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## BIOLOGICAL NUTRIENT REMOVAL USING A NOVEL FIVE-STEP CONTINUOUS FLOW ACTIVATED SLUDGE PROCESS TECHNOLOGY

An anaerobic-anoxic/oxic (AA/O) five-tank biological process called five-step continuous flow activated sludge process (FSCFASP) was developed to force the oscillation of organic matter and nutrient concentrations in process reactors. The run scheme and schematic diagram of FSCFASP was described. The run cycle was divided into two symmetrical half cycles with eight periods during each cycle. The duration of each period was established according to biological process requirements. The optimal running times of the periods were 90, 60, 60, 30, 90, 60, 60 and 30 min at the HRT of 16 h, air/water ratio of 35% and SRT of 21 day at the temperature range of 19–23 °C. The optimized system achieved 88.09±1.43%, 90.33±2.9%, 68.83±5.34% and 87.67±2.9% of the chemical oxygen demand, NH<sub>4</sub><sup>+</sup>-N, TN, and TP removal efficiencies, respectively, during a 11-month operation with the effluent meeting the Chinese sewage discharge standard GB18918-2002 (level A). Simultaneous nitrification and denitrification phenomena were observed in the tank one which is important to reduce the quantity of aeration and the duration of a next anoxic state. Compared with other existing technologies, this system achieved high nitrogen and phosphorus removal without equipment of sludge and mixed liquor return. Thus, it is effective for reducing energy consumption.

### 1. INTRODUCTION

Although biological nutrient removal (BNR) is an effective treatment method, there is a problem associated with competition of denitrifying bacteria and polyphosphate accumulating organisms (PAOs) for organic carbon. The use of denitrifying phosphate-accumulating organisms (DNPAOs) can relieve the competition for organic carbon because they can treat nitrate/nitrite and phosphate using the same car-

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bon sources. Although external nitrification processes such as denitrification and DEPHANOX (phosphate accumulation in anoxic process) and A2N (anaerobic-anoxic/Nitrification) have already been developed for the effective use of DNPAOs, they are very complicated processes that require many reactors and mixed liquor recycling streams. Therefore, it is necessary to develop a simple BNR process that can utilize DNPAOs. To simplify the process, the use of a sequence batch reactor SBR which is one of the effective methods because an SBR makes it possible to remove nutrient in a single reactor without mixed liquor recycling streams. Moreover, it has been verified, in full-scale studies, that this BNR process of using an SBR is cost-effective as compared with continuous flow processes [1]. Although an anaerobic/oxic (with low dissolved oxygen) process and an anaerobic/oxic/anoxic (AOA) process have been proposed for the utilization of DNPAOs in SBRs [2, 3], these processes have some disadvantages. In the former, denitrification is mainly responsible for denitrifying glycogen-accumulating organisms (DNGAOs), competitors of PAOs. In the latter, a large amount of external carbon must be added at the beginning of the oxic stage to prevent aerobic uptake of phosphate by PAOs. The common problem in these processes is that DNPAOs are exposed to oxygen. Although necessary for nitrification, aeration creates hostile conditions for DNPAOs.

Enhanced biological phosphorus removal (EBPR) is the most economical and sustainable process for removing phosphorus from wastewater [4]. EBPR is achieved by recycling polyphosphate accumulating organisms (PAOs) through alternating anaerobic/anoxic and aerobic conditions. PAOs take up carbon sources, primarily volatile fatty acids (VFAs) in the anaerobic stage, and store them in the form of poly-hydroxyl alkanoate (PHA). The energy required is primarily gained from the degradation of their intracellular polyphosphate, which is released to the bulk liquid as orthophosphate. In the subsequent aerobic stage, PAOs grow and take up orthophosphate to recover the polyphosphate level by using the stored PHA as the carbon and energy source. Phosphorus removal is achieved by withdrawing excess sludge at the end of the aerobic stage, when the PAO cells contain a high level of polyphosphate [5]. The conventional biological nitrogen removal is accomplished by a two-stage treatment, i.e. the oxidation of ammonia to nitrite, and then to nitrate in the first aerobic nitrification stage followed by the second anoxic denitrification stage related to the reduction of nitrate to nitrite, and then to  $N_2$  gas [6]. The partial nitrification of ammonia to nitrite has been named nitritation, and the subsequent direct reduction of nitrite to  $N_2$  gas, denitrification [7]. Application of nitritation-denitrification could lead to a considerable saving in aeration costs and external carbon sources as compared to the complete nitrification-denitrification [6; 8]. For the treatment of domestic wastewater, nitritation and denitrification are particularly significant because the organic carbon source in it is typically limiting [9].

Enhancement of biological nitrogen removal is achieved by aerobic nitrification and anoxic denitrification using autotrophic nitrifying and heterotrophic denitrifying bacteria. Thus two separate reactors are required to provide different environments for

the two kinds of bacteria in nitrogen removal process. The key to achieve nitrification-denitrification is controlled oxidation of ammonia to nitrite instead of nitrate and build-up of nitrite. Therefore, nitrite oxidizing bacteria (NOB) have to be inhibited or eliminated while ammonia oxidizing bacteria (AOB) have to become the dominant nitrifying bacteria [10]. Presently, most of the studies on nitrification and denitrification focus on the SBR process [6, 8, 11–14]. In comparison with SBR, it is difficult to achieve nitrite accumulation in a continuous flow system. Only a few studies on achieving nitrogen removal via nitrite in a continuous process for treatment of wastewater with high ammonia concentrations [11, 15] and anoxic-aerobic (A/O) processes [16] have been carried out.

Therefore, in this study, a unitank process with AA/O has been proposed to enhance biological phosphorus and nitrogen removal. A new technology is developed to remove biological phosphorus and nitrogen with a strong point of unitank with AA/O process under alternating environment state whereas unitank refers to multi-tank connected in series system, AA/O refer to anaerobic/anoxic/oxic process and the strong point is the period of time necessary for reaching the main function. It is different from a normal multireactor process such as A/O or UCT processes because it does not need equipment to return sludge and mixed liquor. Five-step continuous flow process is considered as modified SBR but it is different from SBR in configuration and hydraulic condition because both influent and effluent are continued. It consists of five tanks hydraulically connected to maintain constant wastewater level and high phosphorus and nitrogen removal so that it is different from other multi-tank configurations. Recirculation of mixed liquor and sludge was completed through direction change at each half cycle without additional sludge and mixed liquor return so that this process does not require equipment to return sludge and mixed liquor. This is the main difference between our technology and other common activated sludge process technologies. The advantages of this system are flexible operation and convenient maintenance. This system is run automatically through the programmable logic controller PLC. The operation mode and control status can be adapted with enough flexibility, maintenance and easy management.

## 2. MATERIALS AND METHODS

*Experimental set-up.* The main parts of a pilot plant utilized in this study are the main body which are a rectangular box of 750×630×900 mm, air compressor, pre-static pumps, mechanical agitation mixers, PLC programmable logic control, LCD display screen, inlet wastewater electromagnetic valves, outlet water electromagnetic valves, aeration electromagnetic valves, sludge discharge electromagnetic valves, and PVC pipes and others.

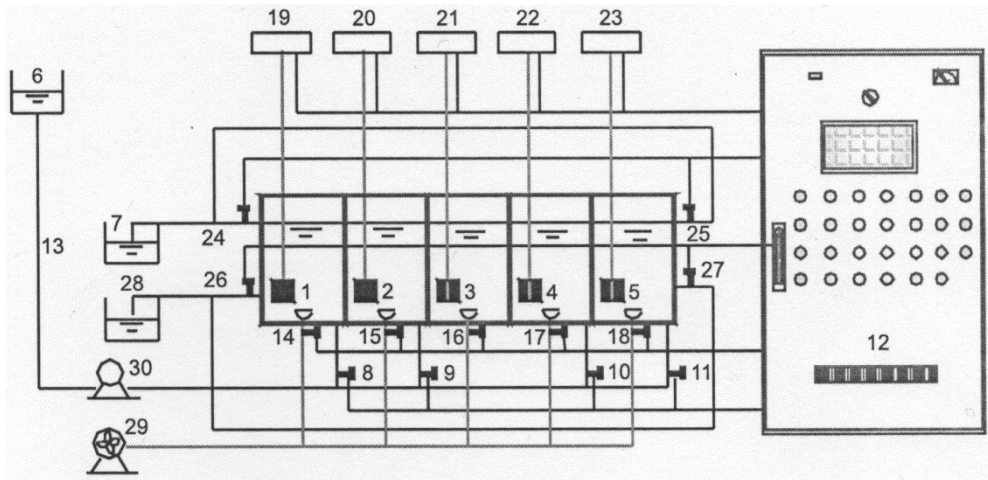


Fig. 1. Schematic diagram of the experimental device with all main parts: 1 – tank one, 2 – tank two, 3 – tank three, 4 – tank four, 5 – tank five, 6 – influent storage tank, 7 – effluent storage tank, 8 – influent electromagnetic valve of tank one, 9 – influent electromagnetic valve of tank two, 10 – influent electromagnetic valve of tank four, 11 – influent electromagnetic valve of tank five, 12 – programmable logic control unit PLC, 13 – influent pipe, 14 – aeration electromagnetic valve of tank one, 15 – aeration electromagnetic valve of tank two, 16 – aeration electromagnetic valve of tank three, 17 – aeration electromagnetic valve of tank four, 18 – aeration electromagnetic valve of tank five, 19 – mixer of tank one, 20 – mixer of tank two, 21 – mixer of tank three, 22 – mixer of tank four, 23 – mixer of tank five, 24 – effluent electromagnetic valve of tank one, 25 – effluent electromagnetic valve of tank five, 26 – sludge electromagnetic valve of tank one, 27 – sludge electromagnetic valve of tank five, 28 – sludge reservoir, 29 – air compressor, 30 – feed prestatic water pump

A scheme of a pilot plant with all major components is shown in Fig. 1. The effective wastewater depth in the five-step continuous flow activated sludge system is 650 mm while the total depth is 900 mm. The effective volumes of tank two, three, and four are  $250 \times 250 \times 650$  mm while those of tank one and five are  $380 \times 290 \times 650$  mm; the volume ratio of rectangular to square tanks is equal to 1.75.

*Experimental procedure.* An operation cycle is composed of two half-cycles with similar running schemes, in which the raw wastewater flows from tank one to tank five during the first half-cycle, and from tank five to tank one during the second one. Therefore, only one half-cycle is examined in this study. The scheme of the first half cycle is shown in Fig. 2. It is divided into four periods named as period I, II, III and IV, respectively. In this scheme, tank one, tank two, tank three and tank four operate as a reactor, and tank five as a settler. The direction of flow is changed automatically via changing of intake location so that the system achieved automatic recirculation without equipment to return sludge and mixed liquor. Therefore, this system is effective for reducing energy consumption. Time and environmental conditions was controlled during each period to achieve the function of AA/O process in the unitank system.

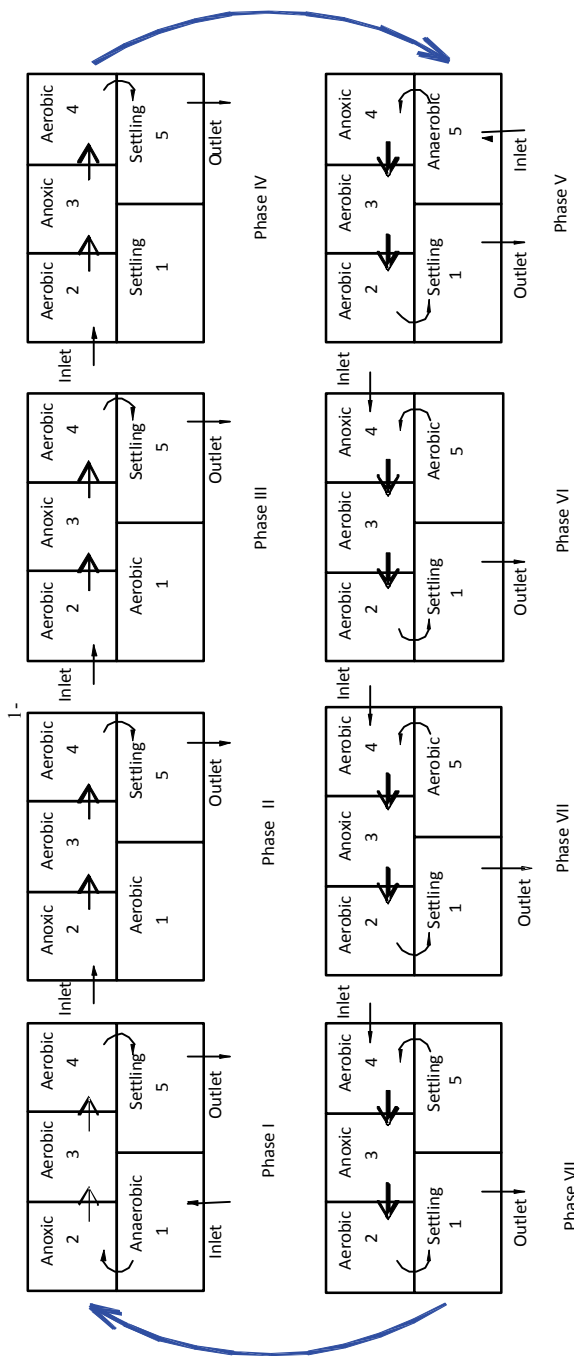


Fig. 2. Run scheme of five-step continuous flow activated sludge process

*Wastewater quality.* The raw wastewater used in the experiment was collected from a main manhole of Wuxi Campus, Southeast University. Characteristic of wastewater quality is given in Table 1.

Table 1

Characterization of the wastewater used in the experiments

Item	Range	Average
Chemical oxygen demand COD (mg/dm <sup>3</sup> )	207.2–339	257
Ammonia-nitrogen concentration NH <sub>4</sub> <sup>+</sup> -N (mg/dm <sup>3</sup> )	15.7–41.6	33.2
Total nitrogen concentration TN (mg/dm <sup>3</sup> )	19.6–53.2	47
Nitrite-nitrogen concentration NO <sub>2</sub> -N (mg/dm <sup>3</sup> )	0–0.13	0.09
Nitrate-nitrogen concentration NO <sub>3</sub> -N (mg/dm <sup>3</sup> )	0.1–0.97	0.68
Total phosphorus concentration TP (mg/dm <sup>3</sup> )	2.51–4.59	3.2

*Activated sludge.* The seeding activated sludge used in the experiment was taken from a urban wastewater treatment plant (WWTP) in Wuxi city. During the start-up period, the reactor operated for 34 days until the removal efficiency of NH<sub>4</sub><sup>+</sup>-N and COD were over 85% and 95%, respectively. Mixed liquor suspended solids (MLSS) in the five step continuous flow activated sludge process during experimental period remained between 1750 and 2200 mg/dm<sup>3</sup> in tank two, three, and four while it was between 3500 and 6000 mg/dm<sup>3</sup> in tank one and five.

*Analytical methods.* COD, NH<sub>4</sub><sup>+</sup>-N, NO<sub>2</sub>-N, NO<sub>3</sub>-N, and TN were analyzed according to standard methods [17]. NO<sub>2</sub>-N and NO<sub>3</sub>-N were analyzed by the IC method (Metrohm 761 compact IC equipped with Metrosep asupp. 5 column) and TN was analyzed with an Analytic Jena AG multi N/C 3000 apparatus.

### 3. RESULTS AND DISCUSSION

#### 3.1. OPTIMAL OPERATING PARAMETERS

The experimental results showed that a HRT of 16 h, sludge age of 21 days and air/water ratio of 35% are optimal operating parameters (Table 2). The duration of running periods are established in this study under optimal operating parameters and according to biological process requirements and sludge settling properties as shown in Table 2. The optimal time required for period I is 90 min, for period II – 60 min, and period III – 60 min according to biological process requirements while for period IV is 30 min according to sludge settling properties.

Table 2

Effect of operating parameters and duration of the period on pollutants removal efficiency

Flow rate [m <sup>3</sup> /min]	HRT [h]	Air/water ratio [%]	Duration of the period [min]			Removal rate %			
			I	II	III	COD	NH <sub>4</sub> <sup>+</sup> -N	TN	TP
20	12	35	70	50	50	94.2	90.12	65.13	63.73
20	12	35	90	50	50	89.79	91.81	72.33	83.66
20	12	35	110	50	50	92.62	88.24	62.15	75.21
20	12	35	90	40	50	91.23	87.54	62.37	60.81
20	12	35	90	60	50	88.64	93	74.91	84.69
20	12	35	90	80	50	88.71	94.78	61.21	59.17
20	12	35	90	60	40	90.12	88.51	64.32	71.36
20	12	35	90	60	60	88	93.41	74.17	84.65
20	12	35	90	60	80	88.21	94.1	63.19	61.19
20	12	30	90	60	60	76.55	78.25	42.7	46.67
17.5	14	30	90	60	60	83.16	86.3	53.32	71.93
15	16	30	90	60	60	88.12	88.9	63.9	75.13
12.5	19	30	90	60	60	87.83	90.71	57.78	72.54
10	24	30	90	60	60	88.28	91.2	51.78	60.97
7.5	32	30	90	60	60	88.01	91.68	50.04	60.07
5	48	30	90	60	60	88.43	91.97	49.91	58.76
20	12	25	90	60	60	84.34	80.53	52.51	56.91
20	12	30	90	60	60	86.89	87.68	66.03	82.41
20	12	35	90	60	60	87.84	90.37	67.12	73.5
20	12	40	90	60	60	87.38	92.01	58.97	66.74
20	12	45	90	60	60	87.04	92.14	57.02	62.46
20	12	50	90	60	60	86.87	92.20	56.68	62.88

### 3.2 MECHANISMS OF NITROGEN AND PHOSPHOURS REMOVAL IN FSCFASP SYSTEM

The first half cycle was divided into four periods which are period I of 1.5 h, period II of 1 h, period III of 1 h, and period IV of 0.5 h.

*Processes in tank one.* During the first half cycle, tank one operated a continuous stirred tank reactor (CSTR) from 0 min through 90 min, sequence batch reactor SBR from 90 min through 240 min, and CSTR during the second half cycle thus it is PFR. Tank one during the first half cycle corresponds to tank five, during the second half cycle, therefore this analysis also refers to tank five during the second half cycle. Tank one was an anaerobic tank during period I. Its main biological function during this period was denitrification and phosphorus release. The variations of pollutants concentrations are shown in Fig. 3a.

Tank one was a settling tank during period VIII, thus concentrations of pollutants were low at the beginning of period I (meeting the Chinese standard discharged efflu-

ent) as shown in Fig. 3a. Tank one was an intake tank during period I without aeration. The denitrification process continued for 15 min due to nitrate-N concentration that remained from previous period (period VIII) thus the rate of phosphorus release increased slowly during the first 15 min of period I.

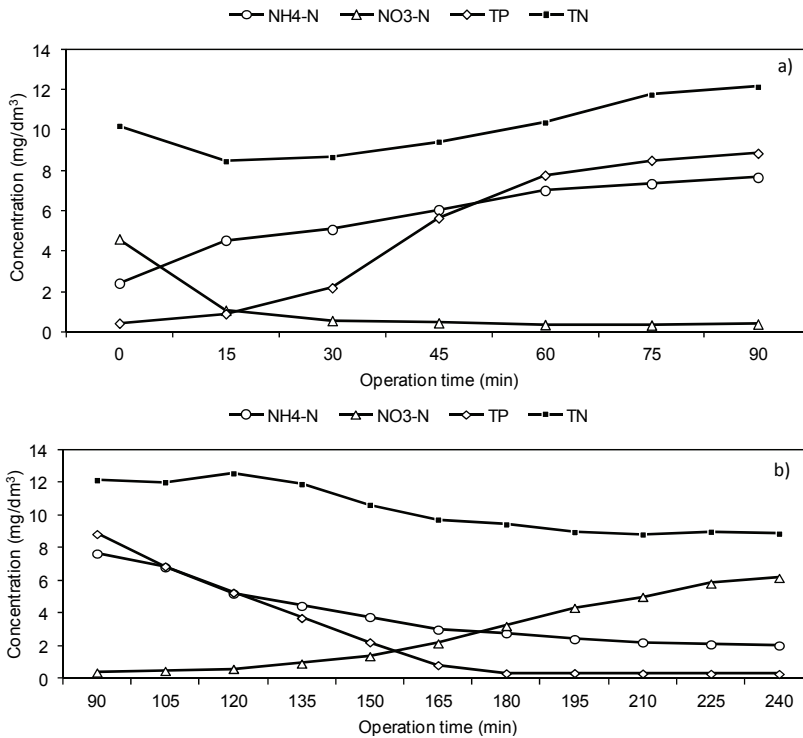


Fig. 3. Typical dynamics of pollutants concentrations during periods I (a), II, III and IV (b) in tank one

Ammonia-N, nitrate-N, total nitrogen (TN), and total phosphorus (TP) concentrations at the beginning of period I were 2.41 mg/dm<sup>3</sup>, 4.61 mg/dm<sup>3</sup>, 10.21 mg/dm<sup>3</sup>, and 0.43 mg/dm<sup>3</sup>, respectively. The experimental analysis showed that ammonia-N concentration increased upon increasing time during period I. It increased from 2.41 mg/dm<sup>3</sup> at 0 min to 7.65 mg/dm<sup>3</sup> after 90 min. In this period, the residual NO<sub>3</sub>-N (electron acceptor) from previous settling period was removed rapidly by denitrification process. It decreased quickly to 1.07 mg/dm<sup>3</sup> within 15 min. Then, it slowly declined to less than 0.5 mg/dm<sup>3</sup> after 30 min. NO<sub>3</sub>-N concentration basically remained unchanged (0.5 mg/dm<sup>3</sup>) after 30 min because denitrification process was completed in tank one. At the beginning of period I, total nitrogen concentration decreased slowly due to dual effect of denitrification process and influent wastewater. It decreased due to reduction in NO<sub>3</sub>-N concentration (electron acceptor of denitrification). This electron acceptor was exhausted highly during 15 min in the denitrification process. TN concentration



increased rapidly after 30 min because denitrification process stopped thus concentration of nitrate-N electron acceptor was unchanged after 30 min ( $0.5 \text{ mg/dm}^3$ ). As a result, TN concentration increased from  $8.66 \text{ mg/dm}^3$  after 30 min to  $12.14 \text{ mg/dm}^3$  at the end of period I due to the dominant effect of influent wastewater in tank one. Anaerobic phosphorus release was the main process in tank one because concentrations of the two electron acceptors of nitrification and denitrification were very low; large amount of organic matter were introduced by the influent wastewater thus phosphorus accumulating organisms (PAOs) created good condition for rapid phosphorus release. TP concentration slowly increased during the denitrification period. It increased from  $0.43 \text{ mg/dm}^3$  at 0 min to  $0.89 \text{ mg/dm}^3$  after 15 min but it increased rapidly after 30 min. It also increased from  $2.18 \text{ mg/dm}^3$  after 30 min to  $8.85 \text{ mg/dm}^3$  after 90 min.

Tank one operated under aerobic condition during periods II and III which is similar to operation of tank five during periods VI, VII while it was under settling conditions during period IV, similarly as in tank five during period VIII. The main functions of tank one during aerobic periods were nitrification, phosphorus uptake, and degradation of organic matter. The variations of concentrations of pollutants during periods II, III and IV are shown in Fig. 3b.

Concentrations of ammonia-N, nitrate-N, total nitrogen, and total phosphorus at the beginning of period II were  $7.65 \text{ mg/dm}^3$ ,  $0.39 \text{ mg/dm}^3$ ,  $12.14 \text{ mg/dm}^3$ , and  $8.84 \text{ mg/dm}^3$ , respectively. Ammonia-N concentration gradually decreased during aeration period from  $7.65 \text{ mg/dm}^3$  after 90 min to  $2.23 \text{ mg/dm}^3$  after 210 min and  $2.04 \text{ mg/dm}^3$  at the end of the static settling period. Nitrate-N concentration of tank one at the aeration state increased slowly reaching  $1.39 \text{ mg/dm}^3$  after 150 min. Then, it increased significantly to  $5.01 \text{ mg/dm}^3$  at the end of period III due to was simultaneous nitrification and denitrification (SND) inside tank one until 150 min. SND phenomenon via  $\text{NO}_3\text{-N}$  is called sometimes aerobic denitrification process or nitrification by heterotrophic organisms. In continuously operated plants, SND offers the potential to save the costs for a second (anoxic) tank, or at least reduce time of its operation, unless a considerable denitrification takes place together with nitrification in the aerated tank. For a sequencing batch reactor, which consists of only one single tank, instead of reducing the space required, SND could reduce the necessary time for complete nitrification and denitrification. The given explanations for the phenomenon of SND can be divided into two broad categories. They are either physical or biological in nature; the physical and conventional explanation is that SND occurs as a consequence of gradients of DO concentration within microbial flocs or biofilms due to diffusional limitations. That is, the nitrifiers exist in regions with high dissolved oxygen concentrations, whereas denitrifiers will preferentially be active in zones with very low dissolved oxygen concentrations; biological explanations for SND are in contrast to the traditional "engineering" concept of nitrification and denitrification [18]. Dissolved oxygen level varied between  $0.2\text{--}2.56 \text{ mg/dm}^3$  during the aeration period. Low dissolved oxygen level conducive to simultaneous nitrification and deni-

trification (SND) phenomenon while high dissolved oxygen level leads to decreasing of ammonia-N concentration and increasing of nitrate-N concentration due to the effect of nitrification process. It can be seen from Fig. 3b that TN concentration decreased but the rate of decreasing was not very high. It fluctuated between 11.9 and 12.14 mg/dm<sup>3</sup> during the first 45 min of period II due to dual effect of ammonia and nitrate concentration. Phosphorus was consumed by phosphorus accumulating organisms (PAOs) thus TP level gradually decreased to less than 0.83 mg/dm<sup>3</sup> at 165 min. TP stabilized at about 0.34 mg/dm<sup>3</sup> after 180 min.

Tank one was under static settling conditions during period IV for preparing it as effluent tank during the second half cycle. Pollutants concentrations were basically stable and met the Chinese discharged standard requirement level – A (GB18918-2002 Grade A) during period IV.

*Processes in tank two.* Tank two operated CSTR during two half cycles. During the first half cycle, tank two is similar to tank four during the second half cycle. Thus, this analysis refers also to tank five during the second half cycle.

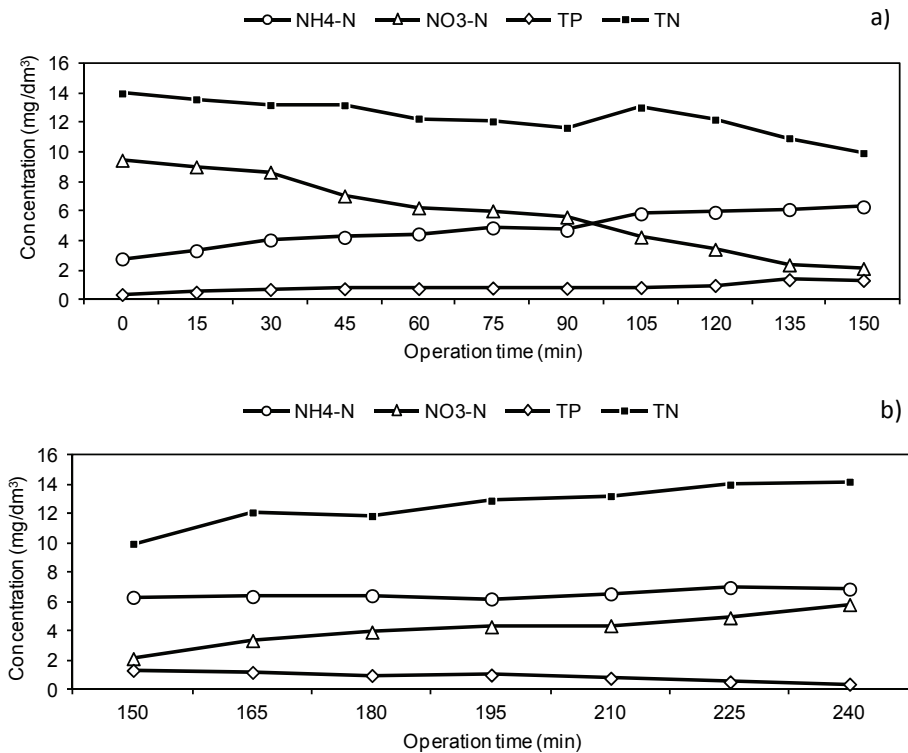


Fig. 4. Typical dynamics of pollutants concentrations during periods I, II (a), III and IV (b) in tank two

Tank two operated under anoxic condition during periods I and II (as tank four during periods V and VI). Its main function during these periods was denitrification. The main difference between period I and II of tank two is the intake location where it was changed from tank one during period I to tank two during period II. The variations of concentration of pollutants were shown in Fig. 4a.

It is visible from Fig. 4a that nitrate-N concentration decreased from  $9.45 \text{ mg/dm}^3$  at the beginning of the denitrification period to  $2.13 \text{ mg/dm}^3$  after 150 min. Nitrate-N concentration decreased slowly within 30 min. Then, it decreased rapidly. The level of dissolved oxygen was high ( $0.73\text{--}2.53 \text{ mg/dm}^3$ ) at the early stage of period I. This happened because tank two operated under aerobic conditions during previous periods and adjacent to other aerobic tanks. It operated under aerobic conditions during six periods of eight, which corresponds to 5.5 h of a cycle time 8 h. Dissolved oxygen level was reduced below  $0.5 \text{ mg/dm}^3$  after 40 min of the denitrification process which met the requirements of the process. It can be concluded that there occurred simultaneous nitrification denitrification phenomena (SND via dissolved oxygen) because the two electron acceptors, dissolved oxygen and nitrate-N of nitrification and denitrification process were available. Thus nitrate-N level decreased slowly during the first 30 min of denitrification. Ammonia-N concentration increased gradually from  $2.78 \text{ mg/dm}^3$  at the beginning of denitrification process to  $6.3 \text{ mg/dm}^3$  after 150 min. It was observed from Fig. 4a that total nitrogen level generally decreased during periods I and II. TN concentration was reduced from  $13.98 \text{ mg/dm}^3$  at beginning of period I to  $9.94 \text{ mg/dm}^3$  after 150 min. The effect of denitrification process was limited till 30 min due to high DO level. TN concentration decreased significantly after 45 min remaining stable without obvious change between 60–90 min; it was  $11.64 \text{ mg/dm}^3$  at 90 min and increased to  $13.02 \text{ mg/dm}^3$  after 105 min. The source point of raw wastewater changed to tank two during period II thus TN increased after 90 min because the raw wastewater was characterized by high nitrogen concentration. However it decreased again to reach  $9.94 \text{ mg/dm}^3$  after 150 min due to the effect of denitrification process. TP concentration increased slowly during periods I and II as shown in Fig. 4a. The initial TP concentration was low ( $0.37 \text{ mg/dm}^3$ ) because tank two operated under aerobic conditions during the second half-cycle. TP concentration did not increase significantly, did not exceeding  $1 \text{ mg/dm}^3$ , during period I even though in the access flow of tank one the phosphorus concentration was high. TP and  $\text{NO}_3\text{-N}$  profiles revealed simultaneous denitrification and phosphorus uptake in tank two. PAOs could use however nitrate nitrogen as electron acceptor for biological phosphorus removal instead of oxygen but it would be inhibited by the presence of COD. The rate of phosphorus uptake in the anoxic periods is related to the concentration of nitrate: higher nitrate concentration could result in higher phosphorus uptake rate within the range of experimental nitrate concentration; but possibly nitrate is not efficient as oxygen for phosphorus removal because the efficiency of PHA consumption in the system in which nitrate was used as electron acceptor is lower than in that using oxygen. The

previous experimental study by Ekama [19] showed that if the nitrate load into the main anoxic reactor is lower than the denitrification potential of XH, the XH will compete with PAOs for using the limited nitrate. If the nitrate load in the main anoxic reactor exceeds the denitrification potential of XH, the PAOs would use the “excess” nitrate and thus develop in the system [19]. Anoxic phosphorus uptake phenomenon may thus occur if under high nitrate-N concentration denitrification ability is exceeded. In tank two, period I started with high nitrate-N concentration. It operated under aerobic conditions during last periods whereas nitrate-N level exceeded denitrification ability. Thus, phosphorus was uptaken by DPAOs and nitrate-N was reduced for denitrification process. The use of a carbon source for denitrification decreased the formation of PHA and the release of the phosphorus. In period II, the flow path started from tank two thus TP concentration increased reaching at the end of the period the value of  $1.33 \text{ mg/dm}^3$ .

Tank two operated under aerobic conditions during periods III and IV which is similar to operation of tank four during periods VII and VIII. The main functions of tank two during aerobic periods were nitrification, phosphorus uptake and organic matter degradation. The variations of concentrations of pollutants during periods III and IV are shown in Fig. 4b.

Ammonia-N level increased slowly (Fig. 4b) as tank two was the intake tank during periods III and IV showing a combined effect of nitrification and influx raw wastewater. Ammonia-N concentration increased from  $6.29 \text{ mg/dm}^3$  at 150 min to  $6.86 \text{ mg/dm}^3$  at the end of nitrification process. At the same time, during nitrification period, nitrate-N concentration gradually increased from  $2.12 \text{ mg/dm}^3$  after 150 min to  $5.81 \text{ mg/dm}^3$  at the end of period IV. The SND phenomenon was unobvious in the tank during aerobic periods due to low sludge concentration whereas DO level increased to  $1.28 \text{ mg/dm}^3$  during 30 min. Total nitrogen concentration increased gradually due to combined effects of ammonium nitrogen and nitrate-N. Aerobic phosphorus uptake occurred in tank two during periods III and IV whereas TP concentration decreased from  $1.33 \text{ mg/dm}^3$  after 150 min to  $0.39 \text{ mg/dm}^3$  at the end of nitrification process.

*Processes in tank three.* Tank three is a mid-, serving as third step of five-step continuous flow activated sludge process. It is different from other tanks due to symmetric operating state conditions during two half cycles. The analysis of operation of tank three during the first half cycle also represented tank three during the second half cycle due to symmetrical in operating conditions.

Tank three operated under aerobic condition during periods I and II which was similar to tank three during periods V and VI. The main functions of tank three during aerobic periods were organic matter degradation, nitrification, and phosphorus uptake. A typical dynamics of offline nutrient measurement during periods I and II is shown in Fig. 5a.

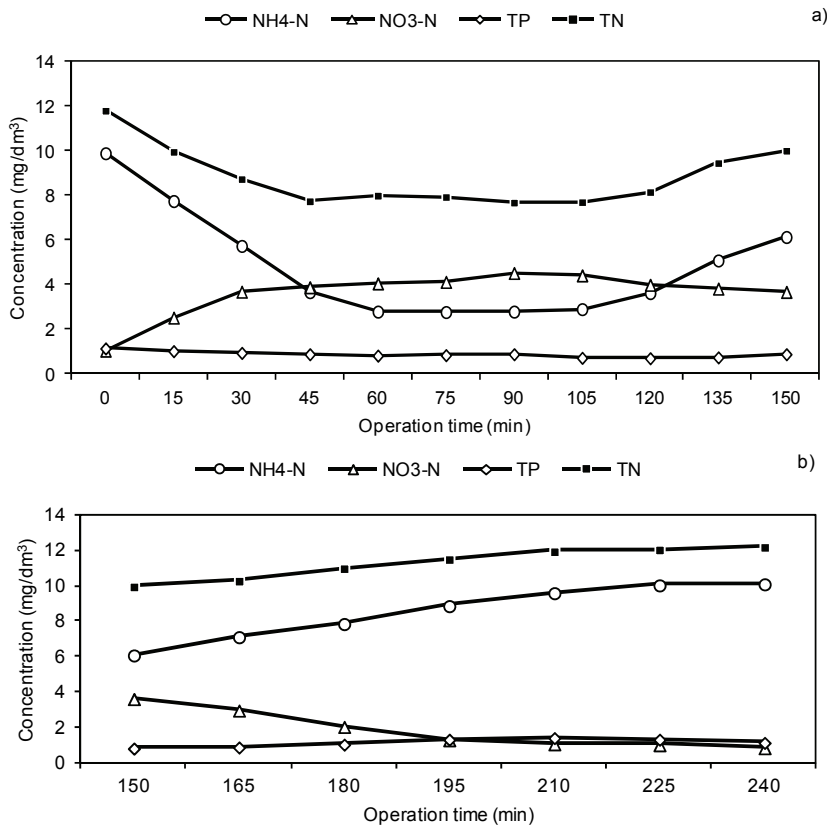


Fig. 5. Typical dynamics of pollutants concentrations during periods I, II (a), III and IV (b) in tank three

It can be seen from Fig. 5a that ammonia-N contents decreased from  $9.87 \text{ mg/dm}^3$  at the beginning of period I to  $2.78 \text{ mg/dm}^3$  after 60 min due to aerobic nitrification. Then, it fluctuated between  $2.78$  and  $2.89 \text{ mg/dm}^3$  till 105 min due to ammonia-N concentration of access water from tank two of ca.  $4.5 \text{ mg/dm}^3$  during period I. In addition, dissolved oxygen level of tank three reached  $2.36 \text{ mg/dm}^3$  after 45min of aeration period because sludge concentration in tank three was low, i.e.  $1750\text{--}2200 \text{ mg/dm}^3$ . Nitrification was thus limited and ammonia-nitrogen was in balance due to interaction of nitrification of tank three and access of water to tank two.  $\text{NO}_3\text{-N}$  concentration increased from  $1.03 \text{ mg/dm}^3$  at early stage of period I to  $4.51 \text{ mg/dm}^3$  at the last stage of this period. During period II, tank one, tank three and tank four operated under aerobic conditions. Hence, oxygen supply of tank three was lower than in period I while nitrogen concentration in the access water from tank two was high. Therefore, the balance between original wastewater of tank three and its nitrification process was broken. Owing to that;  $\text{NH}_4^+\text{-N}$  concentration increased. It reached  $6.12 \text{ mg/dm}^3$  at the end of period II.  $\text{NO}_3\text{-N}$  profile relatively decreased slowly from  $4.51 \text{ mg/dm}^3$  at

90 min to  $3.66 \text{ mg/dm}^3$  at the end of period II. TN concentration was under combined effect of ammonium nitrogen and nitrate-N therefore it decreased during period I while it was slowly increasing during period II as the access wastewater from tank two contained more nitrogen during period II. It can be seen also from Fig. 5a that change of the TP profile is unobvious. TP concentration varied in the range  $0.87\text{--}1.13 \text{ mg/dm}^3$ . It decreased slightly in the early stage. Then, it basically remained unchanged because tank two operated under anoxic conditions without phosphorus release, the sludge concentration in tank three was relatively low thus phosphorus uptake power was not strong.

Tank three operated under anoxic conditions during periods III and IV similarly as during periods VII and VIII. The main function of tank three during anoxic periods was denitrification. The access water flowed to tank three from tank two. Tank two operated under aerobic conditions during periods III and IV. Typical dynamics of off-line nutrient measurement during the first half cycle is shown in Fig. 5b. The electron acceptor  $\text{NO}_3\text{-N}$  concentration in the denitrification process decreased continuously, reaching  $0.89 \text{ mg/dm}^3$  at the end of period IV, although concentration of nitrate-N in the access water from tank two to tank three was high. This indicates that the denitrification process was efficient in tank three during periods III and IV. Ammonia-N concentration increased gradually because its concentration in the access water from tank two increased upon time (tank two was intake tank during periods III and IV). TN concentration increased slowly during periods III and IV due to combined effect of ammonium nitrogen and nitrate-N. It can be seen also from Fig. 5b that TP concentration as a whole increased slowly from  $0.87 \text{ mg/dm}^3$  at the beginning of period III to  $1.46 \text{ mg/dm}^3$  after 210 min. The rate of phosphorus release was low during periods III and IV because the denitrification process was efficient whereas nitrate-N electron acceptor decreased continuously and the phosphorus concentration in the access water from tank two was low.

*Processes in tank four.* Tank four operated CSTR during two half cycles. During the first half cycle its operation was similar to that in the second half cycle thus this analysis refers also to tank two during the second half cycle.

Tank four operated under aerobic conditions during the first half cycle. The main functions were nitrification, phosphorus uptake and organic matter degradation. A typical dynamics of offline nutrient measurement and online monitoring parameters during the first half cycle is shown in Fig. 6.

Ammonia-N and total phosphorus concentrations were high at the early stage of period I because tank four operated as intake tank during the two previous periods (period VII and VIII). It operated under aerobic conditions during the first half cycle. Hence, ammonia-N concentration decreased from  $7.01 \text{ mg/dm}^3$  at the beginning of the first half cycle to  $2.44 \text{ mg/dm}^3$  at its end. Nitrate-N concentration increased also regularly from  $5.48 \text{ mg/dm}^3$  at the beginning of the first half cycle to  $9.8 \text{ mg/dm}^3$  at the end. TN concentration fluctuated between  $12.4$  and  $14 \text{ mg/dm}^3$  according to the com-

bined double effect of ammonia-N and nitrate-N concentration TP concentration decreased from 0.49 mg/dm<sup>3</sup> at the start of period I to 0.34 mg/dm<sup>3</sup> at the end of period IV. TP concentration remained below 0.5 mg/dm<sup>3</sup> which guaranteed more efficient effluent discharge.

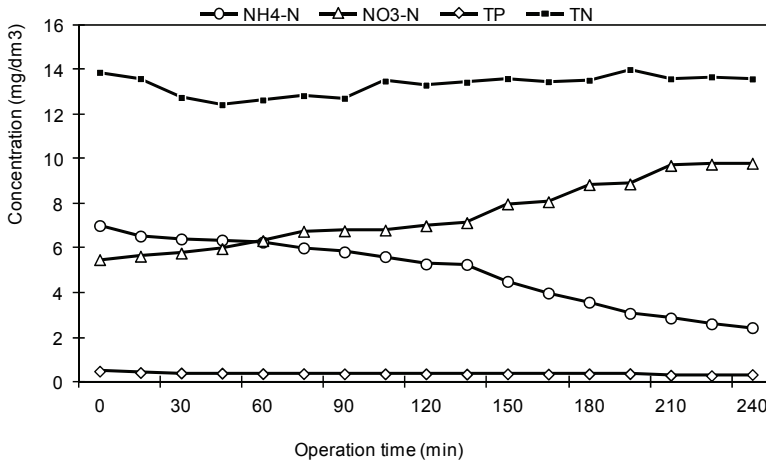


Fig. 6. Typical dynamics of pollutant concentrations during periods I, II, III and IV in tank four

*Processes in tank five.* Tank five operated as settling discharge tank during the first half cycle under consecutively anaerobic/oxic/settling conditions, while during the second half cycle it operated under anaerobic conditions CSTR, aerobic conditions SBR and settling conditions as static settling tank. During the first half cycle its operation was similar to that of tank one during the second half cycle.

The main function of tank five during the first half cycle was preparing it as settling effluent tank during the second half cycle. A typical dynamics of offline nutrient measurement during the first half cycle is shown in Fig. 7.

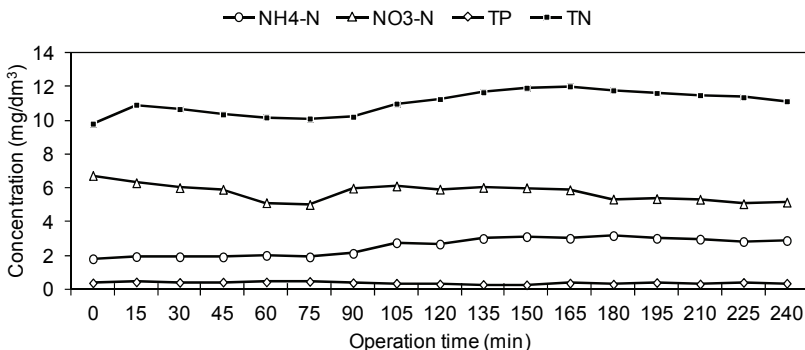


Fig. 7. Typical dynamics of pollutants concentrations during periods I, II, III and IV in tank five

The pollutant concentration was relatively stable. The ammonia-N concentration increased slightly but did not exceed  $3.2 \text{ mg/dm}^3$ . Total nitrogen concentration varied between  $9.81$  and  $12.01 \text{ mg/dm}^3$ , while nitrate-N concentration decreased slightly from  $6.74 \text{ mg/dm}^3$  at the beginning of the first half cycle to  $5.16 \text{ mg/dm}^3$  after 240 min although the access water of tank four flowed to tank five with high concentration of nitrate-N. The denitrification process in tank five however was not very efficient during the first half cycle. Denitrification occurred in tank five due to tiny floated bubbles during the first half cycle. TP concentration was basically stable. It varied between  $0.27$  and  $0.44 \text{ mg/dm}^3$ . As a result, the  $\text{NH}_4^+\text{-N}$  level was lower than  $5 \text{ mg/dm}^3$ , TN was lower than  $15 \text{ mg/dm}^3$ , and TP lower than  $0.5 \text{ mg/dm}^3$ . Therefore the effluent water quality met the Chinese sewage discharged standard GB18918-2002 level-A.

### 3.3. SLUDGE MOVEMENTS

During the sludge incubation period, the sludge concentration increased gradually in the system and the sludge volume ratio (SV) increased as well. After the incubation period, the sludge concentration in tank one was around  $4500 \text{ mg/dm}^3$ . The variations of concentration of the mixed liquor in each tank of the five-step continuous flow activated sludge system was observed during the first half cycle as shown in Fig. 8. The sludge volume ratio reached about 22% while sludge volume index (SVI) was basically stable at around 55. After 31 days of incubation period, the sludge properties can be described as high floc density, good settling properties, brown, clay smell, and gradually mature.

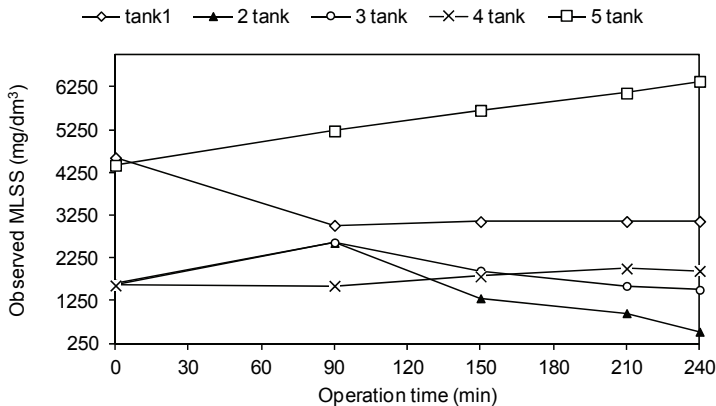


Fig. 8. Observed sludge distribution in each tank of FS-CFASP during the first half cycle

Owing to the flow path, FS-CFASP is entered and discharged on two sides via symmetric alternating way of inlet wastewater and outlet water. Thus, there was no mandatory return sludge and mixed liquor equipments. The system was dependent on



the push stream, opposite flow direction, to implement automatic mixed liquor and sludge recycle. The electromagnetic valves technology in this system promoted mixed liquor and sludge movement from left to right or reverse according to the flow direction. The sludge concentration of FS-CF system at the inlet side gradually decreased while the sludge concentration on the outlet side gradually increased. The sludge surface lifted in a settling tank along with a half cycle time. The cycle time and tank volume were selected to avoid over-reaction zone of sludge concentration. When the sludge surface lifted over the water surface, it would deteriorate the quality of effluent water. In FS-CFASP, the sludge concentration in tank one and tank five during the first half cycle varied between 3000–6500 mg/dm<sup>3</sup> while in all squared tanks it varied between 500 and 3000 mg/dm<sup>3</sup>. The sludge concentration in squared tanks was lower than in tank one and tank five as shown in Fig. 8. In accordance with the data of Fig. 8, the average sludge concentrations in tanks one, two, three, four and five during the first half cycle were 3388 mg/dm<sup>3</sup>, 1404 mg/dm<sup>3</sup>, 1867 mg/dm<sup>3</sup>, 1798 mg/dm<sup>3</sup>, and 5571 mg/dm<sup>3</sup>, respectively while the maximum sludge concentration was observed in tank one during the second half cycle and tank five during the first half cycle.

#### 3.4. PERFORMANCE OF FSCFASP PROCESS

In the FSCFAS process, the average COD removal efficiency was 88.09%±1.43 and the effluent COD concentration was ca. 28.6–35.4 mg/dm<sup>3</sup> during all runs of the experiments. Also, the average ammonia removal efficiency was 90.33 ± 2.9% during all runs of the experiments.

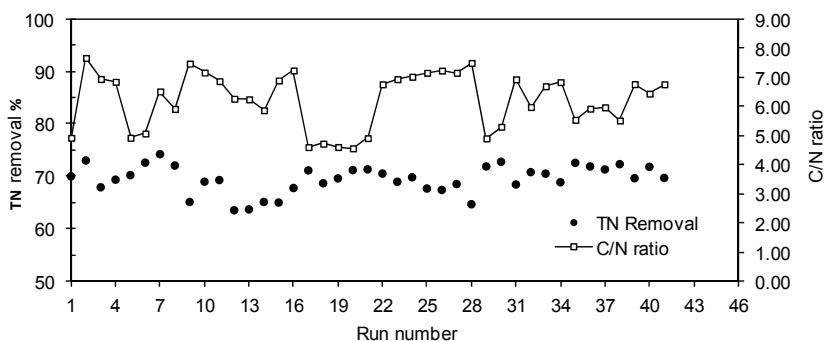


Fig. 9. Nitrogen removal efficiency of FS-CFASP

Figure 9 shows the efficiency of nitrogen removal in FSCFASP. It is obvious that efficiency of phosphorus removal in FSCFAS process was higher and stable. When C/N ratio ranged from 4.5 to 6.6, the nitrogen removal efficiency was maintained at 68.83±5.34%. The effluent nitrogen concentrations of the FSCFASP were

11.68–14.44 mg/dm<sup>3</sup>. Therefore, the effluent nitrogen concentrations met the Chinese National Class I (grade A) Sewage Discharge Standard.

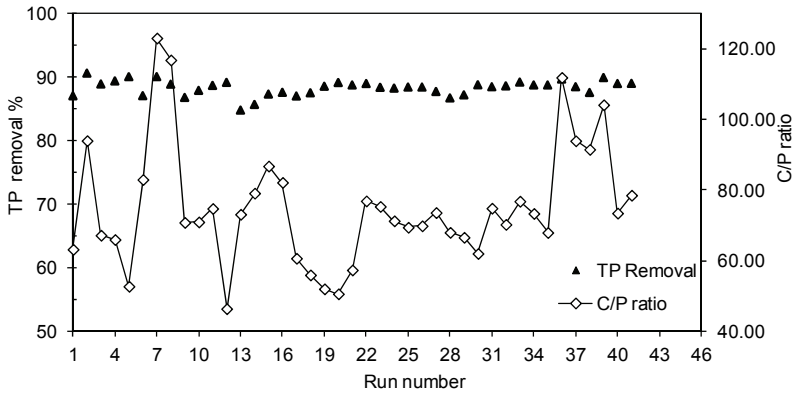


Fig. 10. Phosphorus removal efficiency of FS-CFASP

Figure 10 shows the phosphorus removal efficiency in FS-CFASP. When C/P ratio varied between 46.5–123, the phosphorus removal efficiency maintained  $87.67 \pm 2.9\%$ , whereas the effluent phosphorus concentrations were 0.27–0.49 mg/dm<sup>3</sup>. Therefore, the effluent phosphorus concentrations met the Chinese National Class I (grade A) Sewage Discharge Standard.

#### 4. CONCLUSIONS

The duration of each period was established according to biological process requirements:

- Period I requires 90 min to reach the main function of anaerobic phosphorus release.
- Period II requires 60 min to reach the main function of denitrification and phosphorus uptake.
- Period III takes 60 min to reach the main function of nitrification and phosphorus uptake.
- Period IV requires 30 min to reach main function of settling tank preparation to the next half cycle.

The optimal running was achieved at a HRT of 16 h, sludge age of 21 day and air/water ratio of 35% at temperature range of 19–23 °C.

The optimized system achieved  $88.09 \pm 1.43\%$ ,  $90.33 \pm 2.9\%$ ,  $68.83 \pm 5.34\%$  and  $87.67 \pm 2.9\%$  of chemical oxygen demand, NH<sub>4</sub><sup>+</sup>-N, TN, and TP removal efficiencies,

respectively, during a 11-month operation with the effluent meeting the Chinese sewage discharge standard GB18918-2002 (level A).

Simultaneous nitrification and denitrification (SND) phenomena were observed in tank one which is important to reduce the aeration and the duration of the next process under anoxic/anaerobic conditions.

Compared with other existing technologies, in the system high nitrogen and phosphorus removal was achieved without special equipment for sludge and mixed liquor return. Thus, it is effective for reducing energy consumption.

This system can find many applications because of its low capital and operating costs, small land requirement, and excellent removal of organic carbon, nitrogen and phosphorus nutrient species as compared to other existing technologies.

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