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Nitrogen removal influence factors in A/O process and decision trees for nitrification/denitrification system

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Abstract: In order to improve nitrogen removal in anoxic/oxic(A/O) process effectively for treating domestic wastewaters, the influence factors, DO(dissolved oxygen), nitrate recirculation, sludge recycle, SRT(solids residence time), influent COD/TN and HRT(hydraulic retention time) were studied. Results indicated that it was possible to increase nitrogen removal by using corresponding control strategies, such as, adjusting the DO set point according to effluent ammonia concentration; manipulating nitrate recirculation flow according to nitrate concentration at the end of anoxic zone. Based on the experiments results, a knowledge-based approach for supervision of the nitrogen removal problems was considered, and decision trees for diagnosing nitrification and denitrification problems were built and successfully applied to A/O process.

Keywords: A/O process; nitrification; denitrification; nitrogen removal; decision trees

Introduction

Eutrophication due to the presence of nutrients including nitrogen was a well-recognized environmental problem worldwide. As a result, stringent standards had been imposed on TN(total nitrogen) concentration levels in effluent from wastewater treatment systems in many parts of the world. In China, for example, new built plants were required to achieve ammonia and TN concentration in the effluent of 5 mg/L and 15 mg/L, respectively; existing plants would need to be upgraded to ultimately meet the same standard, GB18918-2002 (China). The tough standard on nitrogen discharge had posed a particular challenge to biological nitrogen removal, known to date there were many influence factors for nitrogen removal, e.g., DO, nitrate recirculation, sludge recycle, SRT, influent COD/TN, and HRT. On-line control of these variables to improve nitrogen removal had been studied by several researchers (Serralta, 2002; Zhiguo, 1997; 2002; Samuelsson, 2002; Jain, 1992).

Currently, most WWTPs were equipped with automatic control and data acquisition systems capable of monitoring plant conditions by retrieving numerical data from database management systems, and of controlling the essential operational and control equipment through a PLC network (Ingildsen, 2002; Jeppsson, 2002). Besides this on-line data, the analytical results and the qualitative observations about the process and sludge quality, supply a type of information that, once processed and interpreted by an expert, were fundamental to increase the reliability of WWTP control and management (Comasa, 2002). Incorporating all these heterogeneous sources of knowledge, and most importantly, reasoning with the whole information collected was beyond the scope of classical control systems. A method based on human reasoning could help in this task.

Knowledge-based systems(KBS) are computational tools that enable the integration of numerical data and heuristic knowledge and mimic the human-decision making processes to solve complex problems. These systems are capable of using the knowledge of human experts, acquired through years of experience, to diagnose the state of a process, and to propose solutions to new problems. The potential use of KBS to support the operation of WWTP came into picture in the early 1980s. In the 1990s several interesting proposals were developed (Chan, 1991; Ladiges, 1993; Ozgur, 1994; Bergh, 1996).

The present work was aimed at improving the nitrogen removal under dynamic inflow conditions. The study was conducted by performing a series of experiments in an A/O reactor. Based on experiment results and corresponding control strategies, the KBS decision tree for diagnosis and solution of the biological nitrogen removal problem was built, with a view to maximize nitrogen removal while saving energy costs.

1 Materials and methods

1.1 A/O reactor system

Experiments were carried out using a bench-scale combined A/O reactor with an operating volume of 48l and a bench-scale settler(diameter 25 cm, 20l), as shown in Fig. 1. The combined A/O reactor was separated into six compartments (8 liters each), the first two compartments were anoxic and the last four were aerated, all compartments were fully mixed. Each mechanical unit of the bench-scale plant(pumps, stirrer, etc.) was controlled by a PC through a data acquisition card, which allowed automating all these elements. Every compartment had in-line sensors(DO, pH, ORP, and temperature) connected to probe controllers. The PC controlled the pH(7—7.5) with direct addition of sodium carbonate to the inflow tank. Also, the PC controlled the DO through manipulating the aeration valves. The inflow, nitrate recirculation flow and sludge recycle flow were controlled by variable speed peristaltic pumps. During the reaction samples were collected from different sections of the reactor at intervals.

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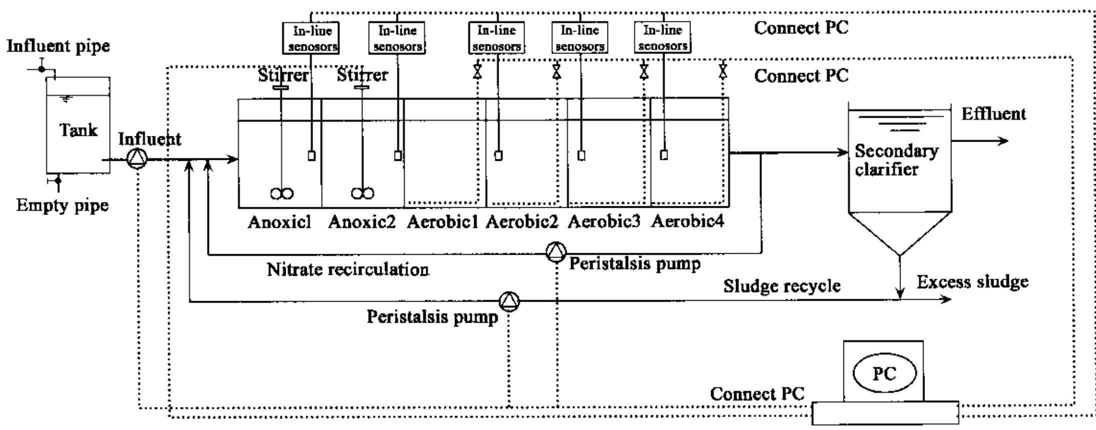

Fig.1 Schematic diagram of A/O (anoxic/oxic) reactor

1.2 Sludge and wastewater

The reactor was seeded with sludge from the final settler of Harbin Wenchang WWTP. The feed was mixed with tap water and starch power, the composition is as follows: starch (0.2—0.6 g/L); NH_4Cl(0.1—0.3 g/L); KH_2PO_4(0.02—0.033 g/L), $NaHCO_3$ (0.05—0.15 g/L), $MgSO_4 \cdot 7H_2O$ (0.09 g/L), $CaCl_2 \cdot 2H_2O$(0.03 g/L), $FeSO_4 \cdot 2H_2O$(0.003 g/L). After the culture of the activated sludge, the experiment lasted for six months.

1.3 Analytical methods

COD_{Cr}, MLSS, alkalinity, NH_4^+-N, NO_2^--N, NO_3^--N, TN were measured according to Standard methods (APHA, 1995). The DO and temperature were measured continuously using a WTW oxygen probe. Continuous monitoring of pH and ORP were carried out using HANNA in-line analyzer.

2 Results and discussion

During experiments, influent flow, MLSS and SRT were controlled at 144 L/d, 2500 ± 100 mg/L and 12 d respectively. Nitrate recirculation ratio was 2.5, sludge recycle ratio was 0.8, DO was controlled at 2 mg/L, influent COD was 350 mg/L, ammonia concentration was 55 mg/L. According to different studies, DO, nitrate recirculation, sludge recycle, influent flow and COD could be changed separately. The temperature was stable (21℃) over all experiments.

2.1 Effect of DO on nitrogen removal

DO concentration was regarded as the most important control parameter in the biological nitrogen removal processes. Too high a DO concentration would lead to unnecessary power consumption due to high aeration and might also affect the anoxic processes. Too low a DO concentration inhibited bacterial growth (especially nitrifying bacteria).

Examining first the effect of DO(Fig.2), it was found that effluent TN concentration past through a minimum(14.9 mg/L) when DO at 1.5 mg/L, and then increased with DO above the optimum. Effluent nitrate concentration increased gradually with DO; effluent ammonia concentration decreased gradually with DO. When DO increased to the optimum(1.5 mg/L), effluent ammonia concentration decreased to 3 mg/L, ammonia nitrogen removal efficiency and nitrification rate got to 94.5% and 0.057 mg NH_4-N/(mgMLSS · d), respectively. It was also seen that ammonia removal and nitrification rate improved imperceptible over the increase range of DO above the optimum. More people considered that aerobic zone oxygen should be kept above 2 mg/L, however, results in Fig.2 showed that DO kept at 1.5 mg/L could meet the effluent standard of GB18918-2002. So the selection of optimal DO concentration should correlate with wastewater characteristics. Based on the experiments, a supervisory control system that allowed optimizing and controlling the DO concentration in the aerobic reactors, adjusting the DO set point according to the effluent ammonia concentration was built, it helps minimize energy consumption and optimize process performance by controlling the amount of air fed into aeration tanks.

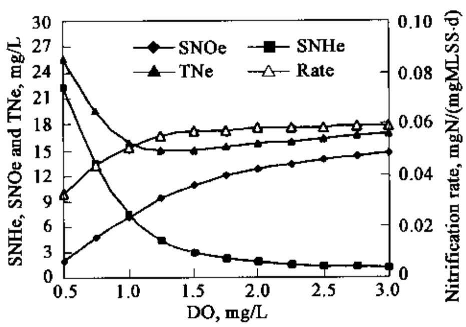

Fig.2 Effect of DO on nitrification rate, effluent ammonia, nitrate and total nitrogen concentration

2.2 Effect of nitrate recirculation ratio on nitrogen removal

The nitrate recirculation regulated the amount of nitrates into anoxic zones where the denitrification process occurred. It was important on-line control this variable to improve nitrate removal, and to ensure a full usage of anoxic zone denitrification potential. If the nitrate were controlled at a zero level, then part of the "anoxic" zone would actually be anaerobic, and this would limit the amount of denitrification taking place.

Fig.3 describes the effect of nitrate recirculation ratio on effluent ammonia, nitrate and TN concentration, results showed that the effluent ammonia concentration was basically kept constant in all the time, not influenced by nitrate recirculation ratio, the effluent nitrate and TN concentration were gradually decreased with the increasing of nitrate recirculation ratio. When nitrate recirculation ratio increased to 1.75, effluent nitrate and TN concentration reached the lowest. But when nitrate recirculation ratio increased continuously, effluent nitrate and TN concentration were gradually increased, which showed that increasing nitrate recirculation flow did not always increase nitrogen removal, it was also correlate with influent carbon source and the denitrification potential of anoxic zone. In addition, keeping a too high recirculation ratio would make plenty DO recirculated to anoxic zones, which seriously deteriorated the denitrification process, reduced the demanded carbon source in the denitrification process. Based on above experiment and analysis, a strategy was to control the nitrate concentration at the end of the anoxic zone at a level of about 1—3 mg/L, which maximized removal of nitrate in the biological reactors, and prevented undesired high nitrate concentration or dissolved oxygen increasing in the anoxic zones. But it had limited effectiveness in maintaining the effluent nitrate level, as the amount of nitrate that could be removed was predominantly determined by the ratio of influent COD to N. It should be supplement external carbon sources to the anoxic zone to increase denitrification rate.

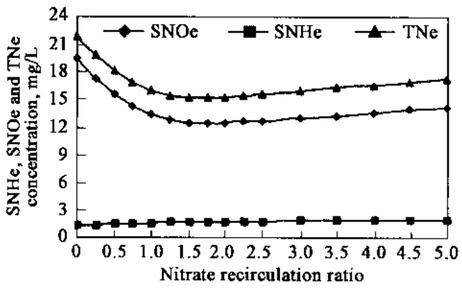

Fig. 3 Effect of nitrate recirculation ratio on concentration of effluent ammonia, nitrate and TN

2.3 Effect of sludge recycle ratio on nitrogen removal

Any solids accumulated in the settler were the bases of the bio-reaction. Through sludge recycle the required MLSS would be transferred to the reactors. If recycle sludge ratio was too low, not got the required MLSS concentration, plenty of nitrifiers would lost, which would reduce nitrification efficiency and increase effluent ammonia concentration; if recycle sludge ratio was too high, more solids transferred to the reactors, it would increase aeration energy cost and secondary clarifier load.

Fig. 4 shows the effect of the sludge recycle ratio on effluent ammonia, nitrate and TN concentration. When the sludge recycle ratio increased to 0.6, the effluent ammonia concentration reached 3.2 mg/L, the corresponding ammonia removal efficiency was 94.2%, and TN removal efficiency was 75%. TN and ammonia nitrogen removal continued to improve imperceptibly as sludge recycle ratio increased. So sludge recycle ratio in biological nitrogen removal process should be kept at 60%—100%, at the least kept above 40%.

2.4 Effect of SRT on nitrogen removal

Aerobic autotrophic bacteria were responsible for nitrification, with a lower biomass yield, required a longer SRT than heterotrophic bacteria. If SRT was shorter, the heterotrophic bacteria would be dominant, and the ammonia removal was impaired, excessive wasting might cause poor

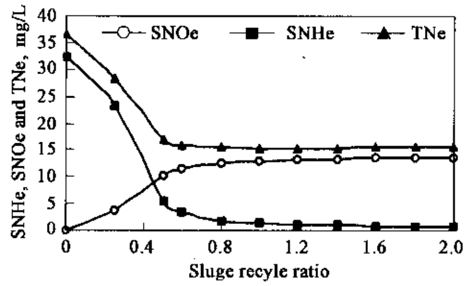

Fig.4 Effect of sludge recycle ratio on concentration of effluent ammonia, nitrate and total nitrogen

removal of soluble pollutants and low DO bulking. If SRT was longer, inadequate wasting might cause clarifier overloading, low F/M bulking, and increased air demand for biomass endogenous respiration.

Fig.5 shows the effect of SRT on effluent ammonia, nitrate and TN concentration, results showed that when the SRT increased to 8 d, would achieve a higher ammonia removal efficiency. Ammonia nitrogen and TN removal continued to improve imperceptibly as SRT increased. In order to keep appropriate nitrification rate, it should be kept SRT in biological nitrogen removal system at 9—12 d, and adjusting SRT according to influent ammonia concentration.

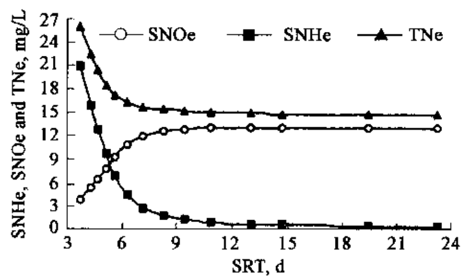

Fig. 5 Effect of SRT on concentration of effluent ammonia, nitrate and TN

2.5 Effect of COD/TN on nitrogen removal

Denitrification bacteria were in need of sufficient amounts of readily metabolized carbon in order to function optimal. The tough standards on nitrogen discharge had posed a particular challenge to biological denitrification, especially for treatment plants with an unfavorable COD to TN ratio. The effective solution known to date was to supplement external carbon sources to the anoxic tanks/zones of the bioreactor to enhance denitrification process.

Fig.6 shows the effect of influent COD/TN on effluent ammonia, nitrate and TN concentration and influent nitrogen load, results showed that nitrogen removal continued to improve as COD/TN increased. According to the theory calculation, influent COD/TN kept at 4 could satisfy denitrification process. But TN removal efficiency was only 50%, because wastewater characteristic was very complex, only a small part biodegradable influent carbon sources could be used as denitrification carbon. In order to keep TN removal efficiency above 80%, the value of influent COD/TN should larger than 8. It was found that nitrification rate gradually decreased as COD/TN increased, when COD/TN increased from 3 to 10, nitrification rate decreased from 0.103 to 0.042 kgTN/(kgMLSS·d). Furthermore, nitrogen removal decreased with the increase of its load, when influent nitrogen load larger than 0.05 kgTN/(kgMLSS·d), nitrogen removal èfficiency clearly deceased, so in the biological nitrogen removal processes the design value of nitrogen load should be kept less than 0.05 kgTN/(kgMLSS·d).

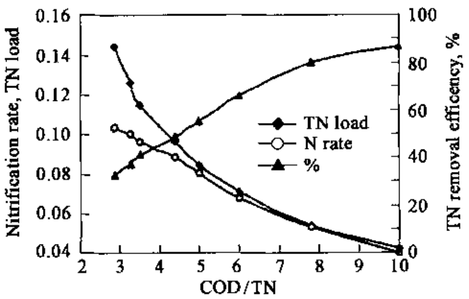

Fig. 6 Effect of COD/TN on nitrification rate, TN removal efficiency and nitrogen load

The nitrification rate would decrease with the increase of influent COD/TN, but denitrification rate was contrary. So when influent COD/TN was low, in order to increase denitrification rate, it needed to dose external carbon sources to compensate for the changes of influent. One should strive to add just enough carbon to cover the need of the denitrification bacteria. A too high dosage of external carbon leaded to increased sludge production, unnecessary high operational costs and might lead to carbon spill in the effluent. In the experiments, it had been found that controlling the nitrate nitrogen concentration at the end of the anoxic zone at a low set-point 1 mg/L minimized the amount of external carbon required, while maintaining the long-term effluent nitrate nitrogen concentration at a pre-specified level.

2.6 Effect of HRT on nitrogen removal

Nitrification and denitrification close to each other, if nitrification was not sufficient, effluent ammonia concentration would be high, denitrification potential not full used, and vice versa. So properly adjusted nitrification and denitrification capacity, furthest used their potential, was an important problem in the design and management of nitrogen removal process. It was known that nitrification and denitrification capacity were correlated with HRT of aerobic and anaerobic zone, that was, their own working volume.

Fig.7 shows the effect of HRT on effluent ammonia, nitrate and TN concentration. Results showed that TN and ammonia nitrogen removal continued to improve as HRT increased. Effluent nitrate concentration continued to improve when HRT less than 8 h, but effluent nitrate concentration gradually decreased when HRT larger than 8 h. In addition, when HRT was 4 h, nitrification was not sufficient, ammonia nitrogen removal efficiency was only 54.5%, when HRT increased to 8 h, ammonia removal efficiency reached 96.6%, and TN removal efficiency achieved 74.54%. Kept HRT at 8—9 h would realize good nitrification and denitrification. In order to get the largest nitrogen removal, it should be determine aerobic zones and anoxic zones volumes according to nitrification and denitrification rate. Owing to effluent standard strictly with ammonia, WWTP control should first satisfy with nitrification. When DO concentration in the aerobic zone increased to the pre-specified level, however effluent ammonia concentration was also high, then it should increase the size of aerobic zone until effluent ammonia concentration meet standard. When influent TN was low, easily realized full nitrification, it should decrease the size of aerobic zone so as to reduce aeration energy cost, and increased the volumes of anoxic zones.

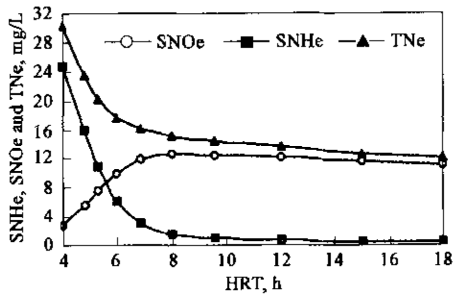

Fig. 7 Effect of HRT on concentration of effluent ammonia, nitrate and TN

3 Decision trees for nitrification and denitrification

The operational problems of the activated sludge process that had biological causes were among the most serious and most difficult to detect and solve in WWTP, a method based on human reasoning could help in this task. The development of a KBS involved the crucial steps of knowledge acquisition, knowledge representation and knowledge implementation. Based on above experiments, a knowledge-based approach for the supervision of the nitrogen removal problem in biological nitrogen removal processes was considered and successfully applied to the lab-scale plant, and the decision trees for nitrification and denitrification were depicted in Fig.8 and 9, respectively. Based on the Effluent Discharge Standard on Pollutant of Wastewater Treatment Plants (GB18918-2002), the minimal and the maximal permit effluent ammonia concentration was fixed 1 mg/L and 5 mg/L, respectively. The maximal permit effluent nitrate concentration was fixed 9 mg/L.

3.1 Nitrification decision tree

Fig.8 shows the decision tree for detecting problem for nitrification system, the problem mainly related to loss of nitrification capacity. First effluent ammonia concentration was checked, if it exceeded the minimal permit value 1 mg/L, the inference path continued to check if it exceeded the maximal permit value 5 mg/L, if it occurred, the system had inability to completely nitrify or loss of nitrification capacity, then the system checked for the probably causes.

First of all, a decreasing in nitrification system pH was tested, if it occurred, then the loss of nitrification was due to an alkalinity deficiency or to a too low pH. To clearly distinguish, the system checked for the influent pH. If it was normal or a little high, then the loss of nitrification was due to insufficient addition of lime to offset alkalinity destruction during nitrification. The decision tree must check for alkalinity in the clarifier effluent. If it was less than 20 mg/L, then start adding lime to nitrification system (also others alkaline agents such as sodium carbonate, caustic soda could be added to the aeration tank influent). If the influent pH was low, then the loss of nitrification was due to a too low pH, which could be produced by the addition of acidic wastes to sewer system. Low pH actuation involved checking for raw wastewater pH and alkalinity and mixed liquor pH, increasing pH with alkaline source to the aeration tank

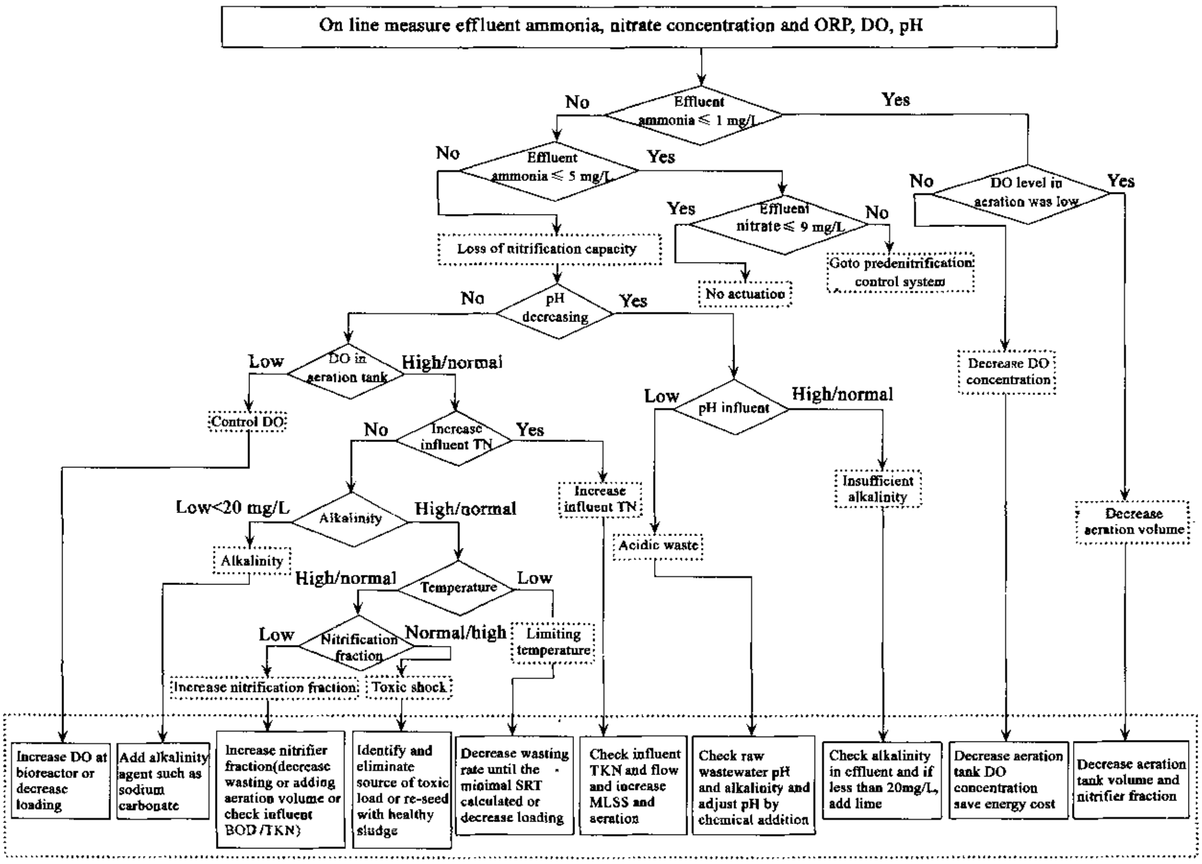

Fig.8 Decision tree for diagnosing nitrification problems

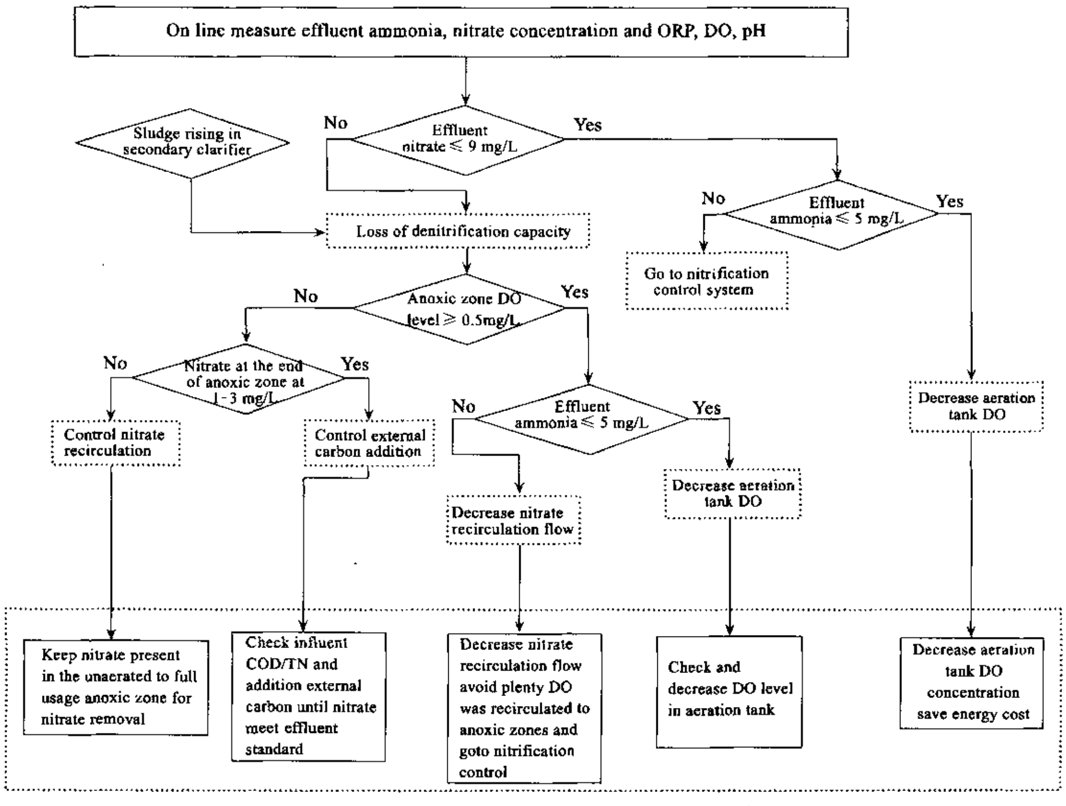

Fig.9 Decision tree for diagnosing denitrification problems

influent.

If a pH decreasing was not experimented in the aeration basin, alkalinity, DO, cold temperatures, an increase nitrogen load, a low nitrifying fraction and toxic shock were going to be explored as the possible causes. First, the DO level at the aeration tank was explored if it was low, then the limiting factor to completely nitrify was the DO concentration. The DO actuation checked for the DO level, and increased aeration based on the DO control strategy or decreased loading on nitrification tanks, as necessary. If the low DO was not the cause, a high TN concentration in the influent was checked, if there had been an increasing in total daily influent nitrogen loads, then this was the cause of poor nitrification. The high TN actuation would check for influent flow rate and TN concentration, increased the MLSS in nitrification tanks by increasing concentration or putting additional nitrification tanks on line and increase aeration. If influent TN not increased and normal, then the influent alkalinity was checked, if it was low, the problem was that there was no enough alkalinity in raw water to offset pH drop. The system would recommend increasing alkalinity (raise pH by adding an alkaline agent such as sodium carbonate, caustic soda or lime to the aeration tank influent). If influent alkalinity was not low, the decision tree checked the mixed liquor temperature. If it was cold, this was the limiting factor to allow complete nitrification, temperature actuation involved checking for nitrification rate and MLSS decreasing loading on nitrification system, or increasing biological population in nitrification tanks by raising sludge recycle or adding nitrification tanks. Finally, if the temperature was not the problem, the cause could be nitrification fraction in nitrification tanks, if a too low nitrifier fraction in nitrification tanks, this low nitrifier fraction could be provoked by these three causes (1) biological solids were escaping in effluent: add polymer to nitrification clarifier to enhance settling of biological solids; (2) too high sludge wasting: decreased wasting sludge from nitrification system; (3) aeration tanks volume very small: increased aeration nitrification tanks volume. If nitrification fraction was not low, the cause could be influent toxic shock, the actuations should include identify and eliminate source of toxic load, eliminated toxics, and wasted sludge gradually, and re-seed the plant with healthy sludge from another well-operated plant.

If effluent ammonia concentration not exceeded the maximal permit value 5 mg/L, then the system checked the effluent nitrate concentration, if it exceeded the maximal permit value 9 mg/L, which showed the system had inability to completely denitrify or loss of denitrification capacity and went to denitrification control system. If it did not, this showed the system had good nitrification and denitrification efficiency, keeping the condition, not need another actuation.

If effluent ammonia concentration less than the minimal permit value 1 mg/L, this showed system had good nitrification efficiency. In order to decrease aeration energy cost, the system checked DO concentration in aeration tanks, if DO concentration was low, in order to decrease aeration energy cost further, it should decrease nitrification fraction and increase denitrification fraction. If DO concentration was not low, it should decrease aeration DO level.

3.2 Denitrification decision tree

Fig.9 shows the decision tree for detecting problems for denitrification system. First effluent nitrate concentration was checked, if it exceeded the maximal permit value 9 mg/L or sludge rising in secondary clarifier, which showed the system had poor denitrification efficiency and loss denitrification capacity, then the system checked for the probably causes.

First of all, anoxic zones DO level was tested, if it exceeded 0.5 mg/L, the loss of denitrification was due to plenty DO recirculated to anoxic zones, then effluent ammonia concentration was checked, if it exceeded maximal permit value 5 mg/L, it showed the system had poor nitrification efficiency, in order to reduce DO recirculated to anoxic zones, it should reduce nitrate recirculation flow and went to nitrification control system. If effluent ammonia concentration less than maximal permit value 5 mg/L, it should reduce DO level in aeration zones to increase denitrification rate.

If anoxic zones DO level less than 0.5 mg/L, then the nitrate concentration at the end of anoxic zone was checked; if it was not kept at 1—3 mg/L, the nitrate recirculation flow control strategy should be used to guarantee nitrate present throughout the unaerated zones to ensure a full usage of this zone for denitrification, minimized the TN in the effluent as well as the possibility of suffering denitrification in the settler, and prevented undesired high nitrate concentration or DO increases in the anoxic zones. If nitrate concentration at the end of anoxic zones was kept at 1—3 mg/L, the cause could be the influent with unfavorable COD to N ratio, although intensify nitrate recirculation flow rate control could increase the utilization of influent COD, denitrification rate was only to a certain extent increased. In order to greatly increase denitrification rate, external carbon source should be supplemented to anoxic zones, experiments showed that maintaining nitrate concentration at the end of anoxic zone at 1 mg/L could realize the lower effluent nitrate and TN concentration with the minimal carbon addition.

If effluent nitrate concentration less than the maximal permit value 9 mg/L, then the denitrification decision tree checked the effluent ammonia concentration, if it exceeded the maximal permit value 5 mg/L, the system had inability to completely nitrify or loss of nitrification capacity and went to nitrification control system. If it did not, this showed system had good nitrification and denitrification efficiency. In order to decrease aeration energy cost, it should decrease the DO level in aeration zones.

3.3 Validation

Results obtained in the application of knowledge based approach to the A/O reactor showed that expert system was able to identify biological nitrogen removal problems with reasonable accuracy, and to maintain the effluent ammonia and nitrate concentration within legal restrictions. In experiments, the sludge rising was always happened. Based on denitrification decision tree, it was found that nitrate concentration in the second zone was very low, denitrification potential was not fully used. The internal reciculation flow control strategy was used. As shown in Table 1, the effluent nitrate, TN, nitrate in the second zone (SNO-2) were different under different internal recirculation ratio. Using the optimal recirculation ratio 2.56, the nitrate and TN removal efficiency were increased by 14.31% and 8.8%, respectively, compared with the ratio 1.5. When internal recirculation continue increased the effluent nitrate and TN concentration, on the contrary increased. Based on denitrification decision tree, sludge rising in the secondary clarifier was successfully overcome.

Table 1 Using DES adjusting nitrate recirculation flow

R, %	SNHe	SNOe	TNe	SNO-2
150	7.25	10.62	18.58	0.65
200	7.23	9.88	17.81	1.32
256	7.20	9.10	16.94	2.02
300	7.22	9.76	17.60	3.21

4 Conclusions

Based on the results of this work, the following conclusions could be drawn:

For any given influent characteristics, there were optimal settings of the operational variables.

The good control system for DO could be achieved by adjusting the DO set point according to the effluent ammonia concentration.

The optimal control strategy for nitrate recirculation flow was control the nitrate concentration at the end of the anoxic zone at a level of about 1—3 mg/L.

Sludge recycle ratio in biological nitrogen removal processed should be kept at 60%—100%.

Nitrogen removal deteriorated sharply at low SRT and was nearly constant at higher SRT, it should be adjusted SRT according to influent ammonia concentration.

Maintaining nitrate concentration at the end of anoxic zone at 1 mg/L could realize the lower effluent nitrate and TN concentration with the least external carbon addition.

In order to keep TN removal efficiency above 80%, the influent COD/TN ratio should be larger than 8. Influent nitrogen load should be less than 0.05 kgTN/(kgMLSS·d).

The decision trees for nitrification and denitrification had been built for diagnosis and solution of the nitrogen removal problems in A/O process, it was able to maintain the effluent ammonia and nitrate concentration within legal restrictions, while saving energy costs.

Notation:

A/O: anoxic/oxic process; DO: dissolved oxygen; SRT: solids residence time; HRT: hydraulic retention time; COD: chemical oxygen demand; TN: total nitrogen; WWTPs: wastewater treatment plants; WWTP: wastewater treatment plant; PLC: programmable logic controller; KBS: knowledge-based systems; ORP: oxidation-reduction potential; PC: personal computer; PID: proportional integral differential; MLSS: mixed liquor suspended solids; F/M: food/microorganism; DES: denitrification decision tree.

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