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Performance evaluation of a full-scale advanced phase isolation ditch process by using real-time control strategies

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Abstract−This paper proposes real-time control strategies that can be applied in a full-scale advanced phase isolation ditch (APID) process. Real-time operation mode control (OMC) and aeration section control (ASC) strategies were developed to cope more stably with fluctuations in the influent loading and to increase the nitrification and denitrification reactions within the entire volume. The real-time OMC and ASC strategies were evaluated using mathematical models. When the NH_4-N in the reactor was maintained at a high level, appropriate control actions, such as continuing the aeration state, stopping the influent inflow and increasing the aeration section, were applied in the APID process. In contrast, when the NO_X-N in the reactor was maintained at a high level, the non-aeration state, influent inflow, and decreased aeration section were continued. It was concluded that stable operation in the APID process could be achieved by applying real-time OMC and ASC strategies developed in this study.

Keywords: APID Process, Real-time Operation Mode Control, Real-time Aeration Section Control, Setpoint Graph, Mathematical Model

INTRODUCTION

For the last 40 years, a recirculation-type, biological nutrient removal process has been mainly applied for the removal of nutrients in wastewater treatment plants. In recirculation-type processes such as A^2/O (anaerobic/anoxic/oxic), Bardenpho and MLE (Modified Ludzack-Ettinger), the operating conditions of the reactors were divided according to their locations and the wastewater was therefore moved and reduced sequentially from the first reactor to the last reactor. Disadvantages of these processes included their relatively large reactor volumes and the difficulty in stably treating the sudden change of influent loading. To compensate for these disadvantages, utilizing improvements in computer processing ability and sensor technology, alternating-type processes have been introduced [1-5]. The alternating process for biological wastewater treatment in general not only improves the nutrient removal efficiency but also reduces initial treatment costs by using intermittent aeration and alternated feeding of the influent [4].

The advanced phase isolation ditch (APID) process we propose is an alternating process introduced by Kim et al. [4] and Yoon et al. [5]. The APID process consists of two reactors run in parallel lanes, similar to the BioDenNitro process which is a patented process developed by I. Krüger System, but which is operated using four influent and return sludge inflow points. Therefore, the APID operation utilizes four operation modes and the aeration and non-aeration of each reactor are determined according to each operation mode. The basic operational mode is to give the influent with four points of the biological reactor called A-B-C-D, with an operational time set to 30 minutes for each, as shown in Fig. 1. Under these operation modes, the APID process has been applied for the last three years in a full-scale plant with a working volume of 10,000 m^3/day. Because the operational mode of biological reactors is changed according to the operational time, the nitrification and denitrification reactions in the identical reactor occur in turn. As a result, the effluent nitrogen concentration, which is lower than the legal standard of 20 mg/L, has been maintained stably. However, during intervals with a high level of fluctuation in the influent loading, it was difficult to maintain a sufficient nitrogen removal rate by using the basic four operation modes. Therefore, an advanced control strategy is required.

Various studies that applied control strategies by changing the operational cyclic time and manipulated variables according to the concentration change of NH_4-N and NO_X-N in the reactor have been introduced [6-13]. In this study, based on these previous research results, we developed a real-time operation mode control (OMC) strategy, which was available in the APID process, and the four basic operation modes were thus increased to 12 operation modes. Additionally, a real-time aeration section control (ASC) strategy was developed to further increase the nitrification and denitrification reactions within the entire volume of the limited reactor. Because the two control strategies, real-time OMC and ASC, were applied in different reactors, they could be applied in the APID process as integrated control strategies without producing a conflict between the two strategies. These real-time OMC and ASC strategies were tested by using mathematical models and the applicability of the developed control strategies was evaluated based on simulation results.

MATERIALS AND METHODS

1. A Full-scale APID Process

The APID process used as the target process here has been oper-

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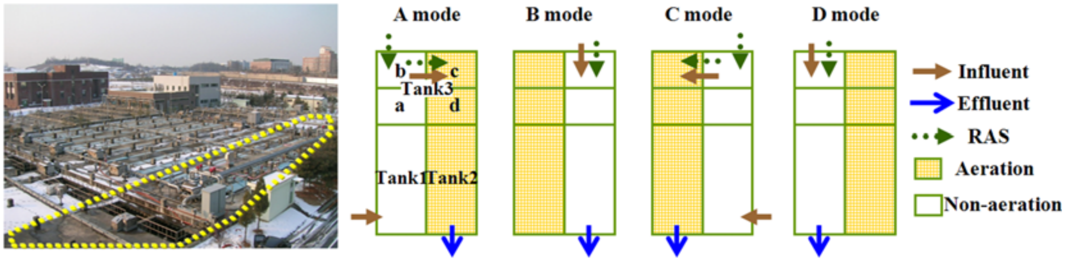

Fig. 1. Picture of field demonstration (left) and schematic diagram for basic operation modes of the full-scale APID process (right) [4].

ated for treating 10,000 m^3/day of wastewater in the J wastewater treatment plant (South Korea). As shown in Fig. 1, the APID process had two identical parallel lanes for intermittent aeration and consisted of six reactors. The volumes of Tank1 and 2 were 660 m^3 each, and each volume of Tank3 (i.e., Tank3a, b, c and d) was 330 m^3. The hydraulic retention time and the sludge retention time of the APID process were about 6.5 hours and 7-30 days, depending on the seasonal temperature and influent variations, respectively. The design and operating conditions of the APID process are shown in Table 1. For real-time monitoring, several sensors were installed 70 cm below the water surface of the reactor, and the measured parameters were dissolved oxygen, oxidation-reduction potential, NH_4-N, NO_3-N, PO_4-P and suspended solids [5].

Table 1. Design and operating conditions of the full-scale APID process

Working volume (m^3)		Flow rate (m^3/d)	
Tank1	660	Influent	9360-9980
Tank2	660	Return activated sludge	2320-2500
Each of Tank3	330	Waste sludge (avg.)	117
2nd Settler	1512	-	-

Fig. 1 shows the basic operation modes (i.e., A, B, C and D modes) of the APID process. The operation periods for each mode were 30 minutes and the air-on/air-off, influent and return sludge inflow points were different from each other in the four modes. In the APID process, the B and D modes were added to the A and C modes, which are similar to the conventional intermittent aeration process because the distributions of organic sources into the reactors are more efficient [4]. When the APID process was operated in the A and D modes, the aeration in Tank1, 3a and 3b was stopped and the denitrification reaction occurred by consuming the organic matter of the influent. At the same time, the nitrification reaction occurred in the opposite reactors because of the aeration in Tank2, 3c and 3d. For the B and C modes, the operating conditions and reactions were reversed as compared to the A and D modes.

2. Development of a Real-time Operation Mode Control (OMC) Strategy

To cope more stably with fluctuations of the influent loading, we developed a real-time OMC strategy, in which eight sub-operation modes were added to the basic four operation modes. In the real-time OMC strategy, the aerations of each reactor in Tank3 were not considered and only the aeration/non-aeration of Tank1 and 2 was considered. The entire aeration states in Tank1 and 2 were set as

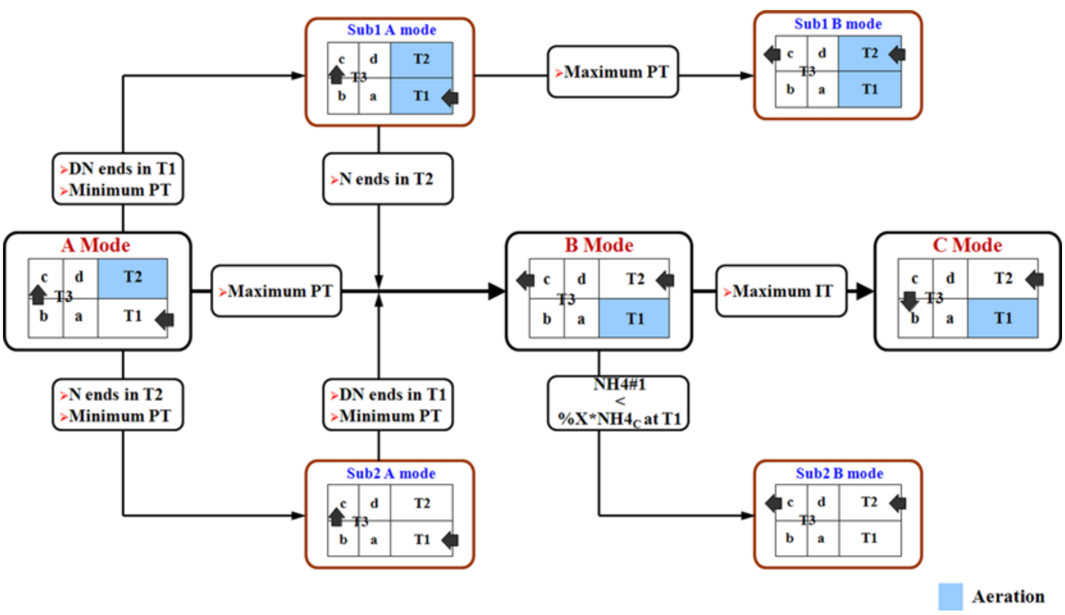

Fig. 2. Schematic diagram of the real-time operation mode control (OMC) strategy for the A and B modes (DN, PT, N, IT, %X, and $NH4_C$ are the denitrification reaction, phase time, nitrification reaction, intermediate phase time, the coefficient for the mode change and the criteria value for change of the Sub2 B mode).

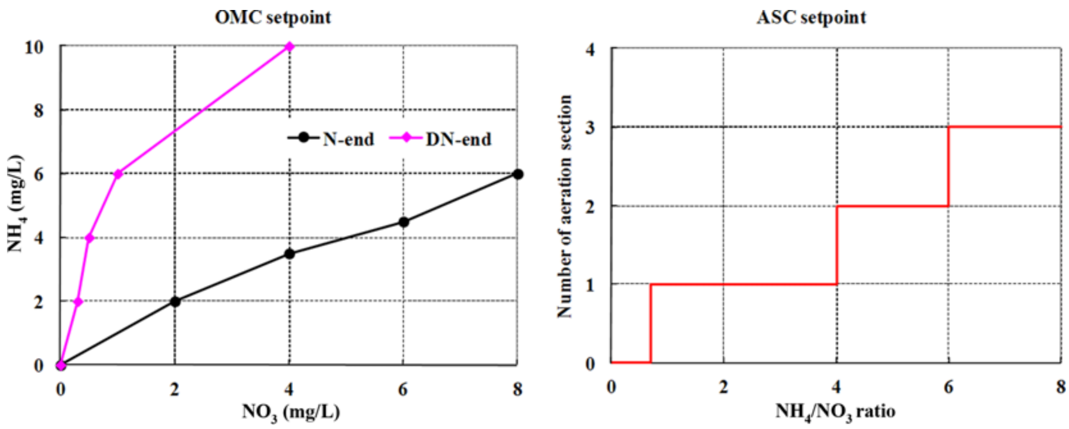

Fig. 3. The real-time OMC (left side) and ASC (right side) setpoint graphs used in this study.

Sub1 modes (i.e., Sub1 A, B, C and D modes) and the entire non-aeration states in Tank1 and 2 were set as Sub2 modes (i.e., Sub2 A, B, C and D modes). The influent and return sludge inflow point in the eight sub-modes was identical to that in the basic four operation modes. By considering the influent inflow point, the aeration/non-aeration state and the maximum and minimum of each mode, the mode change rules for the real-time OMC strategy were decided as shown in Fig. 2. Among all the operation modes, Fig. 2 shows the mode change rules for the A and B modes.

For the A mode, the influent was fed into Tank1 and the operating condition of Tank1 was maintained in the non-aeration state, whereas the operating condition of Tank2 was maintained in the aeration state. To change the A mode to other modes, there were three mode change rules.

First, when the coordinate between the NH_4-N and the NO_X-N was reduced from the denitrification reaction in Tank1 reached the DN-end curve of the OMC setpoint graph (the left side of Fig. 3) and the mode operating time reached the minimum phase time (PT), then the NO_X-N concentration in Tank1 became a low status and the nitrification reaction in Tank2 was not finished. Therefore, the influent was fed into Tank1 identically and the operation mode was changed to the Sub1 A mode in which both Tank1 and 2 were aerated. Through this mode change, the influent was fed into Tank1 while the aeration state for the nitrification reaction in Tank2 was maintained.

Second, if the coordinate of NH_4-N and NO_X-N in Tank1 did not reach the DN-end curve, whereas the coordinate of NH_4-N and NO_X-N in Tank2 reached the N-end curve and the mode operating time reached the minimum PT, then the NH_4-N concentration in Tank2 became a low status and the denitrification reaction in Tank1 was not finished. Therefore, the influent was fed into Tank1 and the operation mode was changed to the Sub2 A mode in which both Tank1 and 2 were not aerated. Through the mode change, the non-aeration state for denitrification reaction in Tank1 was continuously maintained.

Finally, if the operating states of Tank1 and 2 were not suitable for the two mode change rules mentioned above and the mode operating time reached the maximum PT, then the operation mode was changed to the B mode.

There were two mode change rules for the B mode. First, by comparing the measured NH_4-N in Tank1 with the calculated value (%X× $NH4_C$), when the measured NH_4-N value was lower than the calculated value, then the operation mode was changed to the Sub2 B mode in which both Tank1 and 2 were not aerated. The calculated value was obtained by multiplying the NH_4-N value ($NH4_C$) on the N-end curve by the NO_X-N value in Tank1 and the %X value. The mode change coefficient variable, %X was applied to prevent a high nitrification rate in Tank1 and 2 and to adjust the reaction rate in Tank1 and 2. Second, if the operating state of Tank1 was not suitable for this mode change rule and the mode operating time reached the minimum intermediate phase time (IT), then the operation mode was changed to the C mode.

For the C and D modes, the mode change rules were identical to that of the A and B modes; however, the detailed conditions in each rule differed according to the influent inflow point and aeration state in Tank1 and 2. The minimum PT, maximum PT, minimum IT and %X value were set to 20 minutes, 40 minutes, 20 minutes and 0.5, respectively.

3. Development of a Real-time Aeration Section Control (ASC) Strategy

For the four reactors of Tank3 that were not considered in the real-time OMC strategy, a real-time ASC strategy able to control the aeration state was developed. In the basic four operation modes, the two reactors of the single parallel lane in Tank3 were aerated or not aerated simultaneously. However, to improve the nitrification and denitrification reactions for all the reactors, the aeration section of the four reactors in Tank3 should be controlled according to the ratio of the measured NH_4-N and NO_X-N concentrations in the reactors. Therefore, in the real-time ASC strategy, the order of priority for the aeration of the four reactors in Tank3 was set according to the operation mode. To determine the order of priority for the aeration of those four reactors, the influent and return sludge inflow were

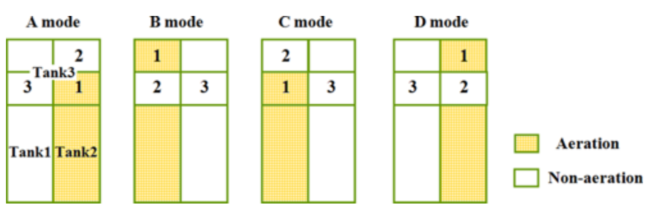

Fig. 4. The order of priority for aeration of each reactor in Tank3 determined by the real-time ASC strategy.

considered. The farthest reactor from the influent and return sludge inflow became the first order, and the second and third orders were determined sequentially. Fig. 4 shows the order of priority for the four reactors in Tank3 according to each operation mode.

The setpoint graph for the sequential aeration of the four reactors in Tank3 is shown on the right side of Fig. 3. For the ratio of the NH_4-N and NO_X-N concentrations shown on the x-axis, the measurement data for Tank1 were used in the A and D modes and the data for Tank2 was used in the B and C modes. Because the non-aeration state should be maintained in the reactor into which the influent and return sludge flow rate is fed, by applying the real-time ASC strategy the maximum number of aerated reactors in Tank3 was limited to three. The setpoint of the real-time OMC and ASC in Fig. 3 was determined based on the empirical knowledge of the field operator. This value may be changed according to the process operational state.

4. The Process Models and the Influent Data

Mathematical models were used to evaluate the developed control strategies. The behavior of organic compounds, nitrogen and phosphorous in the biological reactors was described by using the modified ASM3+Bio-P model [14,15]. A one-dimensional double exponential function model [16] was selected for modeling of the secondary settler. The simulation of the APID process was implemented in the GPS-X simulator (Hydromantis, Inc.). The parameters used for the model simulation were adopted from the typical values listed by Lee et al. [15], Henze et al. [17] and Rieger et al. [18]. To describe the exact behavior of the APID process using mathematical models, a series of model calibrations must be conducted, including a sensitive analysis and estimation of the parameters, and verification of estimated parameter values [4]. However, as the simulation conducted in this paper was focused on evaluating the control strategies for the same process, the default parameter values were considered to be capable of representing the simulation results [4]. Contrary to the objective of this paper, when the simulation results obtained from a mathematical model were directly used to control the target process, the utilized mathematical model should be optimized to describe the behavior of the target process sufficiently.

For evaluation of the control strategies, the influent that was collected from the primary settler was analyzed at two-hour intervals on March 23-25, 2010. The average TCOD, NH_4-H, NO_X-N and PO_4-P concentrations were 137.6, 21.2, 0.6 and 3.2 mg/L, respectively. Because the developed control strategies were applied at minute intervals, the influent data from the two-hour intervals were interpolated to 5-minute intervals. By comparing the simulation results with the real-time OMC and ASC strategies, when a change of the operation mode and/or the aeration section was identified, the operating condition was modified and the simulation was conducted again. Similarly, simulations at 5-minute intervals were conducted repeatedly.

RESULTS AND DISCUSSION

The simulations for cases without and with control were conducted for 864 5-minute interval datasets over three days; "without control" and "with control" signify operation using only the four basic modes and operation which applies control strategies, respectively. The simulation result achieved by using the basic four operation modes and the without control strategy was compared with the simulation result by applying the real-time OMC and ASC strategies. During the application of these control strategies, the maximum NO_X-N and NH_4-N concentrations in Tank1 occurred in the range of 9.67-12 hours and 57.5-60.5 hours, respectively, over the entire simulation period. The NH_4-N and NO_X-N concentrations in Tank2 exhibited behavior contrary to that in Tank1, despite the application of identical control strategies. Therefore, the effect of the control application was evaluated based on the simulation result in Tank1.

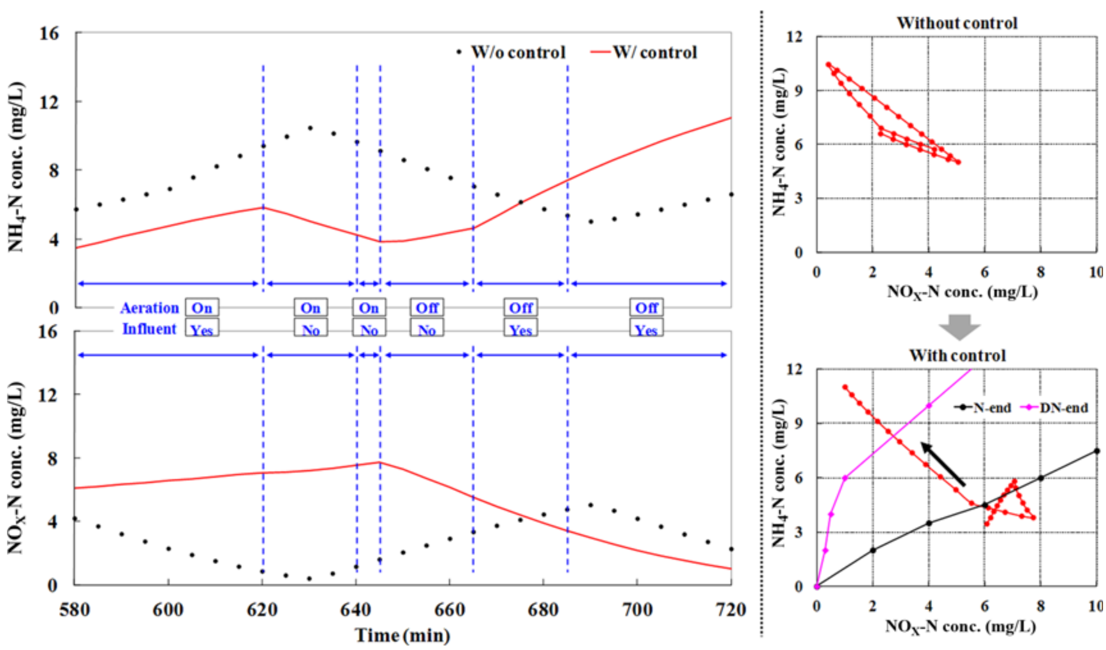

Fig. 5. Simulation results for NH_4-N and NO_X-N concentrations in Tank1 during the 9.67-12 hours in the without and with control cases (left side) and the trajectory change of the coordinate of the NH_4-N and NO_X-N concentrations (right side).

Table 2. The aeration section change in Tank 3 when using the ASC strategy and the state of the operation mode during the 9.67-12 hours

Time (min)	No. of aeration sections in Tank 3	Operation mode	Mode description
580	0	Sub1 A mode	Aeration in Tank 1 and 2
620	1	Sub1 B mode	Aeration in Tank 1 and 2
640	0	Sub1 C mode	Aeration in Tank 1 and 2
645	0	D mode	Non-aeration in Tank 1 Aeration in Tank 2
665	1	A mode	Non-aeration in Tank 1 Aeration in Tank 2
685	1	Sub2 A mode	Non-aeration in Tank 1 and 2

1. Evaluation of the Control Strategies for the Maximum NO_X-N Concentration

The left side of Fig. 5 shows the NH_4-N and NO_X-N concentrations in Tank1 for the applications without and with control during the 9.67-12 hours. The behavior of the NH_4-N and NO_X-N concentrations in Tank1 differed between the basic four operation modes in the without and with control operation modes. This was because the operation periods of each mode were fixed at each 30 minute interval for the basic four operation modes without control, whereas for with the control application, they were changed within the minimum and maximum phase times according to the control rules and setpoints.

For the basic four operation modes without control, the operation modes were changed every 30 minutes regardless of the NH_4-N and NO_X-N concentrations in Tank1. As a result, a denitrification reaction occurred in Tank1. Application of the real-time OMC strategy in the APID process induced a continuous change of the influent inflow point and aeration state in Tank1. The operation modes were changed five times during these periods according to the control rules and the OMC setpoint, as shown in Figs. 2 and 3. The maximum NO_X-N concentration was about 7.73 mg/L at 645 minutes. To reduce the NO_X-N concentration, the aeration in Tank1 was stopped, and after 665 minutes the influent was fed into Tank1 to undergo a further denitrification reaction. As a result, the NO_X-N concentration in Tank1 was decreased to about 1 mg/L at 720 minutes.

The right side of Fig. 5 shows the trajectory change of the coordinate of the NH_4-N and NO_X-N concentrations in Tank1 for the without and with control applications during these periods. When the real-time OMC strategy was applied in the APID process, the trajectory of the coordinate was moved from the outside of the setpoint range to the inside. Application of the real-time OMC strategy enabled the operation mode to be continuously changed to maintain the NH_4-N and NO_X-N concentrations within the setpoint range.

Table 2 shows the change of the aeration section in Tank3 resulting from the application of the real-time ASC strategy during these periods. As shown, in the range of 640 to 665 minutes, in which the NO_X-N concentration in Tank1 reached the maximum value, all the reactors of Tank3 were in non-aeration states. This was because the concentration ratio of NH_4-N and NO_X-N in Tank1 was in the low range of the setpoint graph shown in the right side of Fig. 3 due to the increasing NO_X-N concentration. After that, the NO_X-

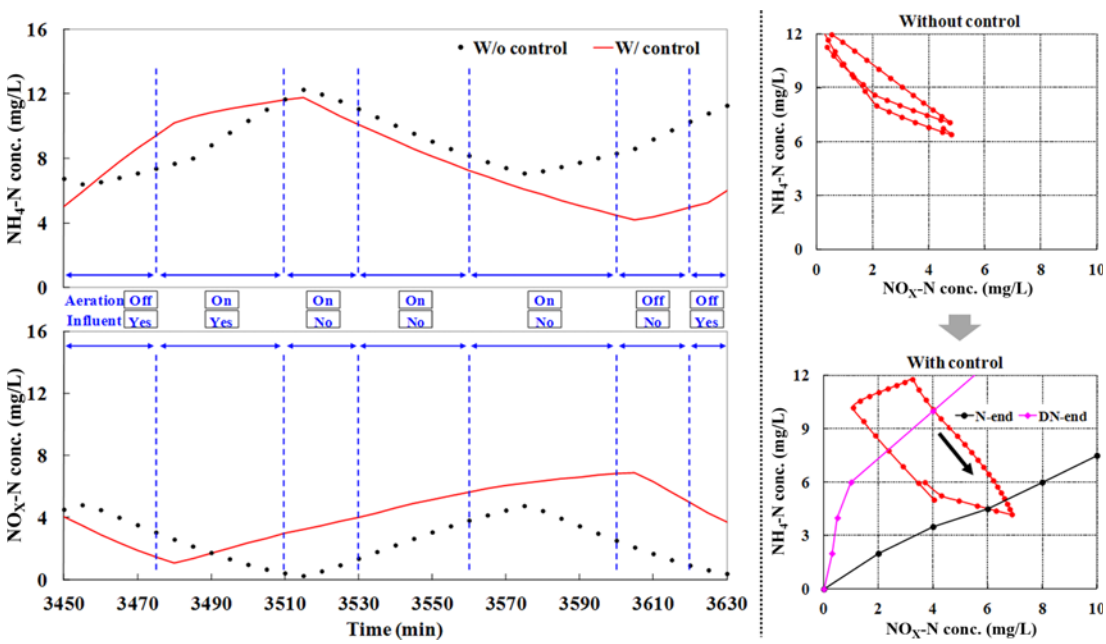

Fig. 6. Simulation results for the NH_4-N and NO_X-N concentrations in Tank1 during the 57.5-60.5 hours for the cases without and with control cases (left side) and the trajectory change of the coordinate of the NH_4-N and NO_X-N concentrations (right side).

N concentration was decreased gradually but the NH_4-N concentration was increased, as shown in Fig. 5. As a result, the concentration ratio of NH_4-N and NO_X-N was increased and the number of aeration sections in Tank3 was also increased. From these results, when the NO_X-N concentration in Tank1 was high, the APID process could be operated successfully to reach an NO_X-N concentration within the setpoint range by using the real-time OMC and ASC strategies developed in this study.

2. Evaluation of the Control Strategies for the Maximum NH_4-N Concentration

The left side of Fig. 6 shows the NH_4-N and NO_X-N concentrations in Tank1 for without and with control applications during the 57.5-60.5 hours. The right side of Fig. 6 shows the trajectory change of the coordinate of the NH_4-N and NO_X-N concentrations in Tank1 for the cases without and with control applications during these periods. The operation modes were changed six times during these periods according to the control rules and the OMC setpoint. Until the 3510 minute time, the influent was fed into Tank1 continuously while the NH_4-N concentration in Tank1 was increased gradually to a maximum of about 11.8 mg/L at 3515 minutes. To reduce the high NH_4-N concentration, the influent inflow in Tank1 was stopped and the aeration states were maintained for 90 minutes. As a result of the continuous nitrification reaction, the NH_4-N concentration in Tank1 was reduced to about 4.2 mg/L at 3,605 minutes. After that, the operation mode was changed again to reduce the increased NO_X-N concentration in Tank1.

The trajectory change of the coordinate shown in the right side of Fig. 6 revealed that the trajectory of the coordinate was moved to the inside of the setpoint range by applying the real-time OMC strategy. For the basic four operation modes without control, an identical operation mode was maintained during the constant periods despite the high NH_4-N concentration in Tank1. However, in the application of the real-time OMC strategy, when the coordinates of the NH_4-N and NO_X-N concentrations were outside of the range of setpoint, the operation modes were changed to maintain the aeration states for a long time. Therefore, by inducing a continuous nitrification reaction, the NH_4-N concentration in Tank1 could be quickly decreased.

Table 3 shows the change in the number of aeration sections in Tank3 when applying the real-time ASC strategy during the 57.5-60.5 hours. The number of aeration sections in Tank3 was maximized from 3,475 to 3,510 minutes. This was because the concentration ratio of NH_4-N and NO_X-N in Tank1 was in the highest range of the setpoint graph on the right side of Fig. 3 due to the decreasing NO_X-N concentration. After 3,510 minutes, the NH_4-N concentration was decreased gradually and the number of aeration sections in Tank3 was maintained at one. Based on these results, when the real-time OMC and ASC strategies were applied in the APID process, increasing the nitrification and denitrification reactions effectively facilitated stable operation in which the NH_4-N and NO_X-N concentrations in reactor were maintained within the setpoint range.

3. Simulation Results Over the Entire Period for the Cases without and with Control Strategies

Fig. 7 compares the simulation results for the cases without and with control applications, using the real-time OMC and ASC strategies in Tank1 over the entire simulation period. For the without control case (i.e., simulation using only the basic four operation modes), the nitrification reaction did not proceed in Tank1, and the high NH_4-N and low NO_X-N concentrations were maintained. However, when the real-time OMC and ASC strategy was applied in the APID process, the control actions were applied continuously according to the change of the NH_4-N and NO_X-N concentrations in the reactor. When the NH_4-N concentration in Tank1 was maintained at a high level, appropriate control actions, such continuing the aeration state, stopping the influent inflow and increasing the aeration section in Tank3, were applied in the APID process. In contrast, when the NO_X-N concentration in Tank1 was maintained at a high level, the non-aeration state, influent inflow and decrease of the aeration section in Tank3 were all continued. The application of these control actions facilitated the optimum nitrification and denitrification reactions in Tank1 over the entire simulation period.

As shown in the right side of Fig. 7, when the real-time OMC and ASC strategies were applied in the APID process, a large number of the coordinates for the NH_4-N and NO_X-N concentrations were included within the setpoint range. In spite of the wide fluctuation in the influent loading, these results indicated that the proper control actions for maintaining the stable nitrification and denitrification reactions were applied by manipulating the setpoint range for the real-time OMC and ASC strategies in the APID process.

The effluent NH_4-N concentrations during the entire period for the cases without and with control strategies were about 7.0 and

Table 3. The aeration section change in Tank 3 when using the ASC strategy and the state of operation mode during the 57.5-60.5 hours

Time (min)	No. of aeration sections in Tank 3	Operation mode	Mode description
3450	1	A mode	Non-aeration in Tank 1 Aeration in Tank 2
3475	3	Sub1 A mode	Aeration in Tank 1 and 2
3510	1	B mode	Aeration in Tank 1 Non-aeration in Tank 2
3530	1	C mode	Aeration in Tank 1 Non-aeration in Tank 2
3560	1	Sub1 C mode	Aeration in Tank 1 and 2
3600	0	D mode	Non-aeration in Tank 1 Aeration in Tank 2
3620	1	A mode	Non-aeration in Tank 1 Aeration in Tank 2

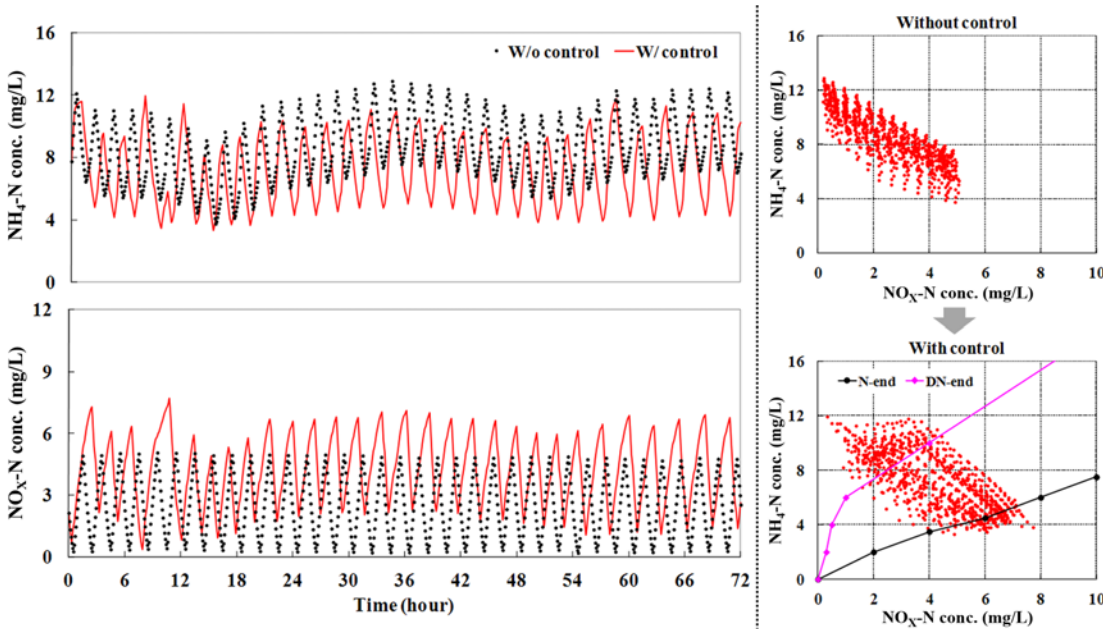

Fig. 7. Comparison of the simulation results for the cases without and with control strategies in Tank1 (left side) and the trajectory change of the coordinate of NH_4-N and NO_X-N concentrations (right side).

5.6 mg/L, respectively. In contrast, the effluent NO_X-N concentrations were about 3.7 and 5.4 mg/L for the cases without and with control strategies, respectively. This result indicated that the balance between the NH_4-N and NO_X-N concentrations in Tank1 and Tank2 could be manipulated by applying the real-time OMC and ASC strategies according to the range of the setpoint graphs as shown in Fig. 3. As a result, the difference between the discharged NH_4-N and NO_X-N concentrations could be reduced when real-time control strategies were applied.

The effluent total nitrogen (TN) concentrations during the entire period for the cases without and with control strategies were about 11.5 and 11.9 mg/L, respectively. The aerated value in terms of k_La (the oxygen transfer coefficient, 1/d) in the case without control strategies was decreased by 37.3% compared with the case where control strategies were applied in Tank1 and Tank2. In contrast, the aerated value for the case without control strategies was increased by 39.1% compared with that of the application of control strategies in all reactors in Tank3. Even though a similar effluent TN concentration was maintained in both instances, the application of control strategies was more energy-efficient than the non-control case.

In the case of the applied real-time OMC strategy in this paper, the change interval for the operational mode was set to a minimum of 20 minutes and a maximum of 40 minutes. Because changes of the aerator, influent gate and pump line were feasible within that time interval, it was considered that the developed real-time OMC strategy applied in the APID process did not produce difficulties for the performance and maintenance of these instruments. However, if the minimum interval of the operation mode needs to be shorter than 20 minutes according to the state of the operation equipment, a detailed analysis such as the consumption time of the residual oxygen should be required for considering the microorganisms' behavior in the reactor. Although the developed real-time control strategies were not applied for the APID process in the field, the available minimum interval for the operational mode was determined to be 15 minutes by these analyses.

CONCLUSION

When the real-time OMC and ASC strategies developed in this study were applied in the APID process, the operating conditions were more complicated than in the case of the basic four operation modes. Nevertheless, because control actions that increased the nitrification and denitrification reaction rates were applied according to the NH_4-N and NO_X-N concentrations in the reactors, stable operations capable of effectively eliminating the fluctuation of the influent loading could be maintained. Therefore, the proposed real-time OMC and ASC strategies can be applied successfully in field plants under the precondition of control system stability.

The effect of application of the real-time OMC and ASC strategies differs according to the range of the setpoint graphs. The process operator could manage the APID process by manipulating the N-end curve, the DN-end curve and the ratio of the NH_4-N and NO_X-N concentrations, as shown in Fig. 3, according to the process state and the seasonal variation. Moreover, when the field operation results for the control strategies are accumulated for a long period, the APID process could be operated more stably by applying the appropriate setpoint range for the process situation.

Although the control strategies developed herein were evaluated theoretically by mathematical models, the simulation results and the field operation results might differ. Therefore, before being applied to field operations, the control strategies should undergo detailed calibration and validation through pretesting over a certain period.

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REFERENCES

1. D. E. Thornberg, M. K. Nielsen and E. Jöran, *Water Sci. Technol.*, **37**(9), 57 (1998).
2. T. B. Önnerth, M. K. Nielsen and C. Stamer, *Water Sci. Technol*., **33**(1), 237 (1996).
3. H. Kim, T. J. McAvoy, J. S. Anderson and O. J. Hao, *Control Eng. Pract.*, **8**, 279 (2000).
4. H. Kim, Y. Kim, J. Cha, K. Min, J. Gee and C. Kim, *Water Sci. Technol.*, **60**(4), 879 (2009).
5. Y. H. Yoon, J. R. Park, S. W. Ahn, K. B. Ko, K. J. Min and J. S. Gee, *Water Pract. Technol.*, **3**(1) (2008).
6. S. Isaacs, *Water Sci. Technol.*, **34**(1-2), 203 (1996).
7. S. Isaacs, *Water Sci. Technol.*, **35**(1), 225 (1997).
8. S. Isaacs and D. Thornberg, *Water Sci. Technol.*, **37**(12), 343 (1998).
9. S. Isaacs and D. Thornberg, *Water Sci. Technol.*, **38**(3), 281 (1998).
10. L. J. S. Lukasse, K. J. Keesman, A. Klapwijk and G. van Straten, *Water Sci. Technol.*, **39**(4), 93 (1999).
11. H. Zhao, H. Isaacs, H. Søeberg and M. Kummel, *Water Res.*, **28**(3), 521 (1994).
12. H. Zhao, H. Isaacs, H. Søeberg and M. Kummel, *Water Res.*, **28**(3), 535 (1994).
13. H. S. Kim, Y. J. Kim, T. Q. Hoang, G. D. Baek, S. S Kim and C. W. Kim, *Korean J. Chem. Eng.*, **30**(8), 1578 (2013).
14. H. S. Kim, Y. J. Kim, S. P. Cheon, G. D. Baek, S. S. Kim and C. W. Kim, *Chem. Eng. J.*, **203**, 387 (2012).
15. S. H. Lee, J. H. Ko, J. R. Kim, Y. J. Kim, J. J. Lee, C. W. Kim and T. H. Lee, *Water Sci. Technol.*, **53**(4-5), 115 (2006).
16. I. Takasc, G. G. Patry and D. Nolasco, *Water Res.*, **25**(10), 1263 (1991).
17. M. Henze, W. Gujer, T. Mino and M. van Loosdrecht, *Activated Sludge Models ASM1, ASM2, ASM2d and ASM3*, IWA Scientific and Technical Report No. 9, London, UK (2000).
18. L. Rieger, G Koch, M. Kuhni, W. Guger and H. Siegrist, *Water Res.*, **35**, 3887 (2001).