Fuzzy control of nitrogen removal in predenitrification process using ORP

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Abstract In order to meet increasingly stringent discharge standards, new applications and control strategies for the sustainable removal of nitrogen from wastewater have to be implemented. In the past years, numerous studies have been carried out dealing with the application of fuzzy logic to improve the control of the activated sludge process. In this paper, fuzzy control strategies of predenitrification systems are presented that could lead to better effluent quality and, in parallel, to a reduction of chemicals consumption. Extensive experimental investigations on lab scale plant studies have shown that there was excellent correlation between nitrate concentration and ORP value at the end of the anoxic zone. Results indicated that ORP could be used as an on-line fuzzy control parameter of nitrate recirculation and external carbon addition. The optimal value of ORP to control nitrate recirculation and external carbon addition was -86 ± 2 mV and -90 ± 2 mV, respectively. The results obtained with real wastewater also showed the good performance and stability of the fuzzy controllers independently from external disturbances. The integrated control structure of nitrate recirculation and external carbon addition in the predenitrification system is also presented.

Keywords Fuzzy control; ORP; nitrate control; predenitrification process

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Introduction

Today, eutrophication due to the presence of nutrients including nitrogen is a wellrecognized environmental problem worldwide. As a result, stringent standards have been imposed on total nitrogen (TN) concentration levels in effluent from wastewater treatment systems in many parts of the world. The tough standards on nitrogen discharge have posed a particular challenge to biological denitrification. To date the two most effective solutions to enhance denitrification, are to control the nitrate recirculation, and to supplement external carbon sources to the anoxic tanks/zones of the bioreactor.

Nitrate recirculation flow has long been identified as a manipulated variable in a predenitrification system. The on-line control of this variable to improve nitrate removal has been studied by several researchers (Londong, 1992; Balslev *et al.*, 1996;Yuan *et al.*, 2002). A common strategy is to control the nitrate concentration at the end of the anoxic zone at a level of about 1–3 mg/l. This strategy maximizes the usage of influent COD for denitrification, but has limited effectiveness in maintaining the effluent nitrate level, as the amount of nitrate that can be removed is predominantly determined by the ratio of influent COD to N. When wastewater treatment plants influent with an unfavourable COD to N ratio, it should supplement external carbon sources to the anoxic zone to increase denitrification rate. But it is noted that the lack of carbon causes incomplete denitrification, while excess dosage of external carbon significantly increases operating costs or causes carbon spill. To solve this problem, many researchers have studied the question of determining the appropriate amount of carbon sources. For a predenitrification system, it has been found that controlling the nitrate nitrogen concentration at the end of the anoxic zone at a low set-point (1–2 mg/l) minimizes the amount of external carbon required, while maintaining the long-term average effluent nitrate nitrogen concentration at a pre-specified level (Lindberg and Carlsson, 1996; Yuan *et al.*, 1997; Samuelsson and Carlsson, 2001).

Fuzzy control has been successfully applied to wastewater treatment, especially in the activated sludge process, because it is a complex dynamic system and it is difficult to build up the exact mathematical model for its discretion. In order to realize on-line control for predenitrification process, a parameter must be found that can represent the change of nitrate concentration and be computer controlled. An ORP sensor has the ability to measure on-line, respons, respond quickly, and be highly accurate. Researchers have carried out many experiments in SBR, and results have show that ORP could be used as a process control parameter in SBR (Peng *et al.*, 1997).

Materials and methods

Lab-scale plant and chemical analysis

Experiments were carried out using a lab-scale combined predenitrification reactor with an operating volume of 48 l and a settler (diameter 25 cm, 20 l). The combined predenitrification reactor was separated into six compartments (8 l each), the first two compartments were anoxic and the last four were aerated; all compartments were fully mixed. Each mechanical unit of the process (pumps, stirrers, etc.) was controlled by a PC through a data acquisition card. Every compartment had on-line sensors (DO meter, pH meter, ORP meter, and thermometer) connected to probe controllers. The PC controlled the pH (7–7.5) with direct addition of solid sodium carbonate to the inflow tank. Also, the PC controlled the DO at 2 mg/l through manipulating the aeration valves. This control was realized based on a digital PID algorithm programmed in the computer. The inflow, nitrate recirculation flow and sludge recycle flow were controlled by a variable speed peristalsis pump. A schematic flow diagram of the lab plant is shown in Figure 1. During the experiments, the influent flow, MLSS, SRT, and sludge recycle ratio were controlled at 144 l /d, 2,500 ± 200 mg/l, 12 days, and 0.8, respectively. Temperature in the mixed liquor was stable (21 °C) over all experiments.

Analyses of total suspended solids (TSS), COD, MLSS, alkalinity, ammonia, nitrate, nitrite, were performed as described in *Standard Methods* (1995). DO and temperature were measured using WTW-300i in-line DO analyser; pH and ORP were detected using HANNA in-line analyser.

Sludge and synthetic wastewater

The biological population used in the process was developed from the full-scale plant of Harbin Wen Chang WWTP with predenitrification process. The reactor feed consisted of

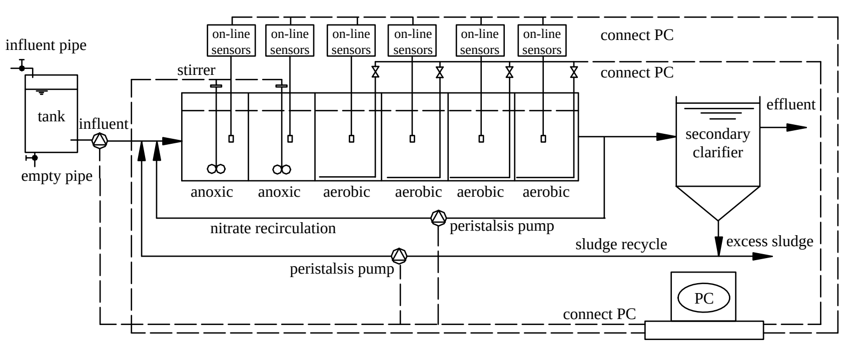

Figure 1 Schematic diagram of a predenitrification process

synthetic wastewater having characteristics similar to domestic wastewater. It was prepared by using tap water and starch power, the composition was 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).

Results and discussion

Correlation between ORP and nitrate concentration at the end of the anoxic zone

In order to validate the feasibility that ORP could be used as a fuzzy control parameter of nitrate recirculation or external carbon addition, the correlation between ORP and nitrate concentration at the end of the anoxic zone with external carbon addition while not changing nitrate recirculation, was studied. Firstly, influent COD and ammonia concentration were kept at 400 mg/l and 55 mg/l, respectively, by changing the nitrate recirculation flow. ORP and nitrate concentration in the second anoxic zone are shown in Figure 2a. After that, influent COD and ammonia concentration were kept at 250 mg/l and 50 mg/l, respectively, and the nitrate recirculation flow ratio was maintained at 2.5 by changing external carbon dosage. ORP and nitrate concentration in the second zone are shown in Figure 2b. It was found that the correlation between ORP and nitrate concentration was excellent, and the correlation coefficients were 0.9553 and 0.9616, respectively. It also proved that the excellent correlation was not disturbed by influent water characteristics. ORP and nitrate concentration in the second zone increased correspondingly with increasing nitrate recirculation flow or decreasing external carbon dosage, and vice versa.

Determination of the optimal ORP value

Based on the above findings, it was considered that ORP could be used as a fuzzy control parameter of nitrogen removal, whereas, there was still the problem of how to effectively control nitrate recirculation and external carbon dosage using ORP, the, determine the optimal ORP value. Firstly, by manipulating the nitrate recirculation flow ratio without external carbon addition, and keeping influent COD and ammonia concentration at 400 mg/l and 58 mg/l, respectively, and the variations of ORP value, effluent nitrate and

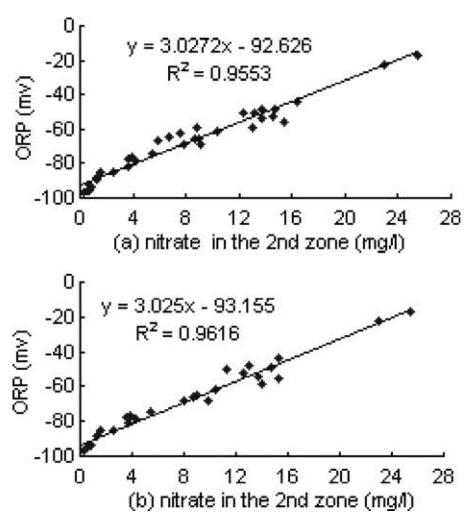

Figure 2 The correlation between ORP and nitrate concentration in the second zone of different (a) nitrate recirculation flow and (b) external carbon dosage

TN concentration as shown in Figure 3(a), it was found that the effluent nitrate and TN concentration gradually decreased with the increase of nitrate recirculation flow. When nitrate recirculation flow ratio increased to 2.3, effluent nitrate and TN concentration reached the lowest point (10.8 mg/l and 14.6 mg/l, respectively), and TN removal efficiency was 74.8%, ORP value was −86 mV, then the corresponding nitrate concentration in the second zone was 2 mg/l. Following that, the nitrate recirculation flow ratio was increased continuously, when it was found that the effluent nitrate and TN removals were gradually decreased. According to the results, it could be shown that increasing nitrate recirculation flow ratio did not always increase nitrogen removal, which also correlated with the influent carbon source, the denitrification potential of the anoxic zone and the amount of oxygen that was recycled from the aerobic zones. In addition, the results proved that the optimal ORP value did not change with the variations of influent water characteristics, and the removals for effluent nitrate and TN reached the highest when ORP in the second zone was kept at −86 ± 2 mV.

Another experiment was also conducted. The external carbon, methanol with COD concentration 600 mg/l, was continuously dripped to the first anoxic compartment using a variable speed peristaltic pump. Influent COD and ammonia concentration were kept at 250 mg/l and 55 mg/l, respectively, and the nitrate recirculation flow ratio was 2.5. Results showed that the effluent nitrate concentration and TN removal efficiency were gradually increased with the increase of external carbon dosage, as in Figure 3(b). When keeping ORP value in the second zone at −90 ± 2 mV, both the lower effluent nitrate and TN concentration with a minimal external carbon dosage could be achieved, and the corresponding nitrate concentration in the second zone was 1 mg/l. The effluent nitrate and TN concentration were 8.45 mg/l and 12.7 mg/l, respectively. Compared with the experiment without dosing external carbon, effluent nitrate and TN removal efficiency were increased by 62.6% and 51.34%, respectively. In addition, the optimal ORP value was not affected by the influent water characteristics during the course of the experiment.

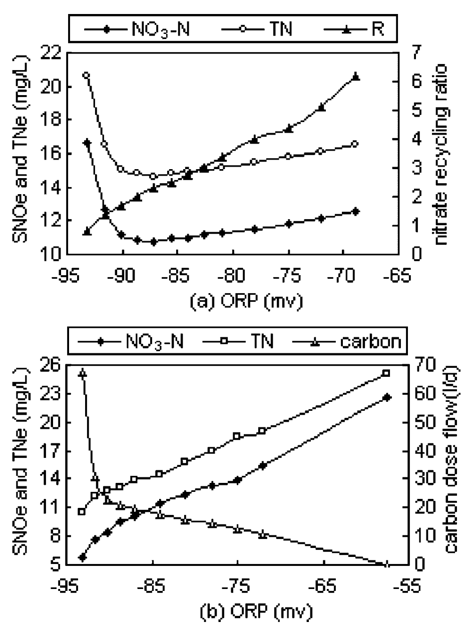

Figure 3 The effect of (a) nitrate recirculation flow and (b) external carbon dosage on the effluent nitrate and TN, and the ORP value at the end of the anoxic zone

Discussions

Nitrate control aims at the optimal use of the denitrification potential of the anoxic reactor at any moment. For this purpose, the proposed control strategy continuously adapts the nitrate recirculation flow in order to maintain the desired nitrate set-point (1.5–2.5 mg/l) at the end of the anoxic zone. This strategy avoids the inhibition of the denitrification by the absence of nitrate in the anoxic zones (associated with very low internal recycle) and prevents undesired high nitrate concentration or DO increases in the anoxic zones (associated with very high internal recycle). The consequence of this strategy is the maximum removal of nitrate in the biological reactors; that is, maximizing nitrate removal and increasing the denitrification rate. The denitrification rate can be decomposed into two parts: $r_d(\tau) = r_{d,end}(\tau) + r_{d,ex}(\tau)$, where $r_{d,end}(\tau)$ is the 'endogenous' nitrate uptake rate, due to oxidation of cell COD, cell storage product, as well as particulate bCOD (biodegradable COD), which is independent of the nitrate recirculation flow; $r_{d,ex}(\tau)$ is the nitrate uptake rate due to the oxidation of soluble bCOD, so maximizing soluble bCOD utilization can increase the denitrification rate. $r_{d,ex}(\tau)$ was determined as $(\mu_{H,\max}\cdot S_{S,AN}\cdot S_{NO,AN}\cdot X_{BH})/((K_S + S_{S,AN})^*(K_{NO} + S_{NO,AN}))$, where $S_{NO,AN}$ and $S_{S,AN}$ are nitrate nitrogen and soluble bCOD in the denitrification zone, respectively; K_S and K_{NO} are the affinity constants for soluble bCOD and nitrate, respectively; $r_{d,ex}(\tau)$ is obviously affected by the nitrate recirculation flow, when the nitrate recirculation flow is increased. $S_{NO,AN}$ will rise because more nitrate is recirculated, and $S_{S,AN}$ will drop because bCOD from influent is increasingly diluted. If nitrate concentration at the end of the anoxic zone was controlled in 2 mg/l, the denitrification rate was not limited by nitrate concentration, soluble bCOD in the denitrification zone become the main control factor Z. Yuan *et al.* (2002) proved that intensified nitrate recirculation flow control can increase the utilization of influent soluble bCOD, so the strategy of nitrate recirculation flow could increase the denitrification rate.

When influent has an unfavourable COD to N ratio, in order to increase denitrification rate greatly, external carbon source should be supplemented to anoxic zones; it was found that maintaining nitrate concentration at the end of anoxic zone at 1 mg/l could minimize the amount of external carbon dosage, oxygen consumption and surplus sludge production, while maintaining effluent nitrogen concentration at a pre-specified level.

Design of fuzzy controllers

The design of fuzzy controllers has been carried out by trial and error, on the basis of the knowledge of the system dynamics and the experience gained in monitoring wastewater plant. Input variables are the error (figured by E) between ORP set-point (−86 mV or −90 mV) and measured value in the last anoxic zone and the change of the error (figured by EC). Output variable (figured by Δu) is the change of the nitrate recirculation flow ratio or external carbon dosage. The fuzzy controller includes three parts: changing exact value into fuzzy variable, designing the arithmetics of fuzzy control and making fuzzy decisions from output information.

Changing exact value into fuzzy variable

The first step to build the control law was the translation of possible values of the different inputs and output variables into linguistic labels given by membership functions (MFs). The fuzzy logic controllers use triangular MFs. Input variables and output variables are all fuzzified by seven MFs, which are negative big (NB), negative middle (NM), negative small (NS), zero (O), positive small (PS), positive middle (PM), positive big (PB). The fields of E and EC were (−6, −5, −4, −3, −2, −1, 0, +1, +2, +3,

+4, +5, +6). the fields of Δu were (−7, −6, −5, −4, −3, −2, −1, 0, +1, +2, +3, +4, +5, +6, +7).

Fuzzy decision and fuzzy control rules

Summarizing the experiences in ORP control by hand in the process of wastewater treatment, the rules designed by the operator are shown as: a) if E is NB and EC is NB then Δu is PB; b) if E is NB and EC is NM then Δu is PB; c) if E is NB and EC is NS then Δu is PB; d) if E is NB and EC is O then Δu is PB; e) if E is NB and EC is PS then Δu is PM; f) if E is NB and EC is PS then Δu is PS; g) if E is NB and EC is PB then Δu is O. When E is NM, NS, O, PS, PM, or PB, there are also 7 control rules. The error being big or bigger, the leading aim of selecting control variables is to eliminate the error as quickly as possible; the error being small, the chief aim of selecting control variables is to avoid more adjustments and to maintain the stability of the control system, which are the principles of selecting different changes of control variables. The summary of the rules implemented in the control law is presented in Table 1.

Fuzzy decision making of output Information

According to fuzzy conditional expression selected in the fuzzy control rules table, the corresponding value of fuzzy control variable Δu can be calculated, and using the reasoning and combining rules of fuzzy theory, the following equation can be obtained: $\Delta u = (E \cdot EC) \cdot R$.

Validation of ORP fuzzy controller

In order to validate the effectiveness of ORP fuzzy controller, the experiments with real wastewater were performed under dynamic conditions (as shown in Figure 4).

In Figure 5(a), it was shown that the ORP and nitrate concentration at the end of the anoxic zone could be maintained stably at −86 ± 2 mV and 2 ± 0.5 mg/l, respectively, by using ORP fuzzy controller to manipulate nitrate recirculation flow. It was proved that ORP fuzzy controller, independently from external disturbances, could realize the optimal control of the nitrate recirculation flow.

Similarly, in Figure 5(b), the ORP and nitrate concentration at the end of the anoxic zone could also be kept stably at −90 ± 2 mV and 1 ± 0.25 mg/l, respectively, by using ORP fuzzy controller to manipulate external carbon dosage. It was found that the ORP fuzzy controller could quickly manipulate external carbon dosage to eliminate the disturbance of influent water quality, and results showed that the denitrification rate and the removal of nitrate and TN were greatly increased. The experiments show that the fuzzy controllers can be easily implemented in modern control and supervision systems and that the control characteristics can be followed and modified during the operation.

Table 1 Summary of rules implemented in the control law

Input Error (E)	The change of error (EC)						
	NB	NM	NS	O	PS	PM	PB
NB	PB	PB	PB	PB	PM	PS	O
NM	PB	PB	PB	PM	PS	O	NS
NS	PB	PM	PM	PS	O	NS	NM
O	PM	PM	PS	O	NS	NM	NM
PS	PM	PS	O	NS	NM	NM	NB
PM	PS	O	NS	NM	NB	NB	NB
PB	O	NS	NM	NB	NB	NB	NB

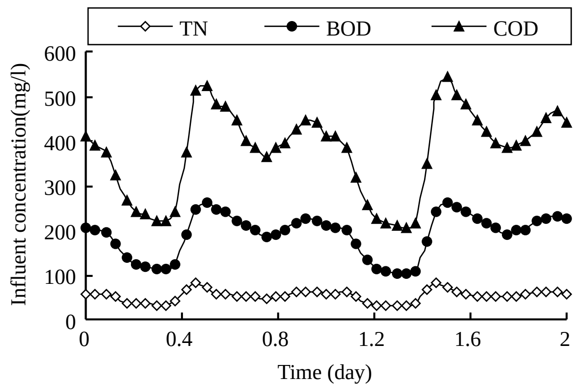

Figure 4 Influent COD, BOD and TN

The combination of both controllers

It was shown that manipulating nitrate recirculation flow, controlling ORP value at the end of the anoxic zone at $-86 \pm 2\,\mathrm{mV}$, leads to optimal reduction of the effluent TN and the use of influent COD. Because the cost of nitrate recirculation in terms of energy consumption is negligible compared to that of external carbon dosage, therefore the only objective of such control strategy is to minimize effluent TN. If the system still does not meet effluent nitrate criteria after implementation of the nitrate recirculation controller, then one option is to add an external carbon source. But the dosage of external carbon should be controlled so as to just meet the effluent criteria for nitrate, as external carbon source is generally expensive and excessive dosage may also lead to problems of effluent requirements on organic matter. The control of the external carbon addition has to be coordinated with the control of the nitrate recirculation as both controls affect the anoxic zone in the medium time-scale. The configuration of integrated control is depicted in

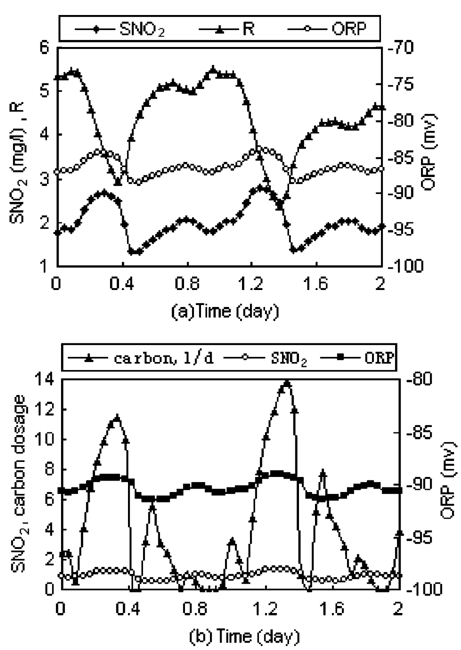

Figure 5 The results of fuzzy controllers, (a) nitrate in the second zone, ORP and nitrate recirculation flow ratio; (b) nitrate in the second zone, ORP and external carbon dosage

Figure 6. Fuzzy Controller A manipulates the nitrate recirculation flow (Q_{int}), controlling ORP at the end of the anoxic zone at a pre-specified set-point −86 mV, and ensures full utilization of the anoxic volume, and hence of the incoming organic matter, regardless of the fact that it stems from an external carbon source, or the influent when the effluent nitrate standard is met without external carbon addition. Controller B manipulates the nitrate recirculation flow, controlling the nitrate concentration at the end of the aerobic zone ($S_{NO,AE}$) at a set-point ($S_{NO,AE,SP}$), which is determined with controller D. This loop is activated only when $S_{NO,AE}$ exceeds the set point, ensuring (together with carbon dose fuzzy controller C) the effluent standard is met. Fuzzy controller C manipulates the external carbon dosage (Q_{carbon}) to the denitrification zone to control ORP at the end of the anoxic zone at a pre-specified set-point −90 mV. This loop is activated only with controller B. Controller D corrects this effluent nitrate set point, which depends on the type of effluent criterion. The combined control system is able to control the effluent nitrate concentration consistently close to the discharge limits with a minimum consumption of external carbon sources.

Conclusions

ORP as a fuzzy control parameter of nitrate recirculation flow and external carbon addition was studied for a predenitrification nitrogen removal process treating synthetic wastewater. Excellent correlation between ORP and nitrate concentration was found in the experiment. Results showed that ORP could be worked as a control parameter of nitrogen removal.

Manipulating nitrate recirculation flow and controlling ORP value at the end of the anoxic zone at −86 ± 2 mV could lead to optimal reduction of the effluent total nitrogen and utilization of the influent COD to the largest extent.

Manipulating external carbon dosage flow and controlling ORP value at the end of the anoxic zone at −90 ± 2 mV could reduce effluent nitrate and total nitrogen concentration to the largest level with a minimal external carbon addition.

The established ORP fuzzy controller could effectively control nitrate recirculation flow and external carbon addition, and quickly weaken the disturbances of influent water quality, improving effluent water quality. The combined control system, which manipulates the nitrate recirculation and external carbon dosage simultaneously, was able to control the effluent nitrate concentration consistently below, but close to, the discharge limits with a minimum consumption of external carbon sources.

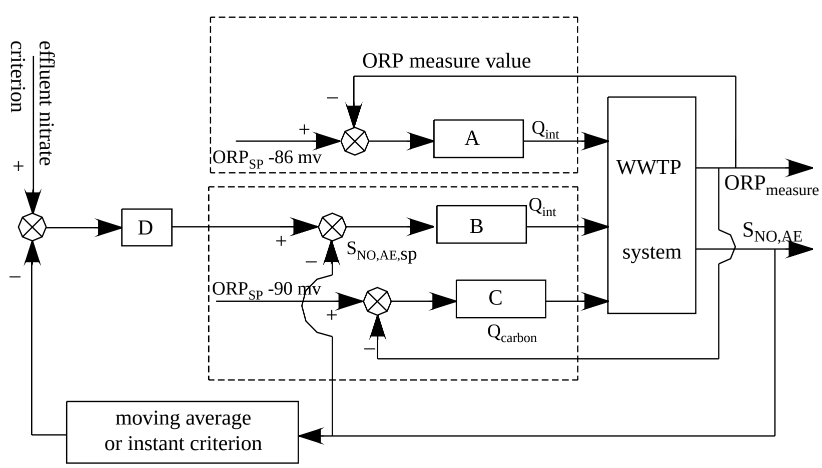

Figure 6 The combined control structure of nitrate recirculation and external carbon addition

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