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Intercross real-time control strategy in a novel phased isolation tank step feed process for treating low C/N real wastewater under ambient temperature

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Abstract−The paper presents a study correlating the profile of on-line monitoring parameters and off-line measurement of nutrient concentrations (NH_4^+-N, TN, NO_3^--N and TP) in a novel technology phased isolation tank step feed (PITSF) system, thereby utilizing the parameters as economical operational tool. A fixed-time control study showed that real control points (RCPs) on pH and oxidation-reduction potential (ORP) profiles accurately coincided with the major biological activities, whereas both DO and pH profiles are applied to control the end of nitrification and phosphate uptake process in aerobic phases, in particular, the “ammonia valley” on the pH profile for nitrification process. The analysis of the first aerobic tanks during the main phases showed that the RCP on DO profile can be used to distinguish the occurrence of simultaneous denitrification and nitrification (SND). Both the RCPs on the ORP profile and “nitrate apex” on the pH profile are applied to control the end of denitrification. The relationship between ORP and phosphorus release is linear and both (dORP/dt) and (dpH/dt) values are applied to control the end of anaerobic phosphorus release. Therefore, a new, reliable and effective real-time control strategy was developed using DO, pH and ORP as control parameters, to improve the performance of the PITSF process. As a final engineering observation, the proposed system is regarded as an effective process because the PITSF system can be operated safely under intercross real time control to treat low C/N domestic wastewater. The total nutrient removal efficiencies of COD, TN, NH_4^+-N, and TP with low C/N ratio and normal water temperature of (17-21) °C were 91.7, 83.2, 95.7 and 92.1%, respectively, which was approximately equal to the complete nitrification-denitrification with the addition of external carbon sources under low water temperature of (8-11) °C.

Keywords: On-line Monitoring Parameters (ORP, DO and pH), PITSF, Nutrient Removal, Low C/N Ratio

INTRODUCTION

The operation of wastewater treatment plants (WWTPs) is challenging for many small communities for economical and technological reasons. The strict discharge requirements defined by the China Environment Protection Bureau (GB18918-2002) [1], which came into effect in the last few years, will possibly have to increase both operation costs and efficient penalties to prevent process failure. Hence, strong incentives to promote the existing wastewater treatment plant to have them cope with the future effluent discharge. For this reason, a novel treatment technology phased isolation tank step feed (PITSF) system was proposed by Southeast University in china to treat domestic wastewaters efficiently with low carbon source. It was designed like SBR in control methodology and AA/O in spatial structure and its own property. Indeed, it is more similar to a normal multi-tank process, such as A2/O or UCT, but it achieves automatic reflow without the need of reflow equipment for mixed liquor and with less sludge recirculation [2]. The direction of flow in the PITSF system is changed automatically through changing intake location, which is the main difference between our technology (PITSF) and other common activated sludge process technologies. Consequently, PITSF is effective for reducing energy consumption. Offline measurements of nutrient and carbon concentrations (NH_4^+-N, NO_3-N, PO_4-P, COD, etc.) are often time uncontrollable and costly, and because of time lapse may discourage accurate control of the process. Nevertheless, if the dynamic behaviors of nutrient concentration in the biological nutrient removal (BNR) system with treatment are somehow connected with the on-line monitored parameters of DO pH, and ORP, the BNR system would be more efficiently controlled.

Real-time control has been proven to be useful in optimizing the energy requirements of biological treatment processes, because aeration and mixing are ceased as soon as the targeted compound is treated [3]. Recently, many studies have considered the oxidation-reduction potential (ORP), the pH, the dissolved oxygen (DO) levels for monitoring and controlling the BNR [4-6]. Several investigators have recognized the potential of ORP as being used as a control parameters for anaerobic under operation of low DO level in a systems [7-9]. Unfortunately, only a few studies have used indicators on line monitoring parameter to investigate the step feed nitrogen removal process control in treating real domestic wastewater with low C/N ratio. Additionally, a few studies on similar relationship have been aimed at treating domestic wastewater at ambient temperature [10-13]. However; use of real domestic wastewater under

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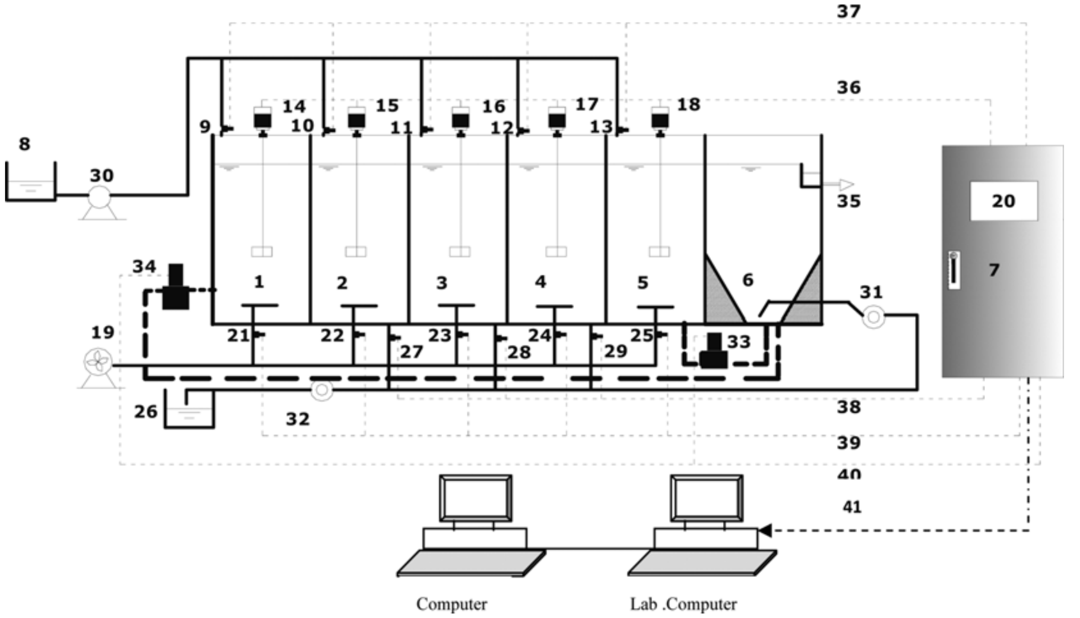

Fig. 1. Scheme of PITSF activated sludge system 1, 2, 3, 4, 5 - five tank, 6 - settling tank, 7- PLC programmable logic controller, 8 - Air compressor, 9 - inlet reservoir 10 - inlet pipe, 9, 10, 11, 12, 13 - inlet electromagnetic valve, 14, 15, 16, 17, 18 - mixer, 21, 22, 23, 24, 25 - aeration electromagnetic valve 26- excess sludge tank 27, 28, 29 - sludge return valve, 30 - inlet pre-static pump, 31-sludge recycle control meter, 32 - excess sludge control meter 33, 34 - sludge discharge valves, 35 - effluent, 36 - electrical mixer line, 37 - electrical inlet valve line, 38- electrical sludge return valve line, 39 - electrical aeration valve line, 40 - electrical sludge discharge valve line, 41 - data cable.

low C/N ratio and low temperature has not been reported under real-time control parameters. Therefore, we aim to investigate, first, a novel technology PITSF activated sludge process in treating domestic wastewater with low carbon source; and secondly, to enhance the nutrient removal of low carbon source domestic wastewater through applying a real time control strategy at ambient temperature. Specifically, the objectives are to (1) identify features points on the DO, ORP and pH profiles and their slope profiles that could be used for nutrient removal control in a new PITSF system; (2) develop a strategy of on-line monitoring parameters pH, DO and ORP and its use as control parameters to optimize the operation of the PITSF system under different conditions.

MATERIALS AND METHODS

1. Reactor and Operation

Lab experiments were conducted in a new pilot scale phased isolation tank step feed which is composed of a rectangular box divided by baffles to form six-zone reactor. All zones except the last one have the same rectangular plane 280×240 mm and are supplied with mechanical mixers and air diffusers for providing a suitable state condition (anaerobic-anoxic/oxic) in the same basin. The ORP, pH and DO probes were inserted into PITSF system. The output signal was converted directly to a PLC. The last zone was operated as a clarifier. The particular advantages of this process are a simple structure, compact volume and safe operation. This process is a continuous flow process with a constant water level which makes high utilization capacity in the system. The main parts of a pilot plant utilized in this study are the main body, which is a rectangular box of 860×535×905 mm, 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. The principal diagram of the pilot plant with all major components is shown in Fig. 1. Oxygen was supplied by an air compressor through an air diffuser inside the reactor.

2. Wastewater and Sludge Characteristics

The raw wastewater was taken from Wuxi campus, Southeast University. Approximately 1,000 L of wastewater was pumped from the sewer line and transported to the hall laboratory every day. To minimize the variation of wastewater characteristics from day to day, municipal wastewater was collected at approximately the same time each day. Average influent COD to nitrogen ratio (C/N) was only about 2.53, and thus the organic matter was typically limiting. The characteristics of wastewater quality are listed in Table 1.

3. Analytical Method

Samples for dynamic studies were collected directly from the PITSF reactor. Conventional parameters such as mixed liquor suspended solids (MLSS), CODCr, NH_4^+-N, NO_2-N, NO_3-N, and alka-

Table 1. Typical characteristics of raw domestic wastewater

Contents	Range	Average
TN (mg/L)	41.5-53	48.8
NH^+-N (mg/L)	28-38	31.7
TP (mg/L)	2.53-4.73	3.68
COD (mg/L)	109.4-220	150.3
MLSS (mg/L)	87-180	89

linity were routinely analyzed according to the standard methods [14]. Multi N/C 3000 (Jena, Germany) and 861 advanced compact IC (Metrohm, Switzerland) were used in the analysis of wastewater samples [14].

4. Operation of PITSF Reactor

An operation cycle is composed of two half-cycles with same running schemes, and thus the analysis discussed only the first half-cycles. It is divided into six phases named as phase I, II and III during a first half cycle and phase IV, V and VI during the second half cycle. Several experiments were implemented for different purposes. One was designed to evaluate the fixed-time operation, of which the control process was performed under different total cycle time. The objective of the fixed-time experiments mainly aimed at tracing the ORP, DO and pH variations during the PITSF process and the relationship between these parameters with water quality. The other sets of the experiment were designed to evaluate the real-time operation. Set 1 was implemented to investigate the nutrient removal under real-time throughout a combination of low C/N ratio and low temperature. Based on the operation in set 1, (NaAc) was added as external carbon source for denitrification during set 2. Set 3 was performed to investigate the performance of PITSF system under low C/N ratio and normal temperature. The experimental procedure and conditions are summarized in Table 2.

RESULTS AND DISCUSSION

Table 3 shows the main biological reaction in each tank of PITSF reactor. It illustrates that the main function of anoxic denitrification/anaerobic phosphorus release - aerobic nitrification, and phosphorus uptake was achieved in tanks 1, 2 and 3. Thus, the real-time control strategy was built depending on these tanks.

1. Fixed Time Control Study in Tank 1

Fig. 3 presents the typical cycle of the DO, ORP and pH profiles along with the nutrient dynamic profiles in tank 1 under fixed-time operation. During first half cycle, tank 1 is operated CSTR during phase I and phase II with the same flow pattern while it is operated as a sequence batch reactor SBR during phase III.

Under anoxic condition during phase I, ORP pattern declines to 80 mv at 90 min. The alkalinity declined during this period in spite of the main function being denitrification The proposed explanation for this observation was the existence of SND phenomenon, capable of using DO as electron acceptor in the anoxic phase, whereas the off line measurement of NH_4^+-N and TN concentrations increased

Table 2. Experimental conditions during operation of PITSF system

Parameter	Fixed time control	Real-time control		
		Set 1 (1-16)	Set 2 (17-42)	Set 3 (43-82)
Control time	Phases I and IV (0-180) min Phases II and V (180-330) min Phases III and VI (330-450) min	Variable	Variable	Variable
DO (mg/L)	2.5-3.3	2.5-3.4	2.5-3.4	2.5-3.4
HRT[a] (hr)	15-18	15-18	15-18	15-18
Temperature (C)	12-17	6-9	8-11	17-21
COD/N	4.22	2.89±0.47	6.5±0.39[b]	3.66±0.28

[a] Hydraulic retention time

[b] NaAc was added as external carbon source (COD=90.4 mg/L)

Table 3. Different biological process in each tank during the first half cycle

Phase	Zone	Environmental state condition	Biological process
I	Tank 1	Anoxic state, inlet wastewater	Denitrification
I	Tank 2	Anaerobic state, inlet wastewater	Phosphorus release
I	Tank 3	Aerobic state	Nitrification, Phosphorus uptake, SND
I	Tank 4	Anoxic state	Denitrification, denitrifying phosphorus removal DPAOs
I	Tank 5	Aerobic state	Nitrification, Phosphorus uptake
II	Tank 1	Anaerobic state, inlet wastewater	Phosphorus release, Denitrification
II	Tank 2	Aerobic state	Nitrification, Phosphorus uptake, SND
II	Tank 3	Anoxic state, inlet wastewater	Denitrification. denitrifying phosphorus removal DPAOs
II	Tank 4	Anaerobic state	Phosphorus release and denitrification
II	Tank 5	Aerobic state	Nitrification, Phosphorus uptake
III	Tank 1	Aerobic state	Nitrification, Phosphorus uptake
III	Tank 2	Anoxic state, inlet wastewater	Denitrification
III	Tank 3	Anaerobic state	Phosphorus release, Denitrification
III	Tank 4	Anaerobic state	Phosphorus release
III	Tank 5	Aerobic state	Nitrification, Phosphorus uptake

slowly during this period. Dissolved oxygen level was maintained between (0.18-0.5) mg/L during period (195-180), which met the requirement of denitrification process. Tank 1 was operated for a long period of aeration in the previous phase. Thus, if dissolved oxygen level reaches a high value in final stage of aeration period, then the denitrification process is faced difficulty for reaching the required dissolved oxygen level. Dissolved oxygen level reached above 4.56 mg/L at the last stage of phase VI; thus the anoxic process needed more than 90 min to reduce DO to the required level of denitrification.

A breakpoint on the ORP profile appeared at 90 min (point A on ORP profile), which indicated a simultaneous nitrification and denitrification process. Then, the decrease rate increased sharply to −100 at 150 min, which can be used to distinguish the end of denitrification. After 150 min, ammonia-N concentration slowly increased because denitrification process was completed, whereas ORP profile decreased slowly, indicating that the anaerobic state condition became the dominant process.

Theoretically, the denitrification process was stopped when nitrate-N concentration was not consumed; thus, the anaerobic state condition commenced in the system. An obvious valley point (point B) appeared on the dORP/dt profile at 150 min. This real control point (RCP) can be used as a signal or indication for distinguishing the end of the denitrification process. Additionally, an obvious real control point (point C) appeared on pH profile indicating the beginning of the denitrification process, whereas releasing OH- ion caused to decrease H^+ ion, so the pH value increased to 6.95 at 150 min. As a result, both points B and C can be applied to the end of the denitrification process.

Under anaerobic condition during phase II, the main functions during this phase are denitrification and anaerobic phosphorus release because denitrification was not significantly complied in phase I and the residual NO_3^--N (electron acceptor) was consumed by denitrification. Note that ammonia-N concentration was not changed notably and ranged between (8.8-9.66) mg/L. TN concentration slowly increased to 17.2 mg/L due to the dual effect of denitrification and influent wastewater. During anaerobic phase, the ORP profile exhibits two stages: the initial sharp decrease at 90 min and then a slow decrease until the end of anaerobic phase, which is different from that observed by [15]. In this study, the ORP value decreased sharply within 2 hr and then reached a plateau from after point d.

In Fig. 2 there is an inflection point on TP profile at 300 min corresponding to the end of phosphorus release (point d). The relationship between the decrease of ORP and the increase of phosphate concentration is linear as shown in Fig. 4, since a larger decrease rate of ORP corresponds to more phosphate release. There was a valley point on dORP/dt profile at 265 min (represented by point E). This valley point can be used as a signal or indication for distinguishing the end of phosphorus release. Consequently, the ORP profile can provide some valuable information about the behavior of PAOs to determine the anaerobic duration.

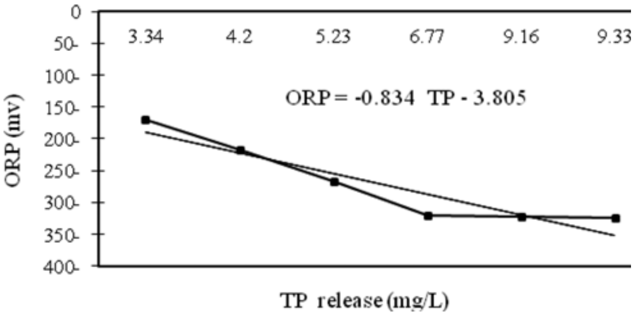

Fig. 2. Relation between ORP value and phosphorus release.

The acidity is increased during anaerobic conditions according to phosphoric acid increasing so that the pH value would be decreased. Even though, pH in tank 1 slowly increased to 6.97 at the end of phase II time for two reasons. First is the occurrence of simultaneous denitrification and phosphorus release in this phase. On the other hand, the intracellular metabolism is divided into catabolism, generating energy for the cell's energy requirements, and anabolism, leading to synthesis of new cell material; both processes take place simultaneously. Theoretically, the transformation of nitrate to nitrite and then to nitrogen generates alkalinity OH- so that pH would be raised. The second reason, pH is increased with VFA uptake and CO2 stripping while phosphorous release and CO2 production will decrease pH; all these biological events are summarized in Table 4. As a result, pH value is increased in this study without showing any characteristic points.

Under aerobic condition during phase III, tank 1 was operated under aerobic condition during this phase to promote the full degradation of organic matter, nutrient removal via nitrification process. It can be seen readily from Fig. 3 that phosphorus was consumed by phosphorus-accumulating organisms (PAOs) in tank 1. ORP pattern was increased significantly from negative to positive values at 360 min due to the interaction between nitrification and phosphorus uptake. This was taking place because tank 1 was operated under aerobic state condition and, thus, there was a large amount of dissolved oxygen in water. According to the relationship between ORP and DO, the ORP pattern is very sensitive to dissolved oxygen variation, whereas small amount of oxygen could cause significant increasing in ORP pattern.

Correspondingly, there was a balance between oxygen consumption rate of microbial cell and oxygen supply rate at early stage of aeration period. This indicates that the ORP parameter is closely related to the biological community that is dominant in the system. It was previously reported that the ORP value is correlated with the logarithm of DO concentration in a linear relationship [16]. Therefore, ORP increases along with DO increase in the aerobic phase. Since the bioprocess involves carbon oxidation, ammonium oxidation and phosphorous uptake, it is difficult to distinguish the biodegradation process of PAOs from other aerobic microorganism. ORP profile was varied with little amplitude after 425 min. This implies that the effect of nitrification reaction and phosphorus uptake was finished.

During aerobic phase, the DO profile was raised immediately to 4.42 at the beginning of phase III till 415 min. It entered a plateau period within 10 min. It can be seen readily from Fig. 4 that an inflection point (RCP) appeared on the DO profile at 420 min. This valley point can be used as a signal or indication for distinguishing the end of the nitrification process. Then, DO slowly increased after 430 min, whereas TP concentration reached less than 0.5 mg/L due to degradation of small part of biodegradable matter, whereas little remained of organic matter. Heterotrophic organism (X_H) could not intake much organic matter because substrate concentration was reduced. Thus, the rate of oxygen consumption was less than oxygen supply rate, and according to that the nitrification process was completed. However, maximum nitrification rate was achieved during the first time of aerobic phase. This implies that two activities occurred in the aerobic phase, the first being degradation whereby the substrate is depleted to a minimum, followed by starvation in which external substrate is no longer available, and bacteria become more hydrophobic, which facilitates microbial adhesion [6]. As expected, dissolved oxygen could be used as a main real time control during aerobic phase.

In phase III, the pH profile decreased to 6.82 through 90 min of aeration period; subsequently, it rapidly increased to 7.16 at 435 min. Then, it appeared with a plateau form in the period of (435-450) min. This can be discussed as follows. The relevant aerobic processes are phosphorus uptake for poly-P formation, glycogen restoring from PHA resources, PAO growth, and lysis and decay. Among them, phosphorus uptake has the highest energy requirement, which is provided by PHA oxidation. According to the biological events occurring in phase III, the pH profile was decreased due to the nitrification reaction, whereas this process produces H+ ion causes consuming of OH+ ion, and thus phosphoric acid reduced alkalinity. On the other hand, the generation rate of acidity is more than alkalinity because HNO3 is strong acid, so the pH profile decreased as a whole.

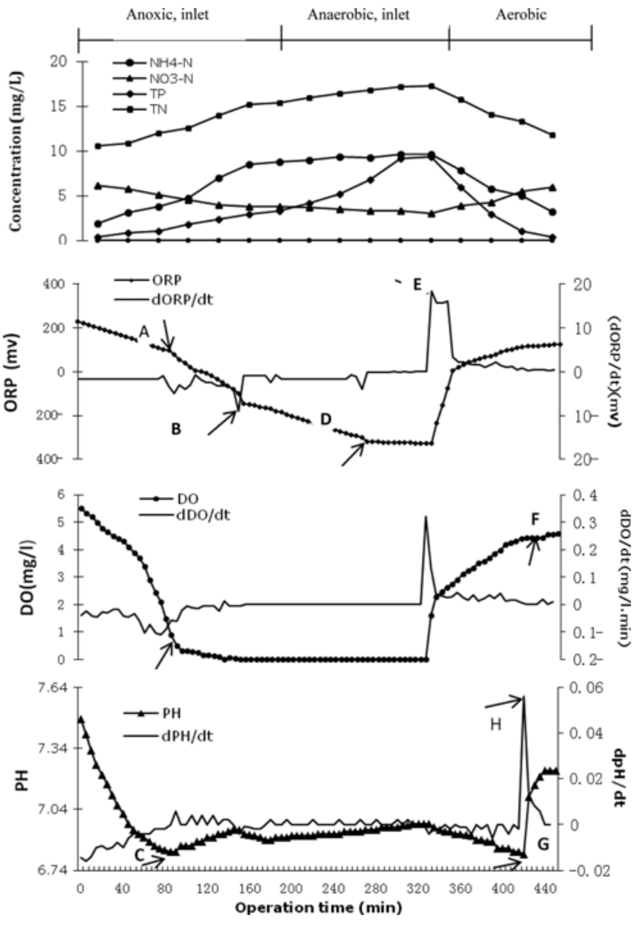

Fig. 3. Typical dynamics of offline measurements of nutrient (NH$_4^+$-N, NO$_3^-$-N, TN and TP) on-line monitoring parameters, pH, DO and ORP and in tank 1.

Fig. 3 shows that the valley signals at 390 min (point G, ammonia valley) indicated the end of ammonium oxidation. At the end of nitrification, the consumption of OH- ion was reduced because nitrification was basically completed, which caused increasing of the pH profile. The increasing of pH pattern after 420 min is due to continuity of phosphorous uptake. When phosphorous uptake terminates, a plateau appears after 435 min, and all aerobic biological events have finished.

In Fig. 3, an obvious knee point (point F) appeared on dpH/dt profile at 420 min, which can be an indicator for the completion of nitrification.

2. Fixed Time Control Study in Tank 2

Fig. 4 represents a cycle of the typical offline measurement and online monitoring profile in tank 2 during the first half cycle of PITSF.

Under anaerobic condition during phase I, the experimental analysis showed that ammonia-N and TN concentrations were rapidly increased during phase II (upward trend-line). In this phase, the residual nitrate-N from previous phase was consumed gradually by denitrification. Anaerobic phosphorus release was the main function in tank 2 because the decrease rate of NO$_3$-N electron acceptors was very low and there was plenty of organic matter from influent wastewater. Thus, phosphorus-accumulating organisms (PAOs) created good conditions for rapid phosphorus release. TP concentration was released quickly to 9.99 mg/L at 150 min because tank 2 was operated under anaerobic condition in the previous phase, which led to immediate phosphorus release. Thus, the ORP profile was decreased to −230 mv at 150 min. The first distinctive turning point (RCP) appeared at point A, corresponding to phosphorus release completed, then it became flattened until point B.

The pH value was low at early stage of phase I because tank 2 was operated under anaerobic state condition during previous phase. It decreased slowly to 7.08 after approximately 60 min, and then it declined quickly at 150 min. This fall in pH profile can be attributed to the release of acid fermentation. Additionally, tank 2 was the intake tank during phase I, so there was a plenty of organic matter which created good conditions for rapid phosphorus release.

In Fig. 4, a real control point (RCP) that appeared clearly on the dpH/dt profile (point B) indicates the end of phosphorus release during phase I.

Under aerobic condition during phase II, the main difference between phase I and II of tank 2 is the intake location where it was changed from tanks 2 and 1 during phase I to tanks 1 and 2 during phase II. At the beginning of aeration-on, nitrate-N concentration increased slowly to 4.23 mg/L at 330 min. This observation suggested that the existence of simultaneous nitrification and denitrification (SND) process was occurring in tank 2 for 1 hr where dissolved oxygen concentration was maintained between (0.5-0.62) mg/L until point D. Low DO is conducive to simultaneous nitrification with denitrification, while high DO is conducive to nitrification. In continuously operated plants, SND offers the potential to save costs for a second (anoxic) tank, or at least reduce its time [17,18]. Consequently, SND is a good phenomenon which enhances nitrogen and phosphorus removal in the PITSF process.

During nitrification and phosphorus uptake processes, autotrophic organisms (X_A) oxidized NH$_4^+$-N, while phosphorus-accumulating organisms (PAOs) degraded PHB at low dissolved oxygen requirement. Whereas, the oxygen consumption rate is less than oxygen supply rate, so the remaining dissolved oxygen of tank 2 was raised slowly but it was raised immediately during period (235-260). An obvious jump point appeared at point E on DO profile after 265 min due to degradation of small part of biodegradable matter, whereas there little remained of organic matter. Heterotrophic organism (XH) could not intake much organic matter because substrate concentration was reduced. Then, dissolved oxygen was increased to 1.24 mg/L at 300 min with little amplitude, which indicates the end of nitrification. TP concentration was not decreased below 2.9 mg/L; thus phosphorus uptake was incomplete in tank 2. However, phosphorus uptake was completed during phase III to meet the Chinese National Class I (Grade A) Sewage.

It is evident from trends displayed in Fig. 4 that there were two distinctive points (RCP) on the dORP/dt profile during aeration period, peak point (6.8 mv/min at point F) and slowly fall point (0.2 mv/min at point G). These real-time control points (RCPs) expressed the organic matter degradation and the end of nitrification process, respectively. Clearly, there were three distinctive points (RCPs) on the pH profile. First, the pH profile increased immediately to 7.16 at point H, even though the aeration-on. The steep rise in pH during the initial 60 min of aerobic phase is attributed to simultaneous nitrification and denitrification occurring in phase II. As to the second stage, starting from point H until point J, a rapid decrease of pH profile occurred as the nitrification began.

It was found from Fig. 4 that an obvious valley point appearing at point J indicates the end of nitrification. Subsequently, pH pattern increased during the period of (270-300) min. This implies that denitrification process was still going on due to the existence of little nitrite and nitrate, whereas NH$_4^+$-N was almost depleted after 300 min.

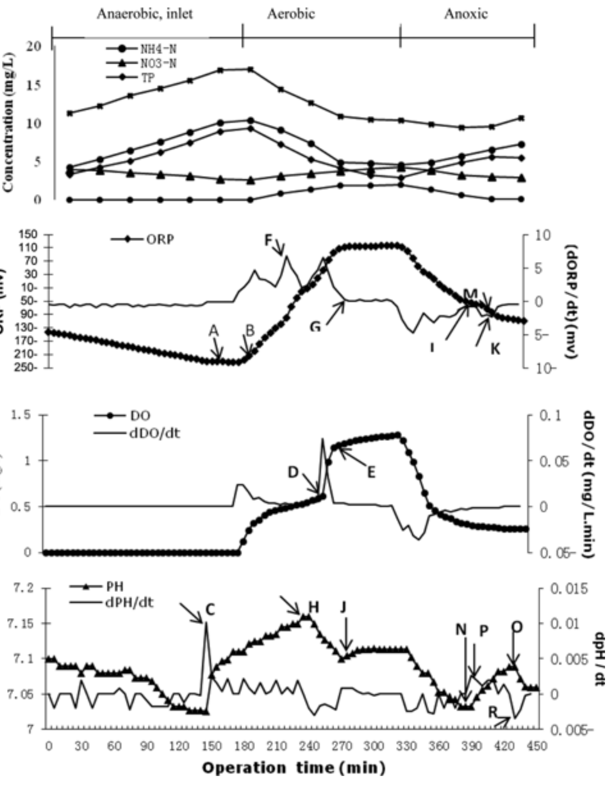

Fig. 4. Typical dynamics of (NH$_4^+$-N, NO$_3^-$-N, TN and TP) with online monitoring parameters in tank 2.

Under anoxic condition during phase III, total discharge of raw wastewater was pumped through tank 2 during phase III; thus a high amount of pollutant concentration was contained in this tank. Ammonia-N concentration increased gradually at the end of mixing time. TN concentration increased slowly during phases III and IV due to the combined effect of ammonium nitrogen and nitrate-N. The ORP pattern rapidly decreased during denitrification followed by consumption of nitrate in phase III. An obvious breakpoint (point K, nitrate knee) appeared on the ORP profile with depletion of nitrate, indicating the end of denitrification. Fig. 4 illustrates two distinctive turning points at the first derivative curve of dORP/dt during denitrification: slowly lift point (−1.2 mv/min at point L) and flat roof point (−0.6 mv/min at 430 min). These two distinctive turning points expressed the depletion of nitrate and the end of denitrification, respectively.

Owing to raw wastewater being slightly acidic, the pH value decreased to 7.033 at point N. However, the pH profile turned quickly from fall to rise at 390 min. This implies that alkalinity was produced during denitrification. Then, the pattern of pH profile trended downward because denitrification is complementary to alkalinity. An obvious real control point appeared at point O till denitrification ended. In Fig. 4 two obvious points are observed on the dpH/dt profile, apex point (0.0026 at point P), valley point (–0034 at point R). These distinctive turning points expressed the beginning and the ending of anoxic denitrification in tank 2.

3. Fixed Time Control Study in Tank 3

Tank 3 is the mid-tank and third step of the PITSF process. It is different from other tanks due to symmetric operating state condition during a two half cycles.

Under anaerobic condition during phase I, it can be seen from Fig. 5 that ammonia-N concentration decreased to 3.5 mg/L within 150 min due to aerobic nitrification process. Since the maximum DO level was below 1.5 mg/L, the free ammonia concentration in phase I was not decreased more than mg/L. Phosphorus was consumed by phosphorus-accumulating organisms (PAOs). It was basically stabilized at about 2.1 mg/L at 180 due to phosphorus uptake completion. Hence, TP concentration did not meet the Chinese National Class I (Grade A) Sewage Discharge Standard in tank 3; it was necessary to operate tank 5 under aerobic condition.

In the early stage of phase I, nitrate-N decreased to 2.4 mg/L through 60 min due to low DO concentration at this period (less than 0.5 mg/L), which met the requirement of the denitrification process. It clearly demonstrated the positive rule of ultimate nitrate-N as an electron accepter in aerobic denitrification (SND). This implies the ability of microorganisms to denitrify while they sense oxygen, as has been illustrated by several microbial studies [19,20]. Both conversion possibilities imply the simultaneous use of oxygen and nitrate as electron acceptor leading to an increased specific growth rate for the corresponding organisms. Nitrate-N increased to 3.54 mg/L at the end of aeration period, which indicates the aerobic denitrification process was completed and aerobic nitrification was the dominant process. As clearly seen from Fig. 5, there is jump on the DO profile at point A min due to degradation of small part of biodegradable matter, whereas little remained of organic matter. Heterotrophic organism could not intake much organic matter because substrate concentration was reduced. Thus, the rate of oxygen consumption was less than oxygen supply rate and therefore, the nitrifi-

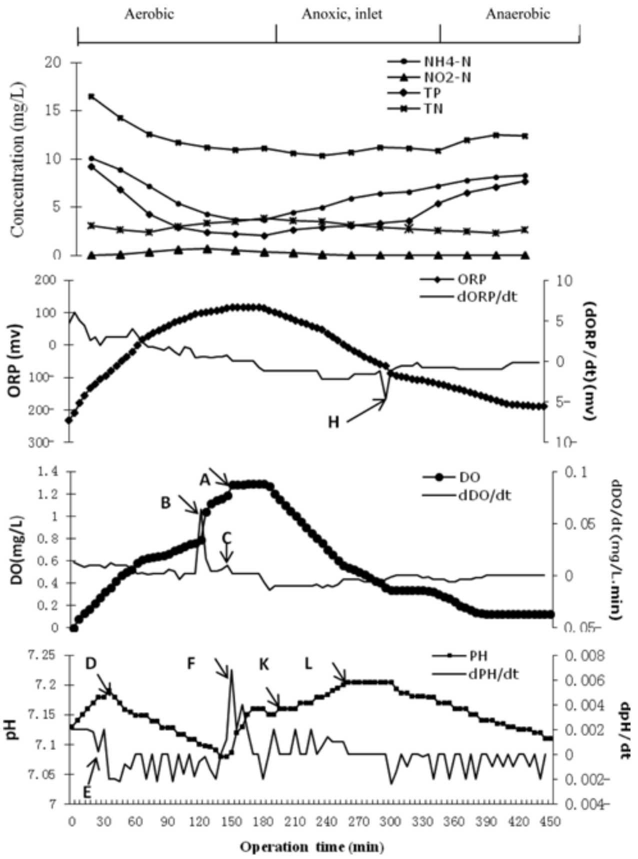

Fig. 5. Typical dynamics of (NH_4^+-N, NO_3^--N, TN and TP) with on-line monitoring parameters in tank 3.

cation process was completed.

Fig. 5 illustrates two real control point (RCPs) on the dDO/dt profile, a clear apex point of 0.064 at point B and apex point of 0.01 at point C. These distinctive turning points expressed the degradation a small part of biodegradable matter and the end of aerobic nitrification. As a result, DO parameters could be considered to be more convenient and reliable as process control parameters to control the main functions nitrification, SND and aerobic phosphorus uptake in tank 3.

Fig. 5 shows that the pH profile increased, decreased, and increased again as a general phenomenon; this was similar to SBR system during aerobic phase [21]. According to the biological process of that event under aerobic condition (Table 4), the pH profile increased with time along with degradation of organic matter because heterotrophic organisms degraded organic matter and released OH- and so the alkalinity was increased.

From Fig. 5 there is an inflection point at 35 min which indicates complete organic matter degradation, which corresponded with point D. Subsequently, the pH pattern trended downward due to phosphorus uptake via PAOs, and CO_2 stripping. Nitrification process produces H^+ ion and consumes OH- ion, although this phase was aerobic phosphorus uptake but phosphoric acid reduced alkalinity. Thus, the pH profile was gradually decreased to 7.08 at 150 min. On the other hand, the generation rate of acidity was more than alkalinity because HNO3 is strong acid, so the pH profile decreased as a whole. At the end of nitrification, the consumption of OH- ion was reduced because nitrification was basically completed after 150 min, which caused increasing of the pH profile. The second increasing in the pH pattern is due to continuous phosphorous uptake, whereas phosphorous uptake terminated with a plateau value. This was because all aerobic biological events were finished after 180 min.

It is evident from trends displayed in Fig. 5 that pH attributed better indications during this phase, whereas two feature indictors were observed on dpH/dt profile. First, the dpH/dt value changed from positive to negative after point E, and that could be used to determine the end of organic matter degradation. As a second stage, the first derivative of pH profile was increased immediately from negative to positive value after 150 min and apex point obviously appeared at point F, which could be used to indicate the end of nitrification.

Under anaerobic condition during phase II, a step feed influent was pumped through both tanks 1 and 3 during phase II; thus, a high amount of pollutant concentration was contained in this tank, whereas TN increased during the period (240-300) min, but it decreased again to 10.4 mg/L at 330 min due to the effect of denitrification.

It was observed from Fig. 5 that nitrate-N concentration was consumed slowly as the whole phase II, because it was compensated by reflux sludge from a settling tank and an excess flow of tank 2

Table 4. Investigation result of the effect of bioprocess on pH pattern

State condition	Biological process	Effect on pH	Induced by
Anaerobic phase	VFA uptake	pH increased	PAOs
	Phosphorous release	pH decreased	PAOs
	CO2 production	pH decreased	PAOs
	CO2 stripping	pH increased	mixer
Aerobic phase	Phosphorous uptake	pH increased	PAOs
	Nitrification	pH decreased	Nitrifies
	CO2 production	pH decreased	Carbon oxidation
	CO2 stripping	pH increased	Aeration
Anoxic phase	Phosphorous uptake	pH increased	DPAOs
	Denitrification	pH increased	Denitrifies
	CO2 production	pH decreased	DPAOs
	CO2 stripping	pH increased	Mixer

contained high nitrate-N, whereas tank 2 was operated under aerobic condition. As well, tank 3 was operated under aerobic condition during the previous phase, which led to increase the electron accepter nitrate-N.

It is demonstrated clearly from Fig. 5 that the ORP pattern dropped quickly in the beginning of phase II, and then it decreased slowly because denitrification and organic phosphorus were weakened. An obvious valley point (point E) appeared on dORP/dt that surely indicated the time when the denitrification of NO_3^--N was completed. As a result, Fig. 5 indicated that the distinctive real control

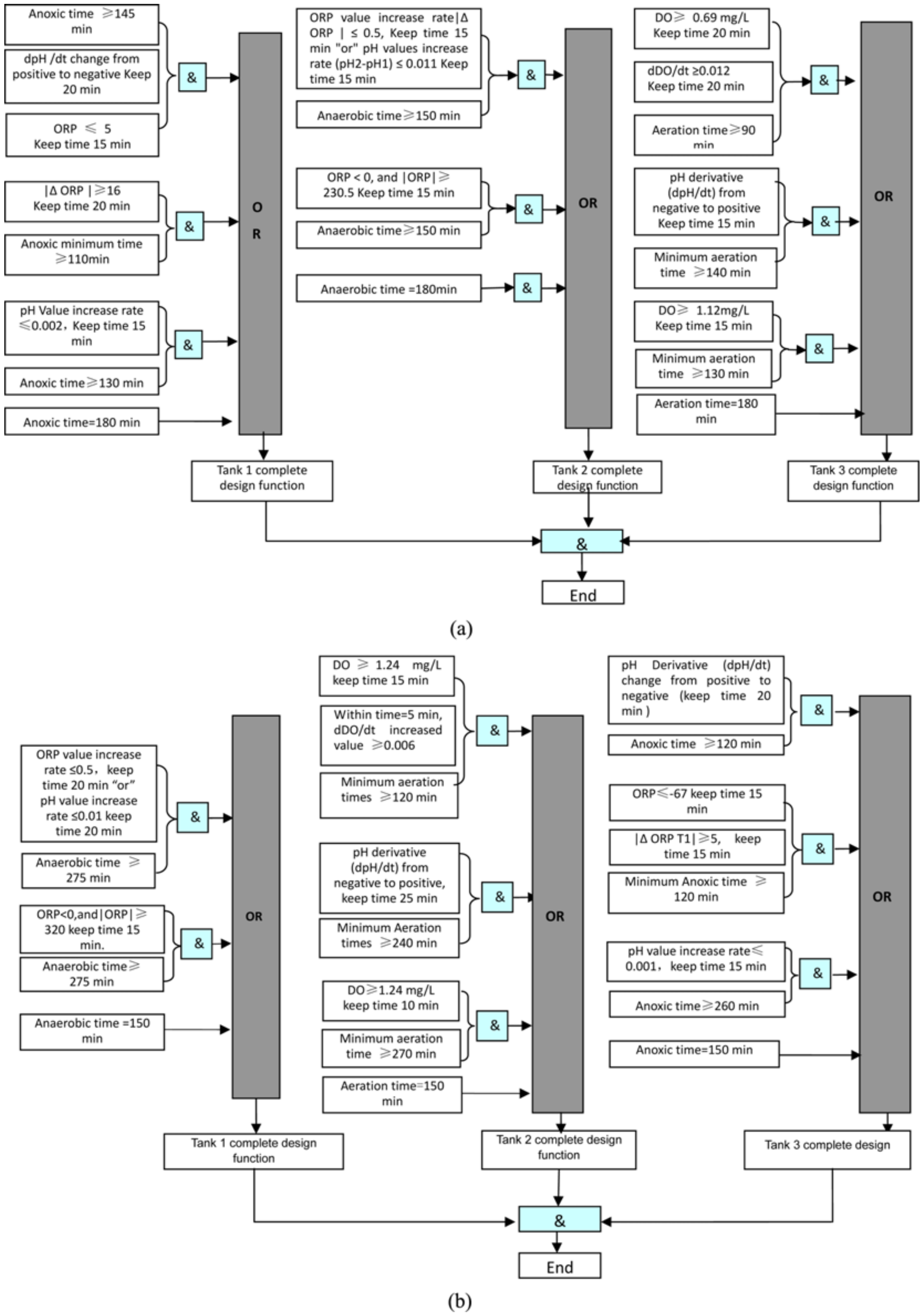

Fig. 6. (a) The decision tree of expert control for conversion phase I to phase II, (b) The decision tree of expert control for conversion of phase II to phase III.

points (RCPs) on the ORP and dORP/dt profiles can be signals to control the denitrification process.

Since the raw wastewater was slightly acidic, the pH value decreased at the beginning of denitrification. However, the pH pattern turned quickly from fall to rise at point J. This implies that alkalinity was produced during denitrification. In Fig. 5 there is a real control point (RCP) at point K, indicating the denitrification ended. Consequently, both E and K points are used as a signal or indication for distinguishing the end of the denitrification process.

Under anaerobic condition during the beginning of phase III, TN concentration decreased slowly due to the dual effect of denitrification and the excess flow of mixed liquor. It declined due to reduction in NO_3-N concentration (electron acceptor of denitrification). TN concentration increased rapidly to 12.5 mg/L at 420 min because denitrification was completed and the anaerobic phosphorus release was the dominant effect in tank 3 after 360 min. Finally, anaerobic phosphorus release was the main function in tank 3 because the two electron acceptors of nitrification and denitrification were very low and there was plenty of organic matter from the excess mixed liquor of intake tank; thus phosphorus accumulating organisms (PAOs) created good condition for rapid phosphorus release.

In the anaerobic phase, the ORP profile decreased during the fill period. Note in Fig. 6 that the RCP, which indicates the end of phosphorus release, was not observed clearly on both ORP and pH profile during phase III. This implies that the rate of phosphors release was not completed in phase III. Indeed, TP release did not complete in this phase due to high VFA in a raw wastewater. However, it would be completed in tank 4 for depletion the pollutant concentration in tank 5.

4. Real-time Control Strategy Based on the Feature Points of ORP, DO and pH Profiles

The results of the fixed-time study indicate that through applying pH and DO parameters as a real time control to SND can instruct practical operation to avoid over-aeration, so as to maintain higher energy efficiency and operational stability. It showed that both ORP and pH could be applied to control the PITSF system, in particular, the “ammonia valley” on the pH profile for nitrification, and the “nitrite apex” on the pH profile and the “nitrite knee” on the ORP profile for denitrification. It is reliable and accurate to use pH and DO profiles as real time parameters to control the nitrification and phosphorous uptake in the PITSF. However, the application of derivatives is more convenient than their absolute values, to judge the feature points, when implementing online operation.

5. Designation of Real-time Control Strategy

The construction of a decision tree for application of real time control strategy is determined by the knowledge base. The decision tree includes knowledge acquisition and establishment of control rules to determine the inference engine; it is a set of “if then-else” statements. The designed program for the integrated strategy of real-time control is outlined in Fig. 6.

5-1. Conversion of Phase I to Phase II

Fig. 6(a) shows the decision tree of expert control for conversion of phase II to phase III. The decision tree of expert control for conversion of phase II to phase III was built according to the main biological events in tanks 1, 2 and 3 during phase II as follows.

(1) In tank 1, ORP and pH are the most important monitoring parameters because the main biological event of this tank is denitrification.

(2) In tank 2; ORP and pH are the most important monitoring parameters because the main biological events of this tank are denitrification and phosphorus release.

(3) In tank 3, DO and pH are the most important monitoring parameters because the main biological events of this tank are nitrification, phosphorus uptake by PAOs in addition to SND phenomena.

5-2. Conversion of Phase II to Phase III

Fig. 6(b) shows the decision tree of expert control for conversion of phase II to phase III. The decision tree of expert control for conversion of phase II to phase III was built according to the main biological events in tanks 1, 2 and 3 during phase II as follows.

In tank 1, ORP and pH are the most important monitoring parameters because the main biological events of this tank are denitrification and phosphorus release.

In tank 2, DO and pH are the most important monitoring parameters because the main biological events of this tank are nitrification, phosphorus uptake by PAOs in addition to SND phenomena.

In tank 3, ORP and pH are the most important monitoring parameters because the main biological events of this tank are denitrification and phosphorus uptake by DNPAOs.

6. Integrated Real-time Control System Performance

We performed the PITSF system for treating domestic wastewater with low (C/N) ratio using the real-time control strategy. Fig. 7 shows the concentration profiles of TP, TN and NH_4^+-N during all operation runs. In set 1, influent COD concentration fluctuated with

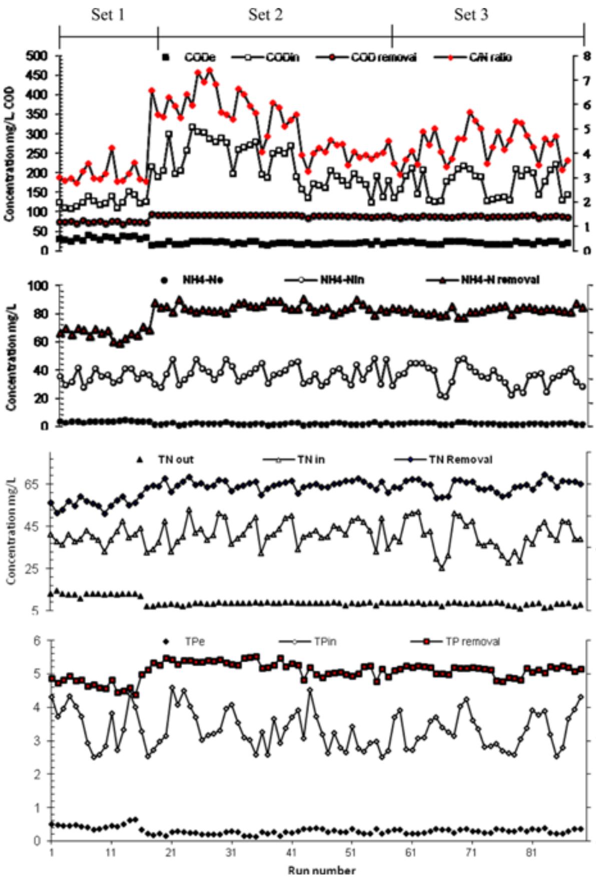

Fig. 7. Pollutant removal rate in PITSF system under real time control strategy.

a low concentration 108 mg/L on average, which resulted in unsteady fluctuation in C/N ratio. The total removal efficiency of COD and NH$_4^+$-N was 79%, 89%, on average, respectively, while TN removal was only 69% because of the low C/N ratio and low water temperature. For this reason, NaAc was added (COD 90 mg/L) in set number 2, which resulted in increasing in C/N ratio to 6.3 on average; thus, good nutrient removal was obtained during run 2 where the effluent COD, TN, NH$_4^+$-N, and TP was below 28, 8.2, 1.8 and 0.18 mg/L, respectively; as shown in Table 6. The result found was that low temperature (7-9) did not deteriorate the phosphorus removal, while the nitrogen removal decreased significantly due to incomplete nitrification. This result coincided with another [22], but PITSF could provide near optimal conditions under low C/N ratio also. As the temperature increased further (17-21) in run 3, TN and NH$_4^+$-N removal efficiency increased gradually to 95% and 83%, respectively, in spite of insufficient organic matter during this run (C/N less than 4) as shown in Fig. 7. Similarly, perfect phosphorus removal efficiency (more than 90%) was accomplished in PITSF system where the effluent TP concentration was below 0.5 mg/L. Table 5 shows the average performance for total P and Total N removal for a number of biological P-removal processes [23]. Four technologies were identified to meet the low concentration limit with low variability. These are the 4- and 5-stage Bardenpho processes, the step-feed activated sludge process, concentric oxidation ditches, and denitrification filters with carbon sources. COVs for these processes are below 50 percent, and the technologies achieve annual average TN effluent concentrations below 3 mg/L. Seven technologies were identified for mid-level nitrogen removal between concentrations of 3 and 8 mg/L. Biological phosphorus removal (without filters or chemical addition) achieved an annual average effluent concentration of 0.26 mg/L with a COV of 35 percent. Excellent performance with low variability was reported for biological phosphorus removal processes, which achieved mean effluent concentrations down to 0.12 mg/L with a COV of 19 percent and 0.14 mg/L with a COV of 12 percent in another plant. In this study, TN and TP removal was achieved by online monitoring parameter with effluent concentration less than

Table 5. Comparison of TP and TN removal between a novel technology (PITSF) and different BNR

		Nitrogen and phosphorus removal variability (mg/L)							
N (ppm)	Technology	Range of values observed (mg/L)	Std dev./ COV %	Annual average (50%)	Max. month (92%)	Max. week (98.7%)	Max. day (99.7%)	Reference	P (ppm)
10	Johannesburg	TN: 2.03 to 11.44 TP: 0.19 to 8.3	1.66/21 0.96/145	7.86 0.66	10.41 2.49	11.57 3.9	13.28 8.3	Hagerstown, Maryland	
	UCT	TN: 8.9 to 10a TP: 0.3						WEF and ASCE 1998	2 1
	IFAS	TN: 5.6 to 11.3a TP: 0.2 to 1.7a						Broomfield, CO McQuarrie 2004	0.5
5	VIP	TN: 3 to 10 TP: 0.19 to 5.75						Rabinowitz 2004	
	VIP with VFA addition	TN: 5 to 10 TP: 0.6 to 0.8						Neethling 2005	
	Step-feed with fermenter	TN: <5.0; 3 to 13 TP: <0.3; 0.1 to 5	1.48/57 0.08/89	2.59 0.09	4.30 0.20	5.89 0.31	9.16 0.52	Piscataway, MD	
	Biodenipho/PID	TN: 1.78 to 7.02 TP: 0.09 to 1.99	0.93/14 0.27/64	3.67 0.38	4.46 1.06	5.87 1.45	6.79 1.78	North Cary, NC	
	Modified UCT with VFA addition	TN: 5 to 6 TP: 0.1 to 2.7		0.10	0.25	0.75	3.75	McDowell Creek, NC 2005	0.1
11	PITSF (this study)	TN: 2 to 5 TP: 0.05 to 1.2	0.52/15 0.07/72	2.11 0.08	3.1 0.11	4.75 0.25	6.23 0.46	Rusul N., 2013	2

Table 6. Comparison Performance of PITSF system under fixed time control and real time control

Index	Fixed time control technology			Real time control technology								
				Set 1			Set 2			Set 3		
	Inlet	Outlet	R.rate %	Inlet	Outlet	R. rate %	Inlet	Outlet	R.rate %	Inlet	Outlet	R.rate %
COD	209	31	90.7	128	34	73.4	277	22	91.8	189	19.8	89.7
NH$_4^+$-N	34.2	3.11	98.33	33.09	3.57	89.8	36.5	1.23	96.2	33	1.49	95.3
TN	48.63	10.2	82	43.7	13.1	69.5	47.6	7.87	83.6	49	8.8	83.1
TP	3.37	0.28	91.54	2.9	0.4	86.34	3.14	0.16	94.6	4.3	0.33	91.2

Table 7. Comparison of phase time under fixed time control and real time control

Item	Half-cycle time	Phase I	Phase II	Phase III
Fixed time control technology (min)	450	180	150	120
Real time control technology (min)	382	152	120	110
Time reduction percentage (%)	15.11	15.5	20	8.3

0.5 mg/L of TP and less than 7 mg/L of TN with a COV of 35 percent by a new process of PITSF activated sludge process. Table 6 shows the compression study of COD, NH_4^+-N, TN and TP removal under real-time control and fixed time control. It showed, under a real-time control pattern, an average 91%, 96%, 84% and 91% of COD, NH_4^+-N, TN and TP removal efficiency was achieved, which showed that the system had a greater ability to accomplish nitrogen removal compared with steady-state control operations. The effluent organic matter, TP, NH_4^+-N and TN were met with Chinese discharged standard requirements of municipal wastewater treatment plants (GB18918-2002) level-A. Also, Table 7 shows the comparison of length of phase time with the two technologies in PITSF. The percentage of time reduction can reach to more than 20% for each cycle under real time control technology, which gives a good indication for more energy saving.

CONCLUSION

An innovative PITSF system was employed to treat low C/N ratio domestic wastewater. It was operated for more than three months to investigate the offline measurement of (NH_4^+-N, TN, TP and NO_3^--N) under fixed time operation and to develop a strategy of on-line monitoring parameters pH, DO and ORP as control parameters, which was expected to optimize the operation of the PITSF system and save aeration energy costs significantly. The study of fixed time revealed that the variation profile of the on-line monitoring parameters pH, DO and ORP represents the dynamic characteristics of a PITSF system treating actual wastewater.

The real control point (RCP) appeared on both DO and pH profiles. Thus, both DO and pH profiles are applied to control the end of the nitrification phosphate uptake process in the PITSF system, in particular, the "ammonia valley" on the pH profile for nitrification process. The analysis of tank 2 during aerobic process showed that the RCP on DO profile can be used to distinguish the occurrence of simultaneous denitrification and nitrification (SND).

The analysis of tanks under anoxic condition showed that both ORP and pH break points (RCPs) are applied to distinguish the end of denitrification. This study revealed that there was a valley point on dORP/dt profile that can be used to identify the simultaneous denitrification and denitrifying phosphorus removal. The analysis of tanks under anaerobic state condition showed that ORP value was decreased to a minimum value, then it became flattened at the end of phosphorus release. Both (dORP/dt) and (dpH/dt) are used as a condition to distinguish the end of anaerobic phosphorus release.

As a final engineering observation, the PITSF system is regarded as an effective process because it can be operated safely under intercross real time control with limited carbon source. The total nutrient removal efficiencies of COD, TN, NH_4^+-N, and TP with low C/N ratio and normal water temperature of (17-21) °C were 91.7, 83.2, 95.7 and 92.1%, respectively, which was approximately equal to the complete nitrification–denitrification with the addition of external carbon sources under low water temperature of (8-11) °C.

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