$, was added to enhance the growth and reproduction of activated sludge, which consisted of eight (8) chemical components including ferric chloride, boric acid, cobalt chloride heptahydrate, copper sulfate pentahydrate, potassium iodide, cobalt chloride tetrahydrate, sodium molybdate dihydrate and zinc sulfate heptahydrate. Their mass concentrations were 0.9 $g \cdot L^{-1}$, 0.15 $g \cdot L^{-1}$, 0.15 $g \cdot L^{-1}$, 0.03 $g \cdot L^{-1}$, 0.18 $g \cdot L^{-1}$, 0.06 $g \cdot L^{-1}$, 0.06 $g \cdot L^{-1}$ and 0.12 $g \cdot L^{-1}$, respectively.

2. Main Operating Parameters of MUCT System

The MUCT test system as shown in Fig. 1 included a sewage tank, MUCT reactor (made of plexiglass), clarifier and automatic control system. The effective volume of the sewage tank was 252L (L×B×H=80 cm×70 cm×45cm, 5 cm high), the submersible pump was installed to keep the water quality uniform. The MUCT reactor consisted of four sections:

a. Anaerobic section (ANS), with an effective volume of 18 L (L×B×H=30 cm×15 cm×40 cm, super high 5 cm),

b. Pre-anoxic section (PAnS), effective volume is 9 L (L×B×H= 15 cm×15 cm×40 cm, super high 5 cm),

c. Main anoxic section (MAnS), effective volume is 18 L (L×B× H=30 cm×15 cm×40 cm, super high 5 cm)

d. Aerobic section (AS), the effective volume is 45 L (L×B×H= 75 cm×15 cm×40 cm, super high 5 cm)

The reactor was designed as a double corridor, and each corridor was divided into five compartments by a partition making ten compartments. A stirrer was installed in the sewage tank, anaerobic section, pre-anoxic section, and main anoxic section. An air diffuser was installed in the aerobic section, to ensure uniform mixing of sewage/mixed liquid. The mixture in the reactor flowed into a clarifier for solid-liquid separation. The clarifier had a diameter of 50 cm and had a scraper with a rotation speed of 5 $rpm \cdot h^{-1}$.

To meet the research needs, the MUCT system was equipped with an automatic control system consisting of a nitrate-nitrogen online detector (WTW Trescon Uno 211), dissolved oxygen (DO) online detector (WTW dissolution Oxi 296, Germany), the PLC (Siemens programmable logic controller CPU314C-2PTP), computer and electric control valves.

3. Test Plan

The operation parameters of the MUCT system, such as hydraulic retention time, sludge load and sludge age were in accordance with ATV-DVWK Code (Germany) [38], Design of Municipal Wastewater Treatment Plants (Volume 2: Liquid Treatment Processes, USA) [39], Biological Phosphorus Removal Manual for Design and Operation (the Netherlands) and Outdoor Drainage Design Code (GB50014)" (2016 version, China) [40]. Flow rate and design parameters are shown in Table 1.

During the start-up, the sludge from the secondary clarifier of the North Suburb Sewage Treatment Plant, Changchun, was added to the system as an inoculated sludge, debugged and operated. The quality concentration of each water quality index was measured daily. After 25 days, the effluent concentration of COD, TP, TN, NH_4^+-N and NO_3-N tended to be stable, and the system had the function of degrading organic matter, denitrification and phosphorus removal. The biomass remained unchanged, which indicated that the system had been started successfully and could be tested.

During the test, $c(NO_3)$ was controlled by an automatic control system. The control system adopted a feedback control structure using $c(NO_3)$ as the control parameter, the circulating flow in the nitrifying liquid as the control variable and the actuator was an electric regulating valve. The SAMA diagram and logic control diagram of the automatic control system are shown in Fig. 2. The control process procedure was as follows:

a. The nitrate-nitrogen concentration on-line measuring instrument installed in the main anoxic section detects the nitrate-nitrogen concentration (the output signal is 4-20 mA analogue signal), and then

b. transmits it to the data acquisition card of the PLC system, which

c. converts it into a digital signal by A/D converter, and

d. compares with the setting value of the PID regulator,

e. calculates the deviation, carries on the proportion and comparison.

f. After the control of integral and differential calculation, the result is given and converted into an analogue signal (4-20 mA) by D/A converter. As the output value, the electric control valve of the inner circulation of nitrate is adjusted to realize the purpose of regulating $c(NO_3)$.

The experiment had eight sections. The set values of $c(NO_3)$ in each section were 0.5 $mg \cdot L^{-1}$, 1.0 $mg \cdot L^{-1}$, 1.5 $mg \cdot L^{-1}$, 2.0 $mg \cdot L^{-1}$, 2.5 $mg \cdot L^{-1}$, 3.0 $mg \cdot L^{-1}$, 3.5 $mg \cdot L^{-1}$ and 4.0 $mg \cdot L^{-1}$, respectively, with errors less than 0.8 $mg \cdot L^{-1}$. During the experiment, the operating param-

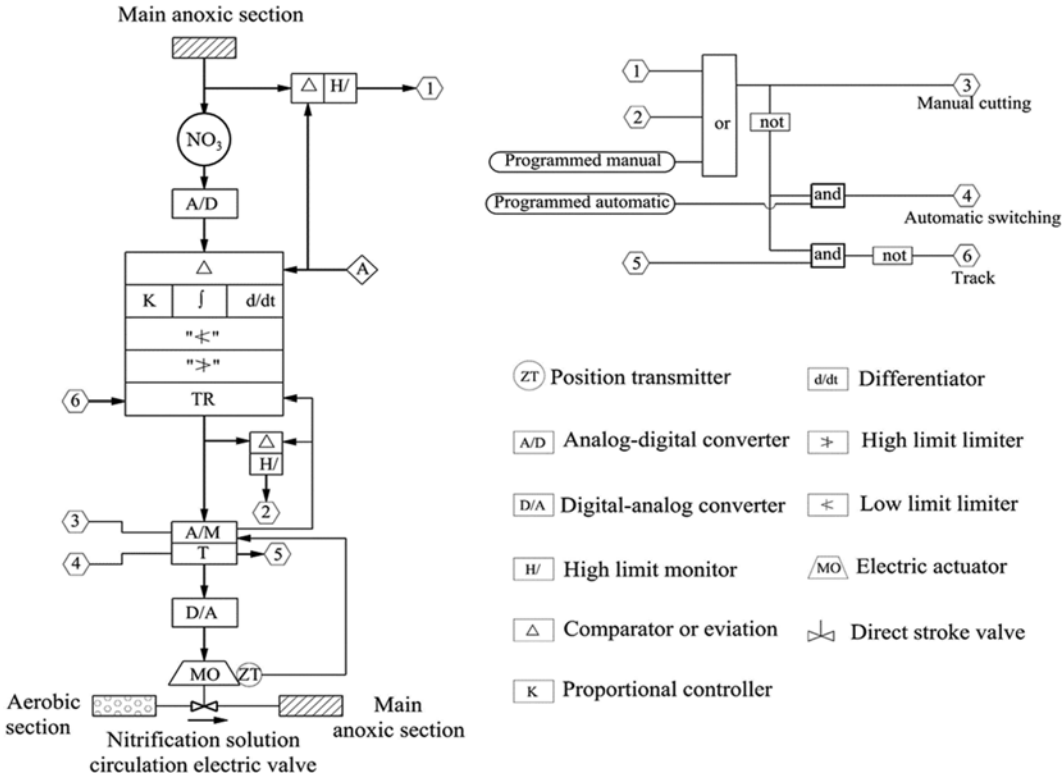

Fig. 2. SAMA diagram and logic control diagram.

eters remained unchanged except the internal circulation flow rate of nitrate. Two to three sludge retention times (SRT) were operated in each section.

4. Detection Indexes and Methods

During the test, the mixture was taken out from the anaerobic section, pre-anoxic section, main anoxic section and the aerobic section of the MUCT reactor and centrifuged at 4,500 rpm for 7 min. The supernatant was taken to measure the concentration of COD, TP, TN, NH_4^+-N and NO_3^-- N; the sludge after centrifugation was taken to measure the content of PHA.

The concentration of each water quality index was determined according to the Standard Methods for the Examination of Water and Wastewater (22nd Edition) [41] issued by the American Public Health Association. COD was determined using closed reflux (colorimetric method), TP by ascorbic acid method, TN by persulfate method and NH_4^+-N by titrimetric method and NO_3^--N was determined using ion chromatography. Ion chromatographer (Dionex ICS-1000, Dionex-The Netherlands) was equipped with AS14A analytical column and AG14A protective column. The eluent was 8 mmol $NaCO_3$+1 mmol $NaHCO_3$ solution (3.39 g $NaCO_3$+ 0.336 g $NaHCO_3$ in 4 ml mill-q water), and the flow rate was 0.7 mL/min.

Gas chromatography (Agilent 7820a) was used to determine PHA (including Poly-β-hydroxybutyrate (PHB) and Poly-β-hydroxyvalerate (PHV)) [42-45]. The centrifuge concentrated sludge was placed in a refrigerator at −70 °C and frozen for more than 24 h. The frozen samples were transferred to the freeze dryer and dried. The dried sludge powder was weighed and placed in the cracking bottle. Quantitative chloroform, sulfuric acid-methanol and benzoic acid-methanol solutions were added successively. After full oscillation, the sludge powder was cracked at 102 °C for several hours. After cooling, quantitative distilled water was added and centrifuged after full oscillation. The organic phase in the lower layer after centrifugation was absorbed into a chromatographic analysis bottle for analysis.

WTW-pH/OXI340 portable on-line tester was used for the determination of DO concentration in each section (except aerobic section). As the water sample was determined after centrifugation by centrifuge, the quality concentration of each water quality index of the aerobic section was taken as the quality concentration of the system effluent. The data used for the analysis of the test results were taken from the index detection concentration of 20 days in the stable operation period of each stage.

5. Material Balance Analysis

To determine the reaction amounts of COD, PHA, DO, NO_3^--N, TN, NH_4^+-N in different sections under different c(NO_3) conditions, it was necessary to use each section as the system boundary and use the substance detection concentration to calculate the material balance. Statistical analysis of the calculation results was expressed as mean±error bars. In the calculation process, it was assumed that the material accumulation was zero when the system ran steadily, and the following equations were used;

Anaerobic section:

$$\Delta S_1 = \left(\frac{dS}{dt}\right)_1 \cdot V_1 = (1+r)\cdot Q\cdot S_1 - Q\cdot S_0 - r\cdot Q\cdot S_2 \quad (1)$$

Pre-anoxic section:

$$\Delta S_2 = \left(\frac{dS}{dt}\right)_2 \cdot V_2 = (1+r+s)\cdot Q\cdot S_2 - s\cdot Q\cdot S_5 - (1+r)\cdot Q\cdot S_1 \quad (2)$$

Main anoxic section:

$$\Delta S_3 = \left(\frac{dS}{dt}\right)_3 \cdot V_3 = (1+s)\cdot Q\cdot S_2 + a\cdot Q\cdot S_4 - (1+a+s)\cdot Q\cdot S_3 \quad (3)$$

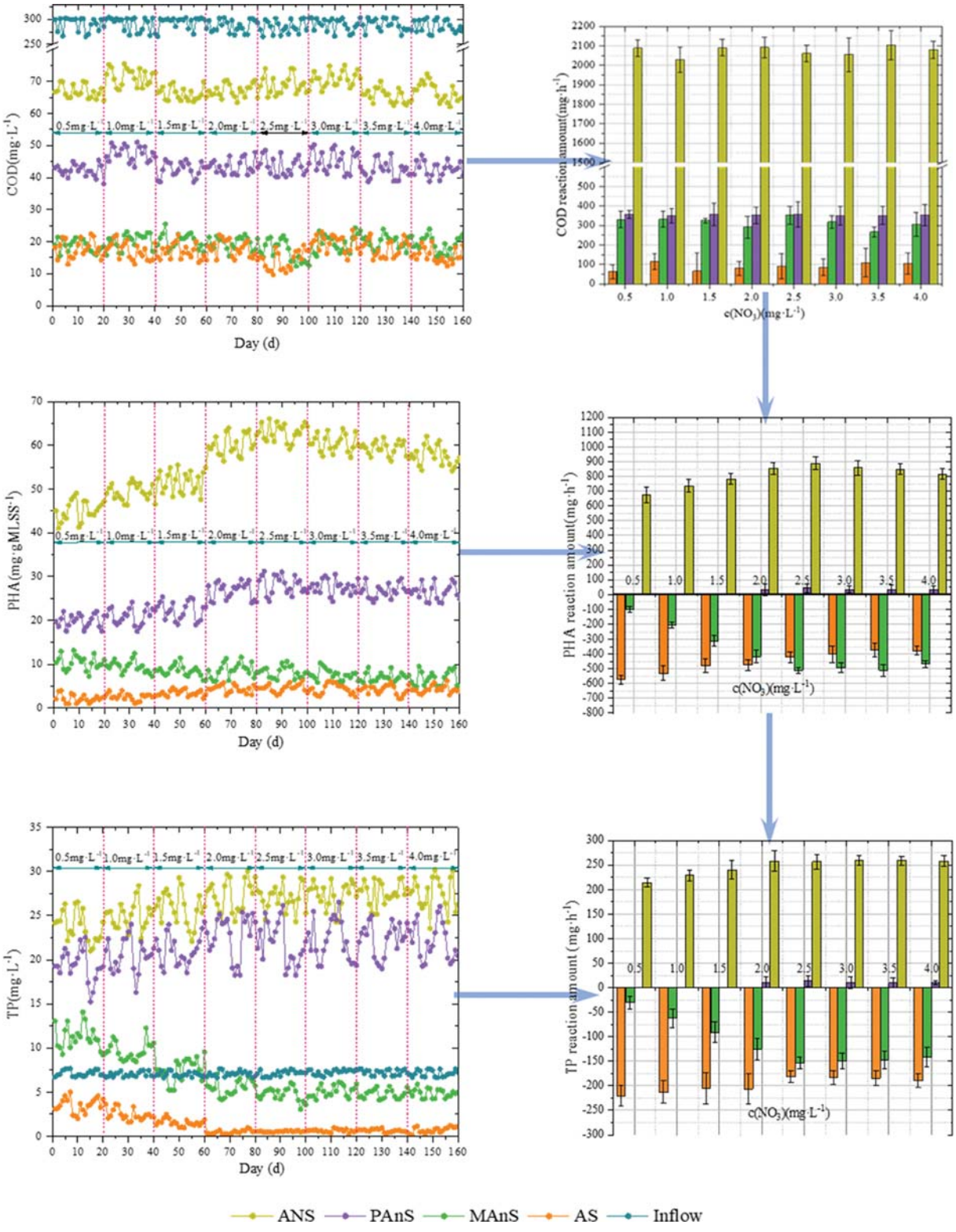

Fig. 3. Concentration variation of COD, PHA and TP, and reaction amount of each section during the experiment (Left part: concentration change rule of COD, PHA and TP; right part: reaction amount of COD, PHA and TP).

Aerobic section:

$$\Delta S_4 = \left(\frac{dS}{dt}\right)_4 \cdot V_4 = (1+a+s)\cdot Q\cdot(S_3 - S_4) \quad (4)$$

where the subscripts 0, 1, 2, 3, 4 and 5 represent the influent, anaerobic, pre-anoxic, main anoxic, aerobic and effluent, respectively;

ΔS represents the reaction amount of COD, DO and other substances, $mg\cdot h^{-1}$;

Q represents the inflow flow rate, $L\cdot h^{-1}$,

V represents the effective volume of the reactor, L,

S represents the concentration of substances, $mg\cdot L^{-1}$,

s represents sludge reflux ratio,

a indicates the ratio of aerobic/main anoxic nitrifying liquid circulation,

r indicates the ratio of pre-anoxic/anaerobic mixture circulation.

RESULTS

1. Index Concentration and Total Reaction amount of Each Section

Fig. 3 and Fig. 4 show the mass concentration variation of COD, N, P, DO and other indexes at each reaction section of the system during the experiment. In Figs. 3 and 4 when the influent carbon and nitrogen were relatively low, with the increase of the control value c(NO_3), the effluent TN, TP, nitrate-nitrogen concentrations decreased first and then remained unchanged. That is, when c(NO_3) was increased to 2.0 $mg\cdot L^{-1}$, the TN, TP, and nitrate-nitrogen mass concentrations of the process effluent were kept low. Based on the concentration measured values of COD, PHA content, total nitrogen, nitrate-nitrogen, ammonia nitrogen, phosphorus and DO, the reaction amounts of each material in each section were calculated by Eqs. (1)-(4). The results are shown in Fig. 3 and Fig. 4.

Based on the principles of biological phosphorus removal and denitrifying phosphorus absorption, combined with Fig. 3, it can be seen that during the experiment, COD in the anaerobic section of MUCT process was converted into volatile fatty acid, which was absorbed by phosphorus-accumulating bacteria and converted into PHA for storage. The required energy came from the hydrolyzing and releasing phosphorus process. However, in the aerobic or anoxic stage, PHA was degraded and most of the energy generated was stored in the form of phosphorus accumulation, during which the required phosphorus came from the sewage. Therefore,

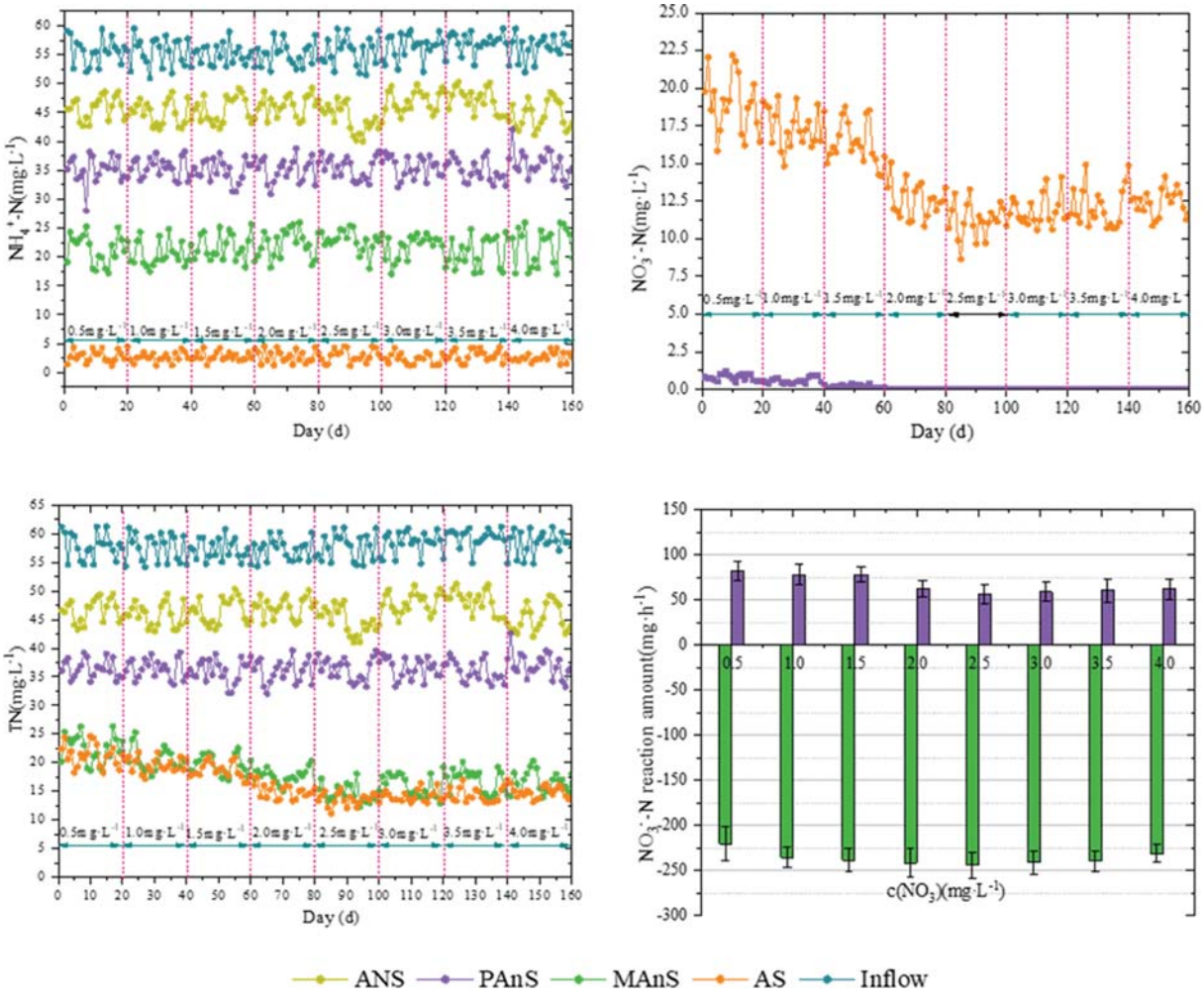

Fig. 4. Variation of ammonia nitrogen, total nitrogen and nitrate-nitrogen concentration and nitrate-nitrogen reaction amount. Note: Negative values of nitrate-nitrogen indicate it was consumed.

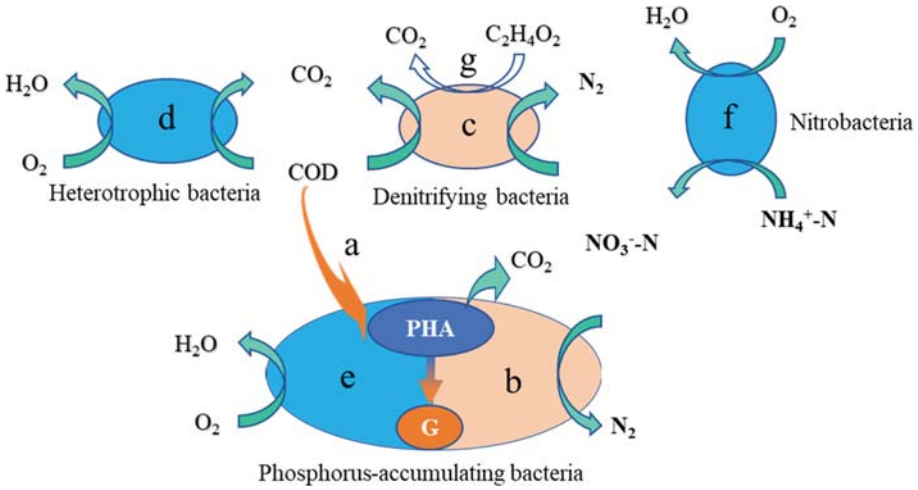

Fig. 5. Distribution and flow chart of carbon, nitrogen, and oxygen in MUCT reactor.

the substance concentration and reaction amount among COD, PHA and TP affected each other and changed regularly.

As can be seen from Fig. 3 and Fig. 4, c(NO_3) had little effect on COD removal at each section, among which the anaerobic section reaction amount was maintained between 2,030 and 2,100 mg·h^{-1}, the pre-anoxic reaction section was maintained at about 350 mg·h^{-1}, the main anoxic section was maintained between 270 and 350 mg·h^{-1}, and the aerobic section was maintained between 60 and 120 mg·h^{-1}. With the increase of control value c(NO_3), the amount of PHA synthesis in anaerobic section, TP release in pre-anoxic section, PHA consumption and TP absorption in main anoxic section increased and reached a higher value when c(NO_3) increased to 2.0-4.0 mg·L^{-1} and remained stable. In a similar condition of increasing the control value of c(NO_3), TN removal increased. When c(NO_3) increased to 2.0-4.0 mg·L^{-1}, TN removal changed slightly and was maintained at 400.40-413.69 mg·h^{-1}. Also from Fig. 3, due to the regulation of c(NO_3) during the experiment, the concentration of COD and ammonia nitrogen in effluent changed slightly, which met the first-class A emission standard (GB18918-2002).

It can, therefore, be concluded that when c(NO_3) is regulated at 2.0-4.0 mg·L^{-1}, the function of denitrifying phosphorus-accumulating bacteria can be strengthened, and better denitrifying phosphorus absorbing effect can be obtained by MUCT process, thus improving the effect of nitrogen and phosphorus removal. However, the removal efficiency of nitrogen and phosphorus in the system was not satisfactory, which was mainly due to the low COD concentration in the influent.

2. Biochemical Reactions and Material Flow

2-1. Tracking of Carbon and Nitrogen Flow and Distribution in the Main Anoxic Section

The MUCT process is an asynchronous denitrification and phosphorus removal process made up of four reaction sections. A variety of microorganisms, such as ordinary heterotrophic bacteria, denitrifying bacteria, phosphorus-accumulating bacteria, and nitrifying bacteria, coexisted in it. There was inevitably a competitive relationship among the microorganisms. In addition, this competition affected the distribution and flow of carbon, nitrogen, and oxygen. The distribution and flow of COD, PHA, nitrate-nitrogen and oxygen between microorganisms are shown in Fig. 5. The character shows the biochemical reaction processes, including;

a. Absorption of COD and storage of PHA for phosphorus-accumulating bacteria.

b. Consumption of PHA by phosphorus-accumulating bacteria with nitrate-nitrogen as the electron acceptor.

c. Nitrate-nitrogen conversion by denitrifying bacteria using COD as a carbon source.

d. Ordinary heterotrophic bacteria degrading COD with oxygen as the electron acceptor.

e. Consumption of PHA by phosphorus-accumulating bacteria using oxygen as the electron acceptor.

f. Conversion of ammonia nitrogen into nitrate-nitrogen by nitrifying bacteria.

g. Nitrate-nitrogen conversion by denitrifying bacteria using acetic acid as a carbon source.

The COD in sewage can be expressed by the empirical formula $C_{18}H_{19}O_9N$ [46], and the empirical formula of cell matter is $C_5H_7NO_2$. Assuming that $C_{18}H_{19}O_9N$ could be oxidized to carbon dioxide, it may result in the following expression, Eq. (5) [46]. The microbiological oxygen consumption in Eq. (5) was calculated at 1.42 g COD/g $C_{18}H_{19}O_9N$.

$$C_{18}H_{19}O_9N+17.5O_2+H^+ \rightarrow 18CO_2+8H_2O+NH_4^+ \quad (5)$$

The biochemical reaction process, its formula and stoichiometric coefficient in the oxidation of $C_{18}H_{19}O_9N$ and MUCT process are shown in Table 2.

Material balance analysis and biochemical reaction metrology and formulas (6) and (7) were used to calculate the amount of COD consumed by ordinary heterotrophic bacteria growing and that transformed by denitrifying bacteria under different c(NO_3) conditions [47,48]. The calculation results are shown in Fig. 6.

Amount of COD converted by ordinary heterotrophic bacteria,

$$\Delta COD_{MAnS,H}=2.19\times\Delta DO_{MAnS} \quad (6)$$

Amount of COD converted by denitrifying bacteria,

Table 2. Chemical reaction equations and stoichiometry coefficients

Reaction process	Electron acceptor	Carbon source	The formula of biochemical reaction process	Stoichiometric coefficient		
				Electronic donor-acceptor	Oxygen consumption	Cellular matter production
Aerobic COD degradation by heterotrophic bacteria	O_2	$C_{18}H_{19}O_9N$	$C_{18}H_{19}O_9N+0.74NH_3+8.0O_2 \rightarrow 1.74C_5H_7NO_2+9.3CO_2+4.52H_2O$	2.19 gCOD/gO_2	0.47 g O_2/gCOD	0.35 $gC_5H_7O_2N$/gCOD
Nitrate-nitrogen conversion by denitrifying bacteria	NO_3	$C_{18}H_{19}O_9N$	$0.61C_{18}H_{19}O_9N+4.54\ NO_3^-\text{-}N+0.39NH_4^+\text{-}N+4.15H^+ \rightarrow C_5H_7O_2N+2.27N_2+5.98CO_2+5.15H_2O$	0.18 gNO_3/gCOD	-	1.78 $gC_5H_7O_2N$/gNO_3^--N 0.33 $gC_5H_7O_2N$/gCOD
Nitrate-nitrogen conversion by denitrifying bacteria	NO_3	$C_2H_4O_2$	$4.69C_2H_4O_2+3.94NO_3^-\text{-}N+NH_4^+\text{-}N+2.94H^+ \rightarrow C_5H_7O_2N+1.97N_2+4.92CO_2+9.9H_2O$	5.10 $gC_2H_4O_2$/gNO_3	-	0.40 $gC_5H_7O_2N$/g $C_2H_4O_2$
Aerobic phosphorus uptake by phosphorus-accumulating bacteria	O_2	$C_{0.5}H_{1.5}O$	$2CH_{1.5}O_{0.5}+0.18NH_4^++1.35O_2+0.21PO_4^{3-} \rightarrow 0.18C_5H_7O_2N+0.21(HPO_3)+1.1CO_2+0.9H_2O+0.45OH^-$	-	1.00 gO_2/gPHA	0.47 $gC_5H_7O_2N$/gPHA
Denitrifying phosphorus uptake by phosphorus-accumulating bacteria	NO_3	$C_{0.5}H_{1.5}O$	$2CH_{1.5}O_{0.5}+0.18NH_4^++1.08NO_3^-+0.21PO_4^{3-} \rightarrow 0.18C_5H_7O_2N+0.21(HPO_3)+1.1CO_2+0.36H_2O+1.53OH^-+0.54N_2$	-	-	0.47 $gC_5H_7O_2N$/gPHA
Ammonia nitrogen conversion by nitrifying bacteria	O_2	CO_2	$NH_4^++1.86O_2+1.98HCO_3^- \rightarrow 0.020C_5H_7O_2N+0.98NO_3^-+1.88H_2CO_3+1.04H_2O$	-	4.25 gO_2/gNH_4^+-N	0.16 $gC_5H_7O_2N$/gNH_4^+-N

Note: The chemical reaction equation in the table was derived from the academic monograph "Wastewater Treatment Biological and Chemical Processes" published by Henze M et al. in 2001.

$$\Delta COD_{MAnS,\,DE}=\Delta COD_{MAnS}-\Delta COD_{MAnS,\,H} \quad (7)$$

Among them, ΔDO_{ManS} value in Eq. (6) is calculated by Eq. (3). When $c(NO_3)$ increased from 0.5 mg·L^{-1} to 4.0 mg·L^{-1}, ΔDO_{ManS} values were 19.76, 27.04, 27.93, 44.17, 57.52, 52.97, 61.11, 59.80 mg·h^{-1}, respectively.

According to Table 2, the metabolic stoichiometric coefficient of denitrifying bacteria was 0.26 gNO_3/g $C_{18}H_{19}O_9N$, which was converted to a COD equivalent of 0.18 gNO_3/gCOD. Therefore, the amount of nitrate-nitrogen consumed by denitrifying bacteria (using COD as carbon source) and phosphorus-accumulating bacteria can be calculated by formulas (8) and (9), respectively. The results are shown in Fig. 6.

Nitrate-nitrogen consumed by denitrifying bacteria,

$$\Delta NO_{3,\,MAnS,\,DE}=0.18\times\Delta COD_{MAnS,\,DE} \quad (8)$$

Nitrate-nitrogen consumed by polyphosphate bacteria,

$$\Delta NO_{3,\,MAnS,\,PAO}=\Delta NO_{3,\,MAnS}-\Delta NO_{3,\,MAnS,\,DE} \quad (9)$$

As seen in Fig. 6, the increase of $c(NO_3)$ affected the material flow direction of COD and nitrogen. The amount of COD obtained by common heterotrophic bacteria increased from 43.28 mg·h^{-1} to 133.83 mg·h^{-1}, while that obtained by denitrifying bacteria decreased from 287.63 mg·h^{-1} to 132.62 mg·h^{-1}. More nitrate-nitrogen flowed to denitrifying phosphorus-accumulating bacteria, and accordingly, the nitrate-nitrogen consumption increased from 168.12 mg·h^{-1} to 215.69 mg·h^{-1}, while that of denitrifying bacteria decreased from 51.77 mg·h^{-1} to 23.87 mg·h^{-1}. Therefore, $c(NO_3)$ affects the flow and distribution of nitrogen and carbon in MUCT process.

2-2. Flow and Distribution of Oxygen in Reaction Processes

Based on the stoichiometry of oxygen consumption in various microbial metabolic reactions and the material balance analysis, the oxygen consumption in each reaction process was calculated using [47,48].

The oxygen consumption of aerobic degradation of COD by heterotrophic bacteria:

$$O_H=0.47\times\Delta COD_{AE} \quad (10)$$

The oxygen consumption of phosphorus-producing bacteria to convert PHA and the phosphorus uptake:

$$O_{PAO}=\Delta PHA_{AE}\times 1.00 \quad (11)$$

And the oxygen consumption of nitrifying bacteria aerobic conversion of ammonia nitrogen:

$$O_{AUT}=\Delta NH_{4,\,AE}\times 4.25 \quad (12)$$

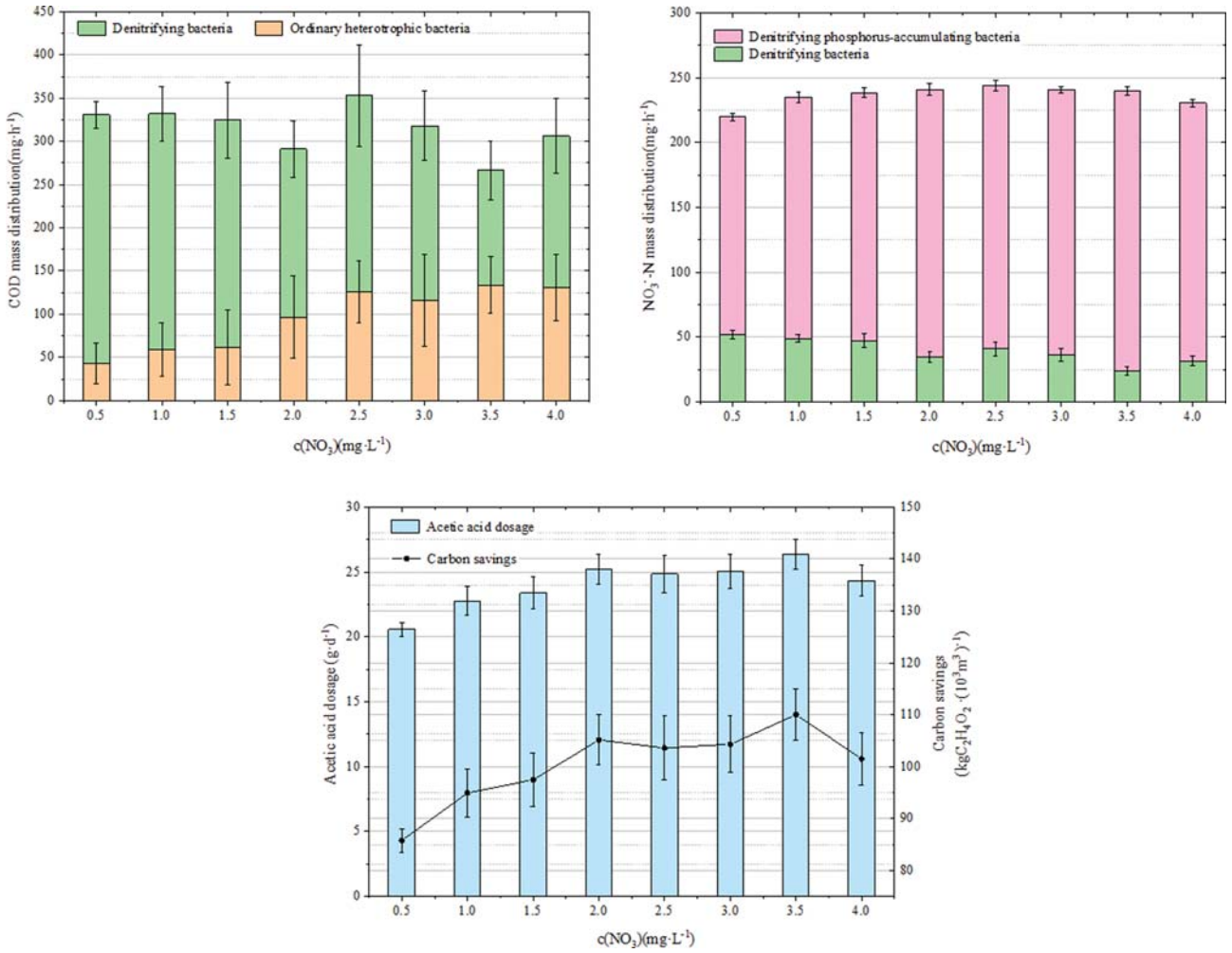

Fig. 6. Distribution and flow of carbon and nitrogen in the main anoxic section, and the amount of acetic acid in the absence of denitrifying phosphorus uptake.

Total oxygen consumption of the system:

$$O_T=O_H+O_{PAO}+O_{AUT}+\Delta DO_{MAnS} \quad (13)$$

The calculation results are shown in Fig. 7.

From Fig. 7, the increase in c(NO_3) affected the flow direction of oxygen. In that,

a. Oxygen consumption of ordinary heterotrophic bacteria increased from 49.04 mg·h^{-1} to 112.34 mg·h^{-1};

b. There was no significant effect on the oxygen consumption of nitrification, and the oxygen consumption of nitrification was maintained in the range of 2,120.75-2,148.08 mg·h^{-1};

c. The oxygen consumption of phosphorus-accumulating bacteria was greatly affected by a decrease from 572.30 to 372.88 mg·h^{-1};

d. The total oxygen consumption of the system decreased from 2,769.42 mg·h^{-1} at 0.5 mg·h^{-1} to 2,607.67 mg·h^{-1} at 4.0 mg·h^{-1}.

2-3. Cellular Mater Production from Mass Flow of Carbon, Nitrogen and Oxygen

Based on the material balance analysis results of the reaction amount in each section, combined with the biochemical reaction metrology of ordinary heterotrophic bacteria, denitrifying bacteria, phosphorus-accumulating bacteria and nitrifying bacteria, Eq. (14) was adopted to calculate the cellular matter productions of denitrifying bacteria in pre-anoxic section. Accordingly, the cellular matter production of ordinary heterotrophic bacteria, denitrifying bacteria and phosphorus-accumulating bacteria in the main anoxic section was calculated by Eqs. (15)-(17). The cellular matter production of heterotrophic bacteria, phosphorus-accumulating bacteria and nitrifying bacteria in the aerobic section was calculated based on Eqs. (18)-(20) [47,48]. The calculation results are shown in Fig. 8.

$$\Delta X_{PAnS,\,DE}=1.78\times\Delta NO_{3,\,PAnS} \quad (14)$$

$$\Delta X_{MAnS,\,H}=0.35\times\Delta COD_{MAnS,\,H} \quad (15)$$

$$\Delta X_{MAnS,\,DE}=0.33\times\Delta COD_{MAnS,\,DE} \quad (16)$$

$$\Delta X_{MAnS,\,PAO}=0.47\times\Delta PHA_{MAnS} \quad (17)$$

$$\Delta X_{AE,\,H}=0.35\times\Delta COD_{AE} \quad (18)$$

$$\Delta X_{AE,\,PAO}=0.47\times\Delta PHA_{AE} \quad (19)$$

$$\Delta X_{AE,\,AUT}=0.16\times\Delta NH_{4,\,AE} \quad (20)$$

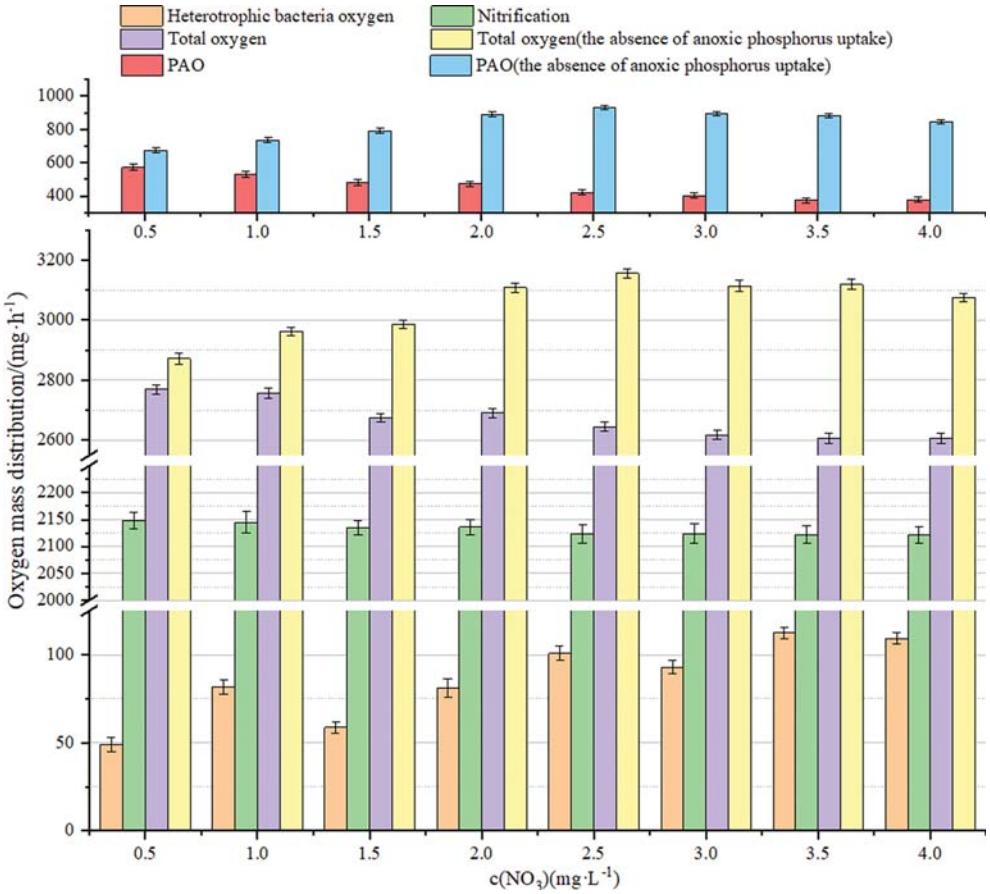

Fig. 7. Oxygen mass distribution under different nitrate-nitrogen concentrations in the main anoxic section of MUCT process.

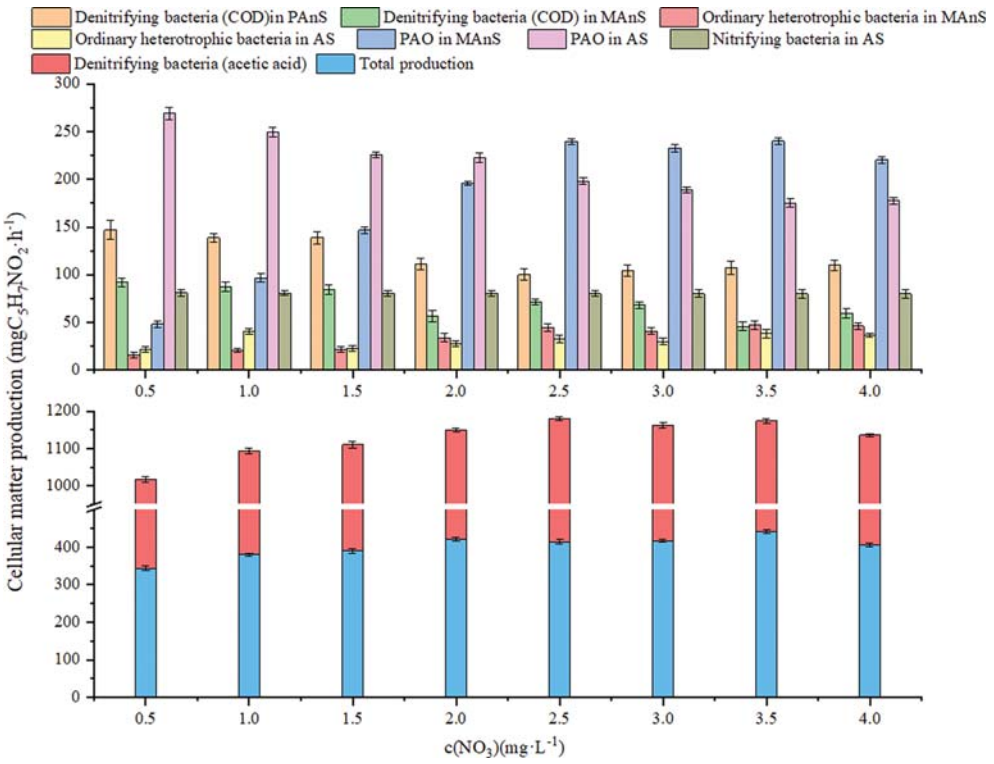

Fig. 8. Cellular matter production under different nitrate-nitrogen concentrations in main anoxic section of MUCT process.

Since phosphorus-accumulating bacteria stored PHA in the anaerobic section, it did not grow or reproduce. Moreover, the electron acceptor oxygen and nitrate-nitrogen reacted very little in anaerobic section, and the growth and reproduction of ordinary heterotrophic bacteria and denitrifying bacteria was negligible. In summary, the total sludge production of the MUCT process system was calculated by:

$$\Delta X_T=\Delta X_{PAnS,DE}+\Delta X_{MAnS,H}+\Delta X_{MAnS,DE}+\Delta X_{MAnS,PAO}+\Delta X_{AE,H}+\Delta X_{AE,PAO}+\Delta X_{AE,AUT} \quad (21)$$

From Fig. 8, the increase in $c(NO_3)$ had a great influence on the cellular matter production of ordinary heterotrophic bacteria, denitrifying bacteria and phosphorus-accumulating bacteria in each section. Among them, the cellular matter production of denitrifying bacteria in the pre-anoxic section and the main anoxic section and that of phosphorus-accumulating bacteria in aerobic section decreased with the increase of $c(NO_3)$. In the main anoxic section, the cellular matter production of ordinary heterotrophic bacteria and denitrifying phosphorus-accumulating bacteria increased with the increase of $c(NO_3)$. However, when $c(NO_3)$ was controlled between 2.0-4.0 $mg\cdot L^{-1}$, the above effects were reduced, and the cellular matter production of ordinary heterotrophic bacteria and nitrifying bacteria in the aerobic section was relatively stable.

3. Carbon Savings, Reduction in Cellular Matter Production, and Oxygen Consumption Reduction under Different $c(NO_3)$ Conditions

3-1. Carbon Source Savings

Assuming there was no denitrifying phosphorus uptake process in the main anoxic section of MUCT system, extra carbon sources, such as acetic acid, were added in order to attain the same treatment effect as shown in reaction process g in Fig. 5. Eq. (22) was used to calculate the amount of acetic acid added under different $c(NO_3)$ conditions.

$$\text{Acetic acid dosage}=5.10\times\Delta NO_{3,MAnS,PAO} \quad (22)$$

The calculation results are shown in Fig. 6. It can be deduced that with the increase of $c(NO_3)$, the acetic acid dosage increased from 20.58 $g\cdot d^{-1}$ to 26.40 $g\cdot d^{-1}$. That is, denitrifying phosphorus uptake in the MUCT process can save this part of the additional carbon source, and the savings are related to $c(NO_3)$, up to 110 kg acetic acid/10^3 m^3 sewage.

3-2. Cellular Matter Production Reduction

Assuming there was no denitrifying phosphorus uptake process in the main anoxic section, it would be necessary to add a carbon source to the main anoxic section. In the experiment, the growth of denitrifying bacteria with acetic acid as a carbon source in the main anoxic section can be calculated using Eq. (23). In addition, the growth of phosphorus-accumulating bacteria can be calculated by Eq. (24), and the total cellular matter production can be calculated by Eq. (25). The calculation results are shown in Fig. 8.

$$\Delta X_{MAnS,DE(Acetic\ acid)}=0.40\times\text{Acetic acid dosage in main anoxic section} \quad (23)$$

$$\Delta X_{AE,N,PAO}=0.47\times(\Delta PHA_{AE}+\Delta PHA_{MAnS})=\Delta X_{MAnS,PAO}+\Delta X_{AE,PAO} \quad (24)$$

$$\Delta X_{T,N}=\Delta X_{PAnS,DE}+\Delta X_{MAnS,H}+\Delta X_{MAnS,DE}+\Delta X_{MAnS,DE(Acetic\ acid)}+\Delta X_{AE,H}+\Delta X_{AE,N,PAO}+\Delta X_{AE,AUT} \quad (25)$$

As shown in Fig. 8, when there was no denitrifying phosphorus uptake, with the increase of $c(NO_3)$, denitrifying bacteria cellular matter production increased from 342.97 $mg\cdot h^{-1}$ to 420.58 $mg\cdot h^{-1}$ with the addition of acetic acid. The cellular matter production of phosphorus-accumulating bacteria in the aerobic section increased from 1,061.98 $mg\cdot h^{-1}$ to 1,180.10 $mg\cdot h^{-1}$. The total cellular matter production increased from 1,096.98 $mg\cdot h^{-1}$ to 1,180.10 $mg\cdot h^{-1}$. In summary, compared with the absence of denitrifying phosphorus uptake process, the presence of denitrifying phosphorus uptake reduced the production of cellular matters and the amount of reduction was affected significantly by $c(NO_3)$.

3-3. Oxygen Consumption Reduction

Assuming that there is no denitrifying phosphorus uptake in the main anoxic section, the oxygen consumption of phosphorus-accumulating bacteria in the aerobic section for the aerobic transformation of PHA and phosphorus uptake is calculated by (26).

$$O_{PAO,N}=(\Delta PHA_{AE}+\Delta PHA_{MAnS})\times 1.00 \quad (26)$$

In summary, suppose there is no denitrifying phosphorus uptake,

$$O_{T,N}=O_H+O_{PAO,N}+O_{AUT}+\Delta DO_{MAnS} \quad (27)$$

Eq. (27) was used to calculate the variation of oxygen consumption under different $c(NO_3)$ conditions without denitrifying phosphorus uptake. The results in Fig. 7 show that the total oxygen consumption of each reaction process increased; meanwhile, the presence of denitrifying phosphorus uptake significantly reduced oxygen consumption, saving up to 51.0 $kgO_2/10^3$ m^3 of sewage with an increase in $c(NO_3)$ concentration.

DISCUSSION

1. Material Flow and Distribution of Carbon, Nitrogen, and Oxygen

From the calculation results of the material balance of COD in Fig. 3, it can be seen that the conversion of COD mainly occurred in the anaerobic section and the pre-anoxic section. Considering the storage capacity of PHA in the anaerobic section, it can be deduced that COD removal was mainly achieved through COD absorption, synthesis into PHA and storage conversion by phosphorus-accumulating bacteria. The conversion rate was therefore slightly affected by $c(NO_3)$. In the MUCT process, the sludge was first returned to the pre-anoxic section, where the COD in sewage was used for denitrification, and then back to the anaerobic section. At this time, the nitrate-nitrogen concentration in sludge was very low (or zero), so it had little effect on the PHA synthesis of phosphorus-accumulating bacteria. During the experiment, about 70% of COD was absorbed and synthesized into PHA by the phosphorus-accumulating bacteria. This greatly affected the flow and distribution of carbon substances in the main anoxic and aerobic sections between ordinary heterotrophic bacteria, denitrifying bacteria and phosphorus-accumulating bacteria (including denitrifying phosphorus-accumulating bacteria).

In the pre-anoxic section, the transformation pathway of COD included anaerobic metabolism of phosphorus-accumulating bacteria and nitrate reduction by denitrifying bacteria. Some studies have shown that the presence of nitrate-nitrogen in the anaerobic

or anoxic section of the synchronous denitrification and phosphorus removal system can lead to a contradiction between denitrifying bacteria and phosphorus-accumulating bacteria in the competition for COD, and during this competition the denitrifying bacteria will have the advantage of dominating [49,50]. Preferentially, the denitrifying bacteria absorbed and utilized the COD in the inlet water. This led to the reduction of PHA content synthesized by phosphorus-accumulating bacteria. Therefore, the flow and distribution of COD and the synthesis of PHA in the pre-anoxic section were related to the amount of nitrate-nitrogen reaction. The nitrate-nitrogen in PAnS was derived from the return sludge, and the amount of the reaction was directly related to the concentration of nitrate-nitrogen in the effluent. From Fig. 4, it can be deduced that the value of $c(NO_3)$ was regulated, and the concentration of nitrate-nitrogen in the effluent was reduced, so the amount of nitrate-nitrogen converted by denitrifying bacteria decreased accordingly. In the end, more COD was synthesized into PHA, which flowed to the phosphorus-accumulating bacteria.

Fig. 3 shows that the COD, PHA, nitrate-nitrogen and oxygen in the main anoxic section were consumed; the transformation pathways of these four substances are shown in Fig. 5, of which included degradation of COD as a carbon source by the ordinary heterotrophic bacteria and denitrifying bacteria using oxygen and nitrate-nitrogen as electron acceptors, respectively; and the consumption of PHA as a carbon source for denitrifying phosphorus-accumulating bacteria using nitrate-nitrogen as the electron acceptor. COD flowed to ordinary heterotrophic bacteria and denitrifying bacteria respectively and material distribution between them was carried out. Nitrogen flowed to denitrifying bacteria and denitrifying phosphorus-accumulating bacteria, respectively, and material distribution between them was carried out. Oxygen flowed entirely to the ordinary heterotrophic bacteria. In the main anoxic section, $c(NO_3)$ could be used as the operation control parameter [31-34], which was regulated by the PLC automatic control system, and the amount of circulating nitrifying liquid was the controlled variable. During the experiment, with the increase of $c(NO_3)$, the required internal circulation ratio of nitrification liquid increased as well as the amount of oxygen carried and nitrate-nitrogen. Considering the stoichiometry of chemical reaction equation, with the increase of the amount of oxygen reaction, the amount of COD allocated to the ordinary heterotrophic bacteria also increased, and the corresponding amount of COD distributed to denitrifying bacteria decreased. As can be seen from Fig. 6, with the increase of $c(NO_3)$, the COD flow to ordinary heterotrophic bacteria increased from 43.28 to 133.83 $mg \cdot h^{-1}$, and the corresponding distribution to denitrifying bacteria decreased from 287.63 to 132.62 $mg \cdot h^{-1}$. Also, the nitrate-nitrogen transformed by denitrifying bacteria was 51.77, 49.06, 47.44, 34.99, 40.89, 36.38, 23.87 and 31.52 $mg \cdot h^{-1}$, respectively, when $c(NO_3)$ increased from 0.5 to 4.0 $mg \cdot L^{-1}$. On the other hand, with the increase of the amount of nitrate-nitrogen carried by the nitrifying liquid circulated to this section, when $c(NO_3)$ increased from 0.5 to 4.0 $mg \cdot L^{-1}$, there was 168.12, 186.10, 191.12, 206.17, 203.12, 204.52, 215.69 and 198.98 $mg \cdot h^{-1}$ nitrate-nitrogen, respectively, that flowed to the denitrifying phosphorus-accumulating bacteria. In summary, with the increase of $c(NO_3)$, the flow direction and distribution of carbon, nitrogen, and oxygen in the main anoxic section among ordinary heterotrophic bacteria, denitrifying bacteria and denitrifying phosphorus-accumulating bacteria were changed.

From Fig. 3, in the aerobic section, COD, ammonia nitrogen, PHA in phosphorus-accumulating bacteria and oxygen were consumed; the biochemical reaction process is shown in Fig. 5, among which COD was degraded as a carbon source by the ordinary heterotrophic bacteria using oxygen as the electron acceptor, PHA was consumed as a carbon source by phosphorus-accumulating bacteria using oxygen as the electron acceptor, and, last, ammonia nitrogen served as a nutrient of nitrifying bacteria, also using oxygen as the electron acceptor. Again, as shown in Figs. 3 and 4, the reaction amount of COD and ammonia nitrogen in the aerobic section slightly changed, and the material flowed into a single direction; thus, COD flowed into ordinary heterotrophic bacteria and ammonia nitrogen flowed to nitrifying bacteria. The synergetic effect of the change in $c(NO_3)$ and the reaction in the main anoxic section resulted in the change of PHA degradation in the aerobic and anoxic sections. It can, therefore, be deduced that the regulation of $c(NO_3)$ varied the consumption distribution of PHA in the main anoxic and aerobic sections.

2. Carbon Source Saving, Cellular Matter Production Reduction and Oxygen Consumption Reduction Induced by Carbon, Nitrogen and Oxygen Material Flow

2-1. Carbon Source Saving

From the above analysis, it can be seen that denitrifying phosphorus uptake took place in the main anoxic section of MUCT process, which determined the material flow direction and distribution of carbon, nitrogen, and oxygen. If it is assumed that denitrifying phosphorus uptake was not present in the MUCT process, an external/additional carbon source would be needed to achieve the same effect. Thus, the presence of denitrifying phosphorus uptake can save some external carbon sources.

According to the analysis in section 4.1, with the increase of $c(NO_3)$, the COD absorbed and consumed by ordinary heterotrophic bacteria increased, and the COD obtained by denitrifying bacteria decreased correspondingly. Meanwhile, with the increase in nitrate-nitrogen entering this section, more nitrate was transformed by denitrifying phosphorus-accumulating bacteria. Therefore, in orde to achieve the same treatment effect in the absence of denitrifying phosphorus uptake, it was necessary to increase the acetic acid dosage.

When $c(NO_3)$ increased from 0.5 $mg \cdot L^{-1}$ to 4.0 $mg \cdot L^{-1}$, the acetic acid dosage was 20.58, 22.72, 23.39, 25.23, 24.86, 25.03, 26.40 and 24.35 $g \cdot d^{-1}$, respectively, and the carbon source saving amount was 85.7, 94.9, 97.5, 105.1, 103.6, 104.3, 110.0 and 101.5 kg acetic acid/10^3 m^3 sewage, respectively.

2-2. Cellular Matter Production Reduction

In the absence of denitrifying phosphorus uptake, acetic acid should be added, which will increase the matter production of denitrifying bacteria. According to the chemical reaction metrology, the production of denitrifying bacteria cellular matter using acetic acid as carbon source was 342.97, 379.65, 389.88, 420.58, 414.37, 417.22, 440.00 and 405.91 mg $C_5H_7NO_2 \cdot h^{-1}$, respectively, with increased $c(NO_3)$.

Hence, when there was no denitrifying phosphorus uptake, with

$c(NO_3)$ increased from 0.5 $mg \cdot L^{-1}$ to 4.0 $mg \cdot L^{-1}$, the total cellular matter production was 1,016.98, 1,093.86, 1,110.10, 1,149.10, 1,180.10, 1,161.65, 1,173.85 and 1,135.46 mg $C_5H_7NO_2 \cdot h^{-1}$, respectively, while denitrifying phosphorus uptake reduced cellular matter production by 33.7, 34.7, 35.1, 36.6, 35.1, 35.9, 37.5 and 35.8%, respectively.

2-3. Oxygen Consumption Reduction

In the MUCT process, oxygen is distributed among ordinary heterotrophic bacteria, nitrifying bacteria, and phosphorous-accumulating bacteria. It, therefore, acts as electron acceptor of ordinary heterotrophic bacteria in the main anoxic section and aerobic section, respectively. Based on the chemical reaction metrology, the oxygen consumption of heterotrophic bacteria is directly related to the amount of COD reaction. As a result, the oxygen flow to the ordinary heterotrophic bacteria in this section was stable corresponding to the less and stable amount of COD reactions in the aerobic section. Again, the amount of oxygen flowing to the heterotrophic bacteria in the main anoxic section is directly related to $c(NO_3)$, in that, with the increase in $c(NO_3)$, the internal circulation flow of nitrifying liquid increased and the oxygen entering the main anoxic section increased, so the oxygen consumption of heterotrophic bacteria increased accordingly. As already established, the regulation of $c(NO_3)$ altered the material distribution of COD between heterotrophic bacteria, denitrifying bacteria and the quality distribution of nitrogen between denitrifying bacteria and phosphorous-accumulating bacteria. Thus, leading to the changes in the consumption distribution of PHA in the main anoxic section and aerobic section.

In the MUCT process, the presence of denitrifying phosphorus uptake in the main anoxic section enables the degradation of PHA using nitrate-nitrogen as an electron acceptor. This reduces the oxygen consumption of the aerobic section and reduces the total oxygen consumption of the process. During the experiment, the ammonia nitrogen conversion in the aerobic section was stable at 499.00-505.43 $mg \cdot h^{-1}$, proving that it was not affected by $c(NO_3)$ regulation. Hence, the oxygen consumption of nitrification was also stable between 2,120.75-2,148.08 $mgO_2 \cdot h^{-1}$.

Assuming the absence of denitrifying phosphorus uptake, all PHA would be consumed using oxygen as the electron acceptor in the aerobic section, thereby leading to a rise in the total oxygen consumption of the process. When $c(NO_3)$ was increased from 0.5 $mg \cdot L^{-1}$ to 4.0 $mg \cdot L^{-1}$, the total oxygen consumption was 2,871.84, 2,963.05, 2,986.19, 3,107.71, 3,155.88, 3,113.32, 3,117.98 and 3,075.66 mg O_2/h, respectively. In the same terms, the process oxygen consumption savings were 10.2, 20.6, 31.2, 41.7, 51.0, 49.5, 51.1 and 46.8 kg $O_2/10^3$ m^3 of sewage.

CONCLUSIONS

This study considered how regulation of $c(NO_3)$ can stimulate the function of denitrifying phosphorus- accumulating bacteria in the MUCT process, and thus can achieve better denitrification and phosphorus removal effect and denitrifying phosphorus uptake performance. The effluent saw its best quality when $c(NO_3)$ was regulated between 2.0-4.0 $mg \cdot L^{-1}$. The PHA consumption and TP uptake in the main anoxic section were both high, thus maintained between 416.75-510.69 $mg \cdot h^{-1}$ and 124.58-153.29 $mg \cdot h^{-1}$, respectively. During the MUCT process, under the regulation of $c(NO_3)$, carbon, nitrogen, and oxygen were flowed and distributed between the ordinary heterotrophic bacteria, denitrifying bacteria and denitrifying phosphorus-accumulating bacteria.

The results also showed that the flow and distribution of carbon, nitrogen, and oxygen under different $c(NO_3)$ conditions led to the change of carbon source savings in MUCT process. This study also concluded that the increase of $c(NO_3)$ from 0.5 $mg \cdot L^{-1}$ to 4.0 $mg \cdot L^{-1}$ has a direct influence on carbon source savings and reduction rate of sewage.

In view of the fine operation state of MUCT process brought by $c(NO_3)$ regulation, as well as the better effect of carbon source saving, reduction of cellular matter and oxygen consumption, parameter control strategy development is encouraged in the future. Meanwhile, the construction of denitrifying phosphorus uptake process control system will also benefit the application of this parameter in the actual operation of nitrogen and phosphorus removal in sewage treatment plant.

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