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Enhanced biological nutrients removal using an integrated oxidation ditch with vertical circle from wastewater by adding an anaerobic column

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Abstract: Compared to conventional oxidation ditches, an integrated oxidation ditch with vertical circle (IODVC) has the characters of concise configuration, simple operation and maintenance, land saving and automatical sludge returning. By the utilization of vertical circulation, an aerobic zone and an anoxic zone can be unaffectedly formed in the IODVC. Therefore, COD and nitrogen can be efficiently removed. However, the removal efficiency of phosphorus was low in the IODVC. In the experiment described, a laboratory scale system to add an anaerobic column to the IODVC has been tested to investigate the removal of phosphorus from wastewater. The experimental results showed that the removal efficiency of TP with the anaerobic column was increased to 54.0% from 22.3% without the anaerobic column. After the acetic sodium was added into the influent as carbon sources, the mean TP removal efficency of 77.5% was obtained. At the same time, the mean removal efficiencies of COD, TN and NH_3-N were 92.2%, 81.6% and 98.1%, respectively, at 12 h of HRT and 21—25 d of SRT. The optimal operational conditions in this study were as follows: recycle rate = 1.5—2.0, COD/TN > 6, COD/TP > 40, COD loading rate = 0.26—0.32 kgCOD/(kgSS·d), TN loading rate = 0.028—0.034 kgTN/(kgSS·d) and TP loading rate = 0.003—0.005 kgTP/(kgSS·d), respectively.

Keywords: integrative oxidation ditch with vertical circle; wastewater treatment; biological nutrient removal

Introduction

The enrichment of nutrients in water bodies is one of the crucial factors affecting water quality (Romanski, 1997). It has been reported that discharging wastewater with high levels of phosphorus (P) and nitrogen (N) can result in eutrophication of receiving waters, particularly lakes and slow moving rivers (Sundblad, 1994; Danalewich, 1998). A series of regulations and policies are thus established and enacted to control the concentration of nitrogen and phosphorus in discharging wastewater. In order to meet the increasing stringent criterions, more effective technologies are required for N and P removal from wastewater (Lee, 1996). Because of its particular recycle mode and convenient operation condition, oxidation ditches have been considered to be an effective and economic wastewater treatment process (Todd, 1996; Zhou, 2000), and have been widely applied in biological nitrogen removal, especially for small wastewater treatment plant. The main disadvantage of the oxidation ditch processes is that it requires a larger land area than other activated sludge treatment systems, which limits the feasibility of oxidation ditches in urban, suburban, or other areas where land acquisition costs are relatively high (USEPA, 2000). Considering this challenge, a novel process, integrated oxidation ditch with vertical circle (IODVC) was developed to treat municipal wastewater, which saved land area and inherited the advantages of conventional integrated oxidation ditches (Xia, 2004). Sound COD and NH_3-N removal efficiencies have been obtained. However, a little of phosphorus removal occurred in this IODVC. In this study, an anaerobic column was therefore attached to the IODVC system to enhance biological phosphorus and total nitrogen removal. The objective of this study was to investigate the impact of wastewater composition and operation conditions on the nutrient removal performance of the system.

1 Materials and methods

1.1 Experimental set-up

The flow sheet of the study system, including an anaerobic column and an IODVC, is shown in Fig.1. It is made of plexiglass. The working volume of the anaerobic column is 12 L, and the total working volume of the IODVC is 30 L with a 7 L clarifier. The IODVC consists of a single-channel, a brush, and an innovative integral clarifier (Table 1). There is an upper and lower compartment inside the single-channel, separated by a horizontal baffle running the length of the IODVC. The flow recycles from the top to the bottom in vertical circle while the brush is running. As a result, the different zones, the aerobic zone in the top and the anoxic zone in the bottom, are formed. In the IODVC, the clarifier is set at the opposite end of the brush in the ditch, but does not affect the hydrodynamic characteristics of the mixed liquid in the ditch. In this layout of the clarifier, the sludge can automatically return to the down ditch without pump. The recycle rate of sludge from clarifier to the anaerobic column was defined as the flow ratio of the returned sludge and the influent, which was changed by adjusting the recycle pump speed.

Table 1 The bench-scale system dimensions of IODVC and anaerobic column

Aeration ditch	Parameters	Aerator	Parameters
Length, mm	760	No. of aerator (Brush)	1
Width, mm	100	Length, mm	80
Effective depth, mm	550	Diameter, mm	150
Effective volume, L	33	Submersion depths, mm	20—25
Rotor power, W	60	Rotation velocity, r/min	60—120[a]
Clarifier		Anaerobic column	
Length, mm	120	Diameter, mm	160
Width, mm	100	Height, mm	800
Effective depth, mm	550	Effective depth, mm	650

Note: [a] The rotation velocity changed between 60 to 120 r/min to keep DO more than 2 mg/L in top ditch

1.2 Analysis

The influent flow, pH and temperature in the IODVC were monitored daily. SS, BOD_5, NH_3-N, NO_2^--N, NO_3^--N, TN, SP, TP and MLSS and MLVSS were regularly analyzed according to the Standard Methods (SEPA, 1998).

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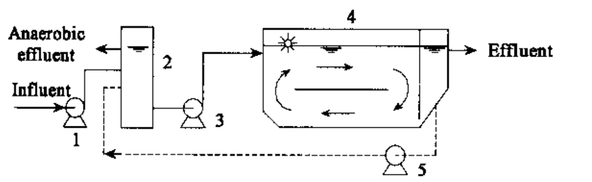

Fig.1 Schematic diagram of the experiment set-up
1. Feed pump; 2. anaerobic column; 3. lift pump; 4. TOD; 5. sludge recycle pump

COD concentration was determined by a CTL-12 COD meter (Huatong Company, China). DO concentration was measured daily with an YSI Model 52 DO meter with the YSI 5739 Field Probe(YSI Incorporated Company, USA).

1.3 Raw wastewater

The experiment was carried out at the Research Center for Eco-Environmental Sciences, Chinese Academy of Science (RCEES-CAS). The raw wastewater from the sewer system adjacent to RCEES was first pumped into a store tank, and then pumped into the experiment system by a peristaltic pump (BT00-100M, Baoding Lange Peristaltic Pump Company, China). Its characteristics throughout the experimental operation period are shown in Table 2. In the influent, NH_3-N concentration accounts for more than 94% of total nitrogen (TN) concentration, and the soluble phosphorus (SP) concentration accounts for about 70% of total phosphorus (TP).

Table 2 Wastewater characteristics during the experiment

Parameter	Range	Mean ± *SD*
COD, mg/L	236—892	530 ± 153
BOD_5, mg/L	190—650	350 ± 118
NH_3-N, mg/L	56—149	79 ± 14
TN, mg/L	61—154	84 ± 13
NO_x-N, mg/L	0.1—7.1	3.0 ± 1.1
TP, mg/L	4.8—21.0	10.4 ± 2.7
SP, mg/L	4.7—17.3	7.1 ± 1.8
COD/TN	2.9—11.3	6.2 ± 2.0
COD/TP	26.7—89.6	53.2 ± 18

1.4 Operation conditions

The operation factors of this test system are shown in Table 3. The system was operated at the ambient temperature ranging from 16℃ to 28 ℃. The HRT was kept at 12 h in the recycle area. The sludge age(SRT) of 25—30 d was controlled and adjusted by daily discharging excess sludge. The pH varied between 7.0 and 8.5. DO concentration in the aerobic zone was kept between 2.0 mg/L and 4.4 mg/L. And the oxidation-reduction potential(ORP) in the anaerobic zone varied from − 138 mV to − 415 mV.

2 Results and discussion

2.1 Performances of COD and nutrients removal

2.1.1 Removal of COD

Similar to a traditional oxidation ditch, the COD removal in the test system was stable and high, and the removal efficiency of 73.6%—94.7% (mean 88.0%) was obtained during the experiment period although the influent COD concentration fluctuated strongly in range of 236.5—892.4 mg/L(Fig.2). The experimental results showed that the organic matters were mainly consumed by both release PO_4^+-P in the anaerobic column and denitrification in the anoxic zone.

Table 3 Operational conditions of the experimental set-up

Parameter	Range	Mean ± *SD*
Temperature, ℃	21—28	24 ± 3.5
pH	6.7—8.0	7.3 ± 0.3
DO, mg/L	1.7—3.5	2.7 ± 0.8
ORP in anaerobic column, mV	(− 510)— − 85	− 237 ± 139
HRT, h	12	12
SRT, d	21—25	23 ± 2.5
MLSS, mg/L	2030—3684	3018 ± 633
MLVSS, mg/L	1543—2925	2379 ± 533
VSS/SS	76—81	79 ± 3.6
Load of COD, kgCOD/(kgMLSS·d)	0.13—0.85	0.37 ± 0.13
Load of BOD_5, $kgBOD_5$/(kgMLSS·d)	0.12—0.57	0.27 ± 0.10
Load of NH_3-N, $kgNH_3$-N/(kgMLSS·d)	0.029—0.099	0.058 ± 0.016
Load of TN, kgTN/(kgMLSS·d)	0.032—0.106	0.062 ± 0.017
Load of TP, kgTP/(kgMLSS·d)	0.003—0.014	0.007 ± 0.002

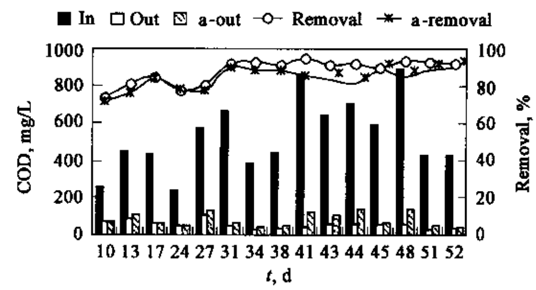

Fig.2 Removal of COD in the system
In: influent; out: effluent; a-out: effluent of anaerobic column; removal: total removal; a-removal: removal of anaerobic column

2.1.2 Removal of NH_3-N and TN

The removal of NH_3-N can be completed through nitrification under aerobic condition in the experiment system. The NH_3-N concentration in the effluent was stable and low (most of the case was under 1.0 mg/L), but occasionally high due to low DO concentration in the mixed liquor in the top ditch caused by the brush skidding(Fig.3). Average of the NH_3-N removal efficiency in the test system was 96.0%.

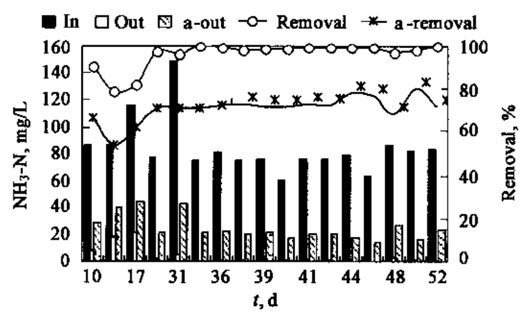

Fig.3 Removal of NH_3-N in the system
The bars and dots are the same as Fig.2

The removal of TN was not as stable as that of NH_3-N in the system(Fig.4). The main reason for the unstable TN removal was the low COD/TN in the raw wastewater and high DO in the IODVC. When acetic sodium was added into the influent as carbon sources, the TN removal increased dramatically and the TN concentration of effluent can be kept stable. The experimental results showed that TN removal efficiency could be remained more than 76% at COD/TN > 6, and the effluent TN was thus under 15 mg/L, meeting with the discharge standard (SEPA of China, GB18918-2002).

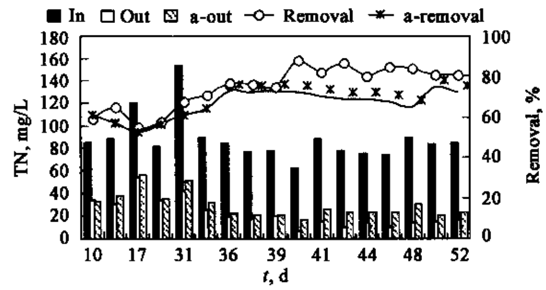

Fig.4 Removal of TN in the system
The bars and dots are the same as Fig.2

2.1.3 Removal of TP and SP

Fig.5 and 6 show experimental results of TP and SP (soluble phosphorus) removal in the test system. After adding the anaerobic column, the removal efficiency of total phosphorous in the test system with the anaerobic column increased to about 54.0% from 22.3%. However, because of deficient carbon sources in the raw wastewater for releasing phosphorous, the phosphorus removal efficiency was unstable at the beginning. Therefore, the acetic sodium was added into the influent so as to increase phosphorous removal. As a result, both TP and SP removal efficiencies were improved rapidly and kept stable till the end of experiment (Fig.5, 6). The removal of TP and SP were 64.4%—87.6% (mean 77.5%) and 55.8%—91.7% (mean 77.1%) respectively. Meanwhile, both TP and SP release rate was improved significantly from 54% to − 270% and 41% to − 256% (minus value means phosphorus release), respectively. During the experiment, the loading rates of TP and SP were 0.004—0.008 kgTP/(kgSS·d) and 0.003—0.006 kgSP/(kgSS·d), respectively.

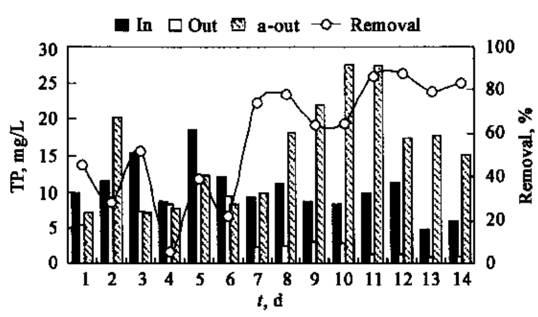

Fig.5 Removal of TP in the system
In: influent; out: effluent; a-out: effluent of anaerobic column; removal: total removal

2.2 Factors affecting nutrients removal

2.2.1 Sludge loading rates

Phosphorous release and denitrification need organic matter as carbon sources, but high concentration organic matter can lead to deterioration of nitrification and the BNR

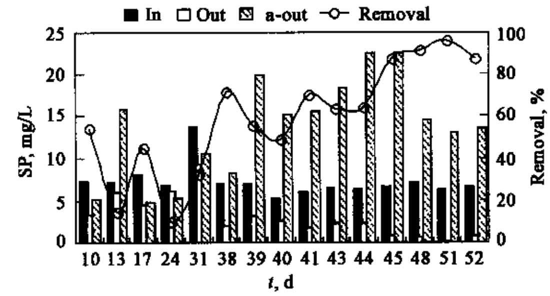

Fig.6 Removal of SP in the system
The bars and dots are the same as Fig.5

process (Morgenroth, 1998). Therefore, the COD loading rate is one of important parameters to design and operate in a process for nutrients removal. It has been reported that sludge with low COD loading rates display a high P-uptake potential, while sludge operating on a high COD loading rate display lower P-uptake potential (Chuang, 1998). Fig.7 and Fig.8 show the experimental results of influence COD loading rate on TN and TP removal, respectively. According to Fig.7, the COD loading rate varied between 0.1 and 0.5 kgCOD/(kgSS·d) while the average TN loading rate was kept 0.049 kgTN/(kgSS·d), ranging from 0.045 to 0.055 kgTN/(kgSS·d). TN removal increased and TN concentration of the effluent decreased along with increasing of COD loading rates. TN removal increased from 58.1% to 83.8% and TN concentration of the effluent decreased from 45.0 to 10.1 mg/L when the COD loading rate increased from 0.1 to 0.3 kgCOD/(kgSS·d). But no increase of TN removal efficiency was observed when COD loading rates exceeded 0.3 kgCOD/(kgSS·d).

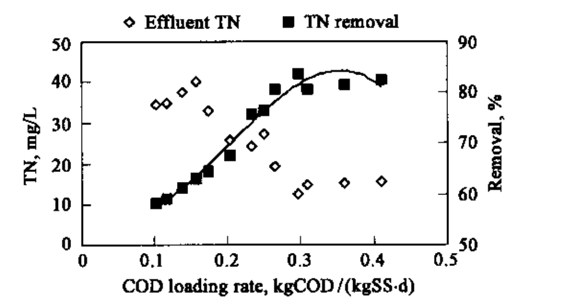

Fig.7 Variation of effluent TN concentration and TN removal with specific COD loading rates

Alike the TN removal and the TN concentration of the effluent, TP removal increased and TP concentration of effluent decreased with the increasing of COD loading rates when the TP loading rates were kept 0.005 kgTP/(kgSS·d) (ranging from 0.004 kgTP/(kgSS·d) to 0.007 kgTP/(kgSS·d) during the experiment period (Fig. 8). TP removal increased from 5.6% to 86.7% and effluent TP concentration decreased from 6.8 mg/L to 0.3 mg/L when the COD loading rate increased from 0.12 to 0.32 kgCOD/(kgSS·d). But the increase of TP removal efficiency stopped when COD loading rates exceed 0.26 kgCOD/(kgSS·d), although a little decrease for the TP removal efficiency was observed when the COD loading rates exceeded 0.32 kgCOD/(kgSS·d).

Obviously, variations in COD loading rates had a significant effect on nutrients removals and nutrients

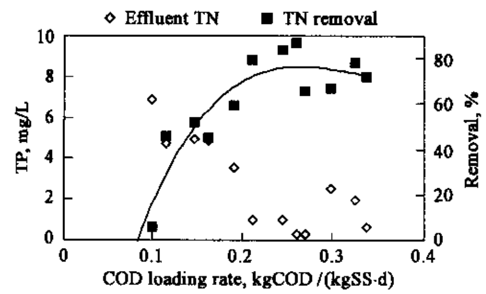

Fig.8 Variation of effluent TP concentration and TP removal with specific COD loading rates

concentrations of the effluent at a relatively determinate nutrient loading rate. The correlation between COD loading rates in TN and TP removals were both significant at the 0.01 level(two-tailed) in this experiment(Table 4). The optimum COD loading rate in this system ranged from 0.26 to 0.32 kgCOD/(kgSS·d). The main reason for COD loading rate affecting TN and TP removal efficiencies at high COD loading rates was that the residual substrate may still support the growth of filamentous bacteria in the oxic zone if the COD was not totally sequestered in the anaerobic zone, and the growth of nitrifier, denitrifier and phosphorus accumulation bacteria would be restrained.

Table 4 Correlation of COD loading rate in TN and TP removals, TN and TP loading rate, COD/TN and COD/TP , recycle rate

	TN removal			TP removal		
	Equation	R^2	Pearson correlation	Equation	R^2	Pearson correlation
COD loading rate	$y = -329.36x^2 + 258.07x + 32.594$	0.9485	0.753**	$y = -2063.6x^2 + 1118.7x - 72.928$	0.8068	0.753**
TN and TP loading rate	$y = -0.0048x^2 + 0.0147x + 86.1$	0.7284	-0.849**	$y = -3.068x^2 + 20.577x + 48.11$	0.868	-0.88**
COD/TN and COD/TP	$y = -0.8323x^2 + 14.547x + 20.5$	0.8413	0.842**	$y = -0.0361x^2 + 5.1236x - 100.52$	0.9136	0.845**
Recycle rate	$y = -6.7486x^2 + 34.912x + 38.016$	0.964	0.924*	$y = 3.482x^2 + 16.159x + 2.0082$	0.9644	0.979**

Notes: ** Correlation is significant at the 0.01 level(2-tailed); * correlation is significant at the 0.05 level(2-tailed)

The TN loading rate varied between 0.028 and 0.068 kgTN/(kgSS·d) while the COD/TN ratio was kept between 6—8. TN loading rates and TN removals had a minus correlation and the correlation was significant at 0.01 level (2-tailed) (Table 4). It was interesting that TN removal efficiency increased from 76.3% to 87.0% when the TN loading rates changed from 0.028 to 0.034 kgTN/(kgSS·d), but the TN removal efficiency decreased rapidly when TN loading rates exceeded 0.037 kgTN/(kgSS·d) (Fig.9), which means that 0.034 kgTN/(kgSS·d) was the optimal TN loading rate in this study. Around this TN loading rate the effluent TN concentration was less than 15 mg/L, and could meet the discharge standard (SEPA of China, GB18918-2002).

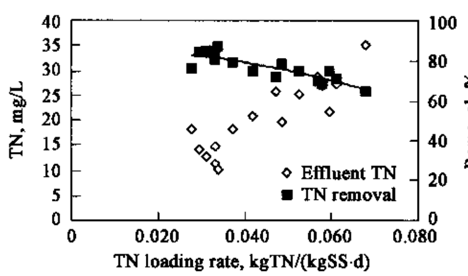

Fig.9 Variation of effluent TN concentration and TN removal with specific TN loading rate

Statistic analysis showed that variations in TP loading rate had a minus effect on the TP removals(Table 4). The TP loading rate varied between 0.003 and 0.008 kgTP/(kgSS·d) while the ratio of COD/TP was kept more than 60. TP removal efficiency increased slowly from 79.7% to 86.7% and TP concentration of effluent decreased from 0.98 to 0.27 mg/L with increasing of TP loading rate from 0.003 to 0.005 kgTP/(kgSS·d). But the TP removal efficiency decreased sharply from 86.7% to 28.41% and the TP concentration of the effluent increased rapidly from 0.27 to 5.42 mg/L while the TP loading rate was continuously increased from 0.005 to 0.008 kgTP/(kg SS·d)(Fig.10). So the optimal range of TP loading rates in this study was

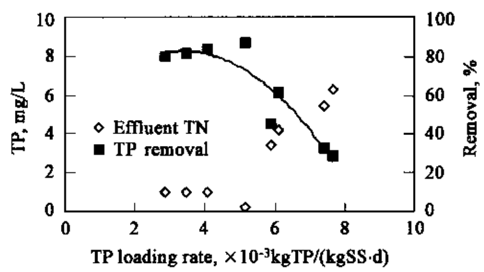

Fig.10 Variation of effluent TP concentration and TP removal with specific TP loading rate

from 0.003 to 0.005 kgTP/(kgSS·d) in this study.

2.2.2 COD/TN and COD/TP

In this study, the COD/TN ratios changed from 2 to 10 while the average TN loading rate was kept at 0.055 kgTN/(kgSS·d)(ranging from 0.051 to 0.069 kgTN/(kg SS·d)). Not only did TN removal increase but also effluent TN concentration decreased correspondingly with increasing of COD/TN(Fig.11). TN removal increased from 58.1% to 87.0% and effluent TN concentration decreased from 54.0 to 10.1 mg/L when the COD/TN increased from 2.89 to 8.32. But the influence of COD/TN on the TN removal efficiency was not obvious when COD/TN exceeded 8.32, and TN removal efficiency decreased slightly. The main reason for this phenomenon is that nitrification ability was restrained in the system by the too high organic loading rate (Wang, 2004). The optimal COD/TN ratio is 6—7 in this study.

The COD/TP ratio varied between 20 and 80 when the TP loading rates were kept 0.0056 kgTP/(kgSS·d) (0.0054 to 0.0060 kgTP/(kgSS·d)). TP removal increased from 5.6% to 86.7% and effluent TP concentration decreased from 8.2 to 1.4 mg/L when COD/TP increased from 27.8 to 80.0(Fig.12). Alike the impact of the COD/TN on TN removal efficiency, the COD/TP had a significant effect on the TP removals and TP concentration in the effluent. However such influence of COD/TP on the TP removal efficiency was not obvious when the COD/TP exceeded 60. And a deterioration of BPR was observed when COD/TP

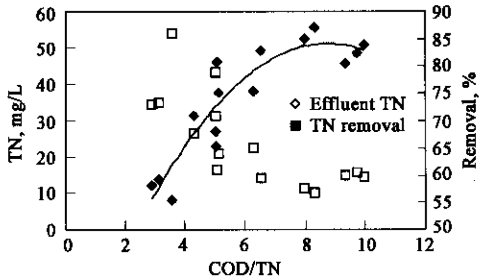

Fig.11 Variation of effluent TN concentration and percent TP removal with specific COD/TN
TN loading rate = 0.055 kgTN/(kgSS·d), T = 21—28℃

exceeded 80. The explanation for that is sludge appear to convert the influent organic matter to the storage product 3-hydroxyvalerate, which is the major storage form utilized by the GAO bacteria with high COD/TP(Liu, 1996). The result from this study showed that it was unnecessary to increase COD/TP more than 60. The statistic analysis of the correlation between TP removal and COD/TP ratio is showed in Table 4.

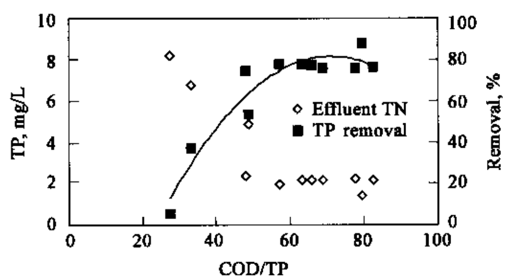

Fig.12 Variation of effluent TP concentration and percent TP removal with specific COD/TP
TP loading rate = 0.0056 kgTP/(kgSS·d), T = 21—28℃

2.2.3 Recycle rate

To determine a suitable recycle rate of sludge for nutrients removal, the recycle rates were controlled by adjusting the speed of the recycle pump and an statistic analysis was made (Table 4). At a given conditions (all of HRT, COD/TN, COD/TP, TN and TP loading rates were maintained constant), TN and TP removal increased and TN and TP concentrations in the effluent decreased with increasing of the recycle rate. TN removal increased from 48.5% to 84.0% and TN concentration in the effluent decreased from 50.0 to 11.2 mg/L when the recycle rate increased from 40% to 300% (Fig. 13). Both similar increase of TP removal (from 5.1% to 86.7%) and similar decrease of TP concentration in the effluent (from 9.2 to 1.2 mg/L) were observed in this study. Obviously, the recycle rate has a significant effect on TN and TP removals and concentrations in the effluent when the recycle rates were below 150%, but such impact on the TN removals became unconspicuous when the recycle rate exceeded 150%. Therefore the optimal recycle rate for nutrients removal in this study was between 150% and 200%.

3 Conclusions

Main conclusions from this investigation can be summarized as follows: (1) The process with an anaerobic column attached before the IODVC was capable of effectively

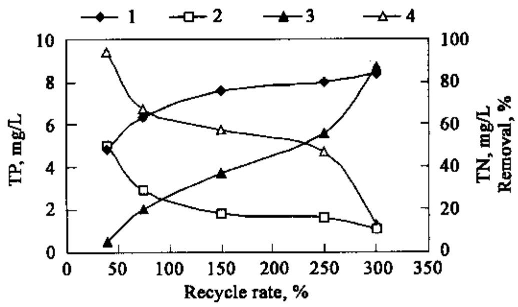

Fig.13 Variation of effluent TN and TP concentration and percent TN and TP removal with specific recycle rate
COD/TN > 6, COD/TP > 60, TN loading rate about 0.05 kgTN/(kgSS·d), TP loading rate about 0.006 kgTP/(kgSS·d)
1: removal efficiency of TN; 2: TN concentration in the effluent; 3: removal efficiency of TP; 4: TP concentration in the effluent

removing phosphorus and nitrogen from domestic wastewater at 12 h of HRT and 23 d of SRT, respectively. The mean removal efficiencies of COD, NH_3-N, TN, TP were 92.2% (ranged from 89.9% to 94.7%), 98.1% (ranged from 96.6% to 99.4 %), 81.6% (ranged from 74.5% to 87.9%), and 77.5% (ranged from 64.4% to 87.6%), respectively. (2) Tested factors, including COD/TN, COD/TP, COD loading rate, TN and TP loading rate, can affect nitrogen and phosphorus removal. The optimal conditions in this study were as follows: recycle rate = 1.5—2.0, COD/TN > 6, COD/TP > 50, COD loading rate = 0.26—0.32 kgCOD/(kgSS·d), TN loading rate = 0.028—0.034 kgTN/(kgSS·d) and TP loading rate = 0.003—0.005 kgTP/(kgSS·d).

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