



Evaluation of aeration energy saving in two modified activated sludge processes



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ABSTRACT

A variety of modified activated sludge processes are widely used in wastewater treatment plants (WWTPs) for removing organics and nutrients (N and P). Since energy consumption in aeration basin accounts for the major part of the overall energy usage in WWTPs, efforts have been made to find ways to reduce aeration energy. In this study, two modified activated sludge processes in a pilot scale designed for nutrient removal were evaluated for the extent of energy saving: (1) ABA² process – adjusting air on/off period (i.e., with a temporal change); and (2) MB-A²O process – changing volume ratio of aerobic tank to anoxic tank (i.e., with a spatial change). For the 1st process, the air on/off period was fixed at 60 min/45 min with aerobic fraction being 0.57, while for the 2nd process, the aerobic/anoxic volume ratio was reduced from 0.58 to 0.42. The results demonstrate that the effluent COD, TN, NH₄⁺ and TP concentrations are acceptable while reduced aeration time/volume certainly saves significant energy consumption. To the best of our knowledge, this is 1st attempt to reduce the aeration period or aeration volume to save the aeration energy in these two modified activated sludge processes. The implication of these observations is further discussed.

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1. Introduction

A variety of modified activated sludge (AS) processes are widely used in wastewater treatment plants (WWTPs) for removing organics and nutrients (N and P). Since energy consumption in aeration basin accounts for the major fraction of the overall energy usage in WWTPs, any measure for the reduction in aeration energy is worth pursuing. The following fundamental equations of blower energy consumption (Eq. (1); Metcalf and Eddy, 2004), pump power (Eq. (2)), and O₂ transfer (Eq. (3)), which are main energy consumption in WWTP operation, are useful to consider energy saving in activated sludge process.

$$P = \frac{wRT}{550ne} \left[\left(\frac{p_2}{p_1} \right)^{0.283} - 1 \right] \quad (1)$$

where P is energy level, w in weight of air flow, R = gas constant, T = absolute inlet air temp, n = constant for air or 0.283, e = efficiency, and p_2 and p_1 are discharge and inlet pressure (absolute), respectively.

$$P = \frac{Q(TDH)\gamma}{e} \quad (2)$$

where Q = water or sludge flow rate, H = total dynamic head, and γ = specific weight of water.

$$\frac{dC}{dt} = k_{La}(C_s - C) \quad (3)$$

where dC/dt is O₂ transfer rate, k_{La} is O₂ transfer coefficient, C_s and C are saturated and operating dissolved oxygen (DO) concentration, respectively.

Thus from the design/operation point of view, reducing terms in numerator coupling with increasing values in denominator of above Eqs. (1) and (2) would reduce energy consumption. By the same token, increasing driving force ($C_s - C$) in Eq. (3) would enhance O₂ transfer. Consequently, the basic task for operators is to provide adequate maintenance for O₂ supply equipments, e.g., blower and diffuser (reducing p_2 in Eq. (1)). For example, the routine diffuser cleaning can reduce average power costs by 18% and various equalization alternatives can reduce power costs by 6–16% (Leu et al., 2009). As for operation and design of these AS processes, the key is (1) to operate low DO in aeration tanks (Holenda et al., 2008; Guo et al., 2010), (2) to provide less mixing

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intensity, e.g., use only 50% of design mixers (Sharma et al., 2011), (3) to use fine or even micro bubble aeration devices (e.g., Jolly et al., 2010) and other aeration devices (Zimmerman et al., 2010) for providing higher O_2 mass transfer efficiency, and (5) to create no DO conditions via different anoxic/anaerobic settings in a variety of modified AS systems.

Use of low DO in aeration tanks not only reduces O_2 input but also enhances driving force for O_2 mass transfer as mentioned before. Of course, use of fine diffusers and/or higher water depth would also enhance O_2 mass transfer, thereby reducing energy consumption. Another alternative is to short-circuit nitrification cycle, i.e., partial oxidation of ammonia to nitrite only which in turn can be reduced to N_2 . In addition to operating at low DO conditions for the partial nitrification (Wang and Yang, 2004) for energy saving, this process also eliminates the additional O_2 need for nitrite oxidation and hence saving a significant amount of energy (Pollice et al., 2002). Unfortunately, many factors affecting nitrite buildup and this process may not be stable for long term operation (Hao and Chen, 1994; Zhou et al., 2011). Recently, incorporation of Microbial Fuel Cell (MFC) into AS has received considerable attention with respect to energy saving (Liu et al., 2011; McCarty et al., 2011). However, the feasibility of stable operation of MFC in WWTPs awaits further studies.

The best sensible approach is to decrease the aeration period while still maintaining the acceptable effluent quality. For example, after nitrification is complete or NH_4^+ concentration below pre-set level, air can be turned off to create anoxic conditions for *in situ* generated nitrate denitrification to remove organics present in wastewater. Such practice has been done to shorten aeration cycle in Sequencing Batch Reactor (SBR) systems (e.g., Kim et al., 2004; Puig et al., 2005) and in intermittently aerated AS systems (e.g., Huang and Hao, 1996; Bournazou et al., 2013). The saving in aeration energy through reduced O_2 consumption is apparent in both systems.

There are several approaches to identify the time needed to turn off air: (1) on-line monitoring of some parameters that can be used to signify the end of nitrification/denitrification so the next cycle can be initiated; and (2) using models to predict the completion of a particular biological reaction. For example, pH/ORP (oxidation reduction potential)/OUR (oxygen uptake rate) profiles have been

Table 1
Performances of the modified ABA² System.

Wastewater characteristics	Influent (mg L ⁻¹)	Effluent (mg L ⁻¹)	Removal Efficiency (%)
COD	210 (110–330)	20 (10–32)	90
TN	34 (27–40)	11 (7.8–14)	67
TKN	34 (27–40)	4.3 (1.8–6.8)	87
NH ₄ ⁺ -N	28 (24–33)	3.7 (1.0–5.9)	87
NO ₃ ⁻ -N		6.7 (4.2–11)	
Phosphorus, TP	2.9 (1.8–3.6)	1.1 (0.1–1.9)	62
<i>Pilot plant conditions</i>			
MLSS, mg L ⁻¹	3500 (3100–4040)		
MCRT, d	13 (12–16)		
HRT, h	5.5		
Fraction ($f_{a,r}$)	0.57		
Total cyclic time (t_c), min	105		
Air on/off time, h/h	1.0/0.75		

used to identify a particular point/time on their profile for indicating the end of nitrification/denitrification, e.g., ammonia valley (Kim and Hao, 2001; Kim et al., 2004) and nitrate apex (Al-Ghusain and Hao, 1995; Martín de la Vega et al., 2012) on pH profile as well as nitrate knee on ORP profile (Hao and Huang, 1996; Kim and Hao, 2001). The use of OUR can also detect the end of aerobic process (Puig et al., 2005). In short, once the end point for any particular reaction is identified, the control scheme should be straightforward to terminate the reaction and to initiate the next biological reaction. Also using a “fuzzy logic based control” incorporating pH/ORP data and/or model-simulated results to control aeration input can result in energy savings of about 10–40% (Ferrer et al., 1998; Fiter et al., 2005; Meyer and Pöpel, 2003).

However, due to complex non-linear reactions and varying influent characteristics, the use of sensor-based controls may not provide correct information, resulting in poor effluent quality. To overcome this concern, the model-predictive control has been used. A variety of control schemes including evolutionary algorithms (Balku and Berber, 2006) have been employed using Activated Sludge Model No. 1 (ASM1) (Insel et al., 2009), ASM2 (Barat et al., 2011), simplified linearized ASM2 (Kim and Hao, 2001), ASM3 (Balku and Berber, 2006) for different activated

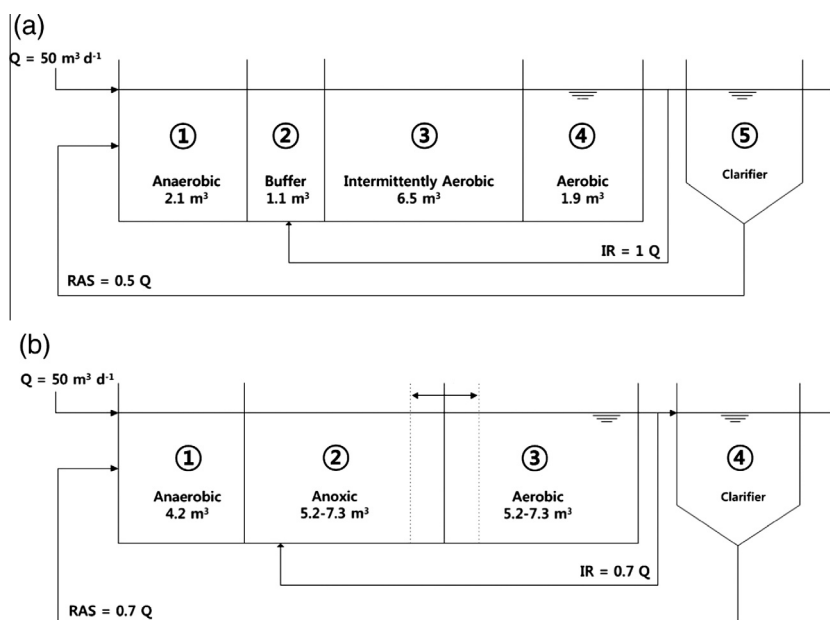


Fig. 1. Schematic diagrams of (a) ABA² plant and (b) MB-A²O.

Table 2
Performances of MB-A²O system.

Wastewater characteristics	Phase I (Anoxic 2.5 h, Oxidic 3.5 h)			Phase II (Anoxic 3.5 h, Oxidic 2.5 h)		
	Influent (mg L ⁻¹)	Effluent (mg L ⁻¹)	Removal Efficiency (%)	Influent (mg L ⁻¹)	Effluent (mg L ⁻¹)	Removal Efficiency (%)
SS	95 (70–120)	5 (0–15)	95	88 (60–120)	7 (0–20)	92
COD	210 (150–260)	30 (20–40)	86	260 (220–290)	35 (25–45)	87
TN	37 (32–47)	7.0 (4.4–15)	81	42 (38–48)	7.2 (5.4–8.9)	83
TKN	37 (32–47)	2.6 (1.0–7.1)	93	42 (38–48)	2.7 (1.7–4.2)	94
NH ₄ ⁺ -N	21 (18–24)	1.3 (0.3–6.6)	94	24 (21–28)	0.9 (0.6–1.5)	97
NO ₃ ⁻ -N		4.2 (2.7–7.9)			4.6 (3.3–6.4)	
Phosphorus, TP	3.7 (2.8–4.7)	1.0 (0.5–1.8)	73	2.9 (2.4–3.4)	0.9 (0.7–1.1)	69
<i>Pilot plant conditions</i>						
MLSS, mg L ⁻¹	3100 (2800–3600)				3000 (2700–3200)	
MCRT, d	12				12	
HRT, h	8				8	
Fraction (<i>f_{a,s}</i>)	0.58				0.42	
HRT _{Aeration} /HRT _{Aeration+anoxic} , h/h	3.5/6				2.5/6	

sludge processes. As high as 20% energy saving can be achieved in three full scale plants by implementing aeration control algorithms, along with an increased TN removal of 40% (Rieger et al., 2012). In short, reducing energy footprint in WWTPs nowadays is a necessity.

From the above discussion, operating alternating aerobic/anoxic is feasible to reduce energy while maintaining the effluent quality. Recently, we have developed two modified activated sludge processes for nutrient removal. Therefore, in this study, we present case studies for energy saving in these two modified AS processes. The first one is a temporal control system with a modified anaerobic/buffer/aerobic/aerobic (ABA²) process (Fig. 1a). The

second anaerobic/aerobic/anoxic (MB-A²O) process is a spatial control system with a movable baffle between aeration and anoxic tanks (Fig. 1b). The ABA² process was originally developed to upgrade a conventional AS process to a biological nutrient removal process, while the MB-A²O was developed to more flexibly operate a conventional A²O responding to any change in operating conditions, e.g., influent strength, and water temperature. The detailed description of these two processes will be discussed below. In addition to demonstration of energy saving by reducing aeration period and volume, effluent water quality was monitored to ensure that it did not suffer with reduced aeration period and volume.

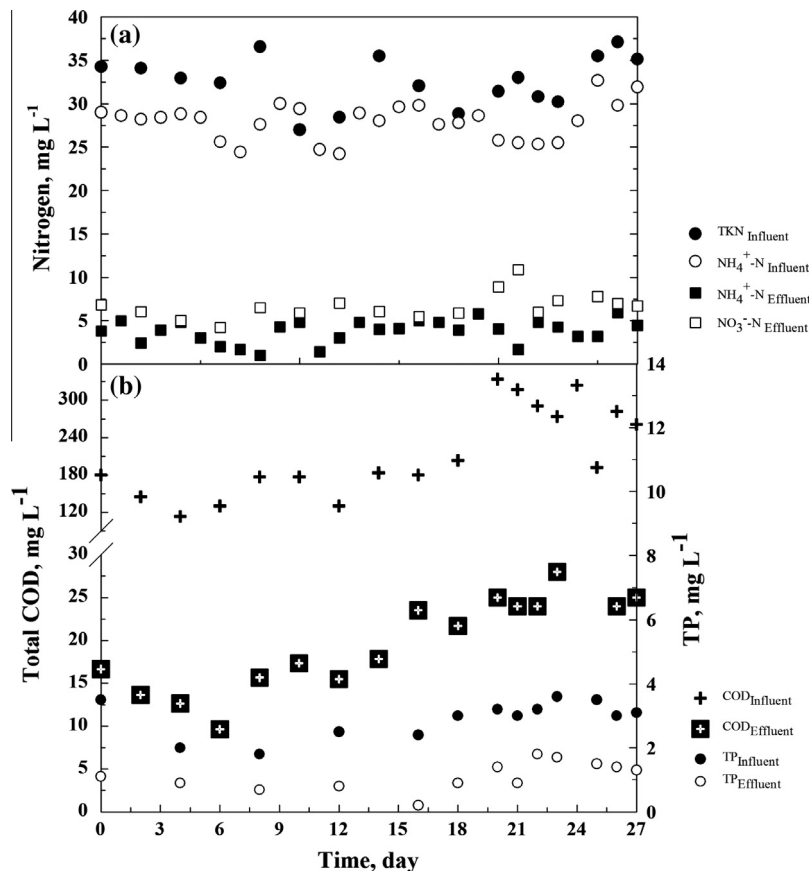


Fig. 2. Overall performance of ABA² system.

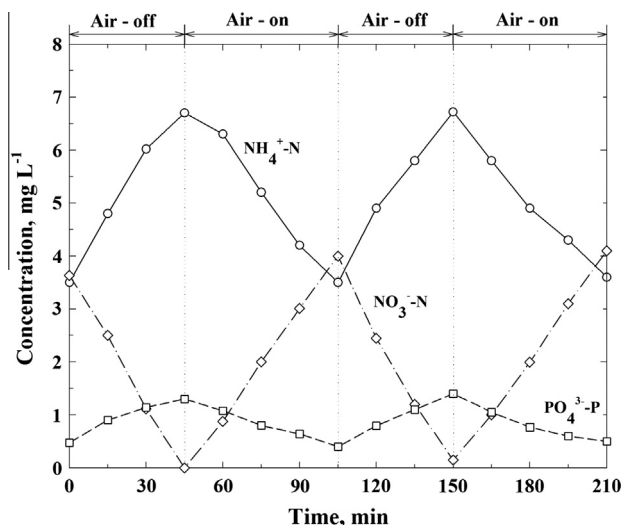


Fig. 3. Profiles of nutrients in intermittently aerated reactor of ABA² system.

2. Materials and methods

2.1. Process description

The modified ABA² process shown in Fig. 1a consists of 4 tanks. Similar to conventional A²O but unlike the conventional setup, a buffer tank is inserted and the third tank is so-called alternating aerobic/anoxic system in which aeration period can be predetermined for nitrification and aeration is then terminated when nitrification is completed and thereafter *in situ* generated nitrate is denitrified under anoxic conditions. The fraction of aeration time to the total aerobic/anoxic time is termed $f_{a,t}$. In order to further remove NH₄⁺ accumulated in the 3rd tank since some fraction of the time ($1 - f_{a,t}$) is not under aeration resulting in NH₄⁺ leaks, the 4th tank is under aeration to ensure removal of NH₄⁺. The internal sludge recycle from the 4th tank to the 2nd tank (buffer zone) is to further remove nitrate and reduce DO level present in the mixed liquor.

The other spatial MB-A²O process consists of three tanks (Fig. 1b) in which a baffle installed between anoxic and aeration tanks can be moved back and forth to adjust the volume ratio of aeration compartment to anoxic compartment. The fraction of aeration volume is called $f_{a,s}$ [aeration volume/(aeration + anoxic volume)]. The baffle is moveable by rails installed on the top of system. The above two newly developed processes provide adequate environmental conditions for nitrification, phosphorus uptake under aerobic conditions, denitrification under anoxic conditions and phosphorus release under anaerobic conditions.

2.2. Pilot plant operation

The pilot ABA² and MB-A²O plants were located inside of Seonam and Joongrang WWTPs, respectively in Seoul with each design capacity of 50 m³ d⁻¹. The influent to these two pilot plants was from primary effluent of the WWTPs. For the ABA² plant (Fig. 1a), the hydraulic retention times (HRT) for anaerobic, buffer, intermittently aerated reactor and aerobic reactor are 1.0, 0.5, 3.1 and 0.9 h, respectively with the total HRT of relatively short 5.5 h. Return activated sludge (RAS) rate was 50% of influent flow rate while internal recycle (IR) rate of mixed liquor suspended solids (MLSS) from the aeration basin to the buffer tank was 100% (50 m³ d⁻¹). The DO concentration during aeration cycle period was maintained approximately at 2 mg L⁻¹ through a programmable logic controller. The

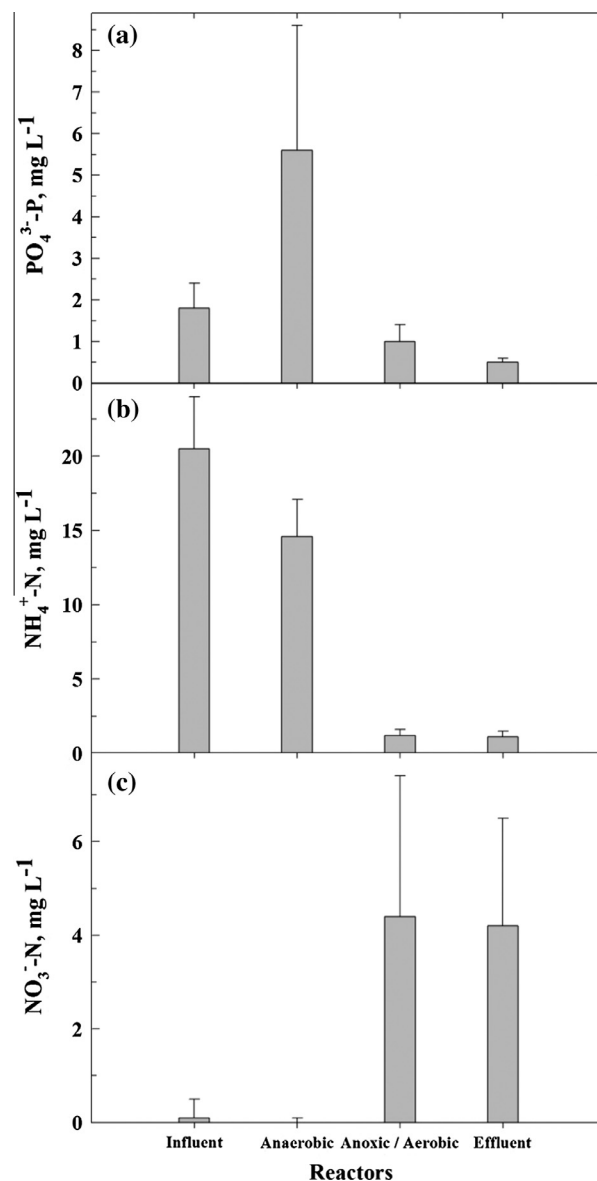


Fig. 4. Nutrient concentrations at each unit process of ABA² system.

mean cell residence time (MCRT) was controlled at 13 d to maintain the MLSS at 3100–4000 mg L⁻¹. The $f_{a,t}$ ratio was controlled at 0.57 with total cyclic time of 105 min (air on/off = 60 min/45 min). The wastewater characteristics and operating conditions are shown in Table 1.

For MB-A²O process (Fig. 1b), the total HRT was 8 h. However, the HRTs for anoxic and aerobic reactors could be changed by moving the baffle between the two reactors. In this study, the MB-A²O was operated for two different phases: in Phase I, the HRTs for anaerobic, anoxic and aeration reactors were 2.0, 2.5, and 3.5 h, respectively, while in Phase II, they were 2.0, 3.5, and 2.5 h (Table 2). RAS and IR of the pilot plant were both 70% over the entire operation period. The MCRT was slightly lower than that of the ABA² plant, i.e., 12 d, maintaining MLSS at 2700–3600 mg L⁻¹.

In order to evaluate the performance of the pilot plants, composite samples of influent and effluent were collected and analyzed following Standard Methods for COD, NH₄⁺, NO₃⁻, and total Kjeldahl nitrogen (TKN), total phosphorus (TP), and PO₄³⁻, and suspended solids (SS) (APHA, 2005).

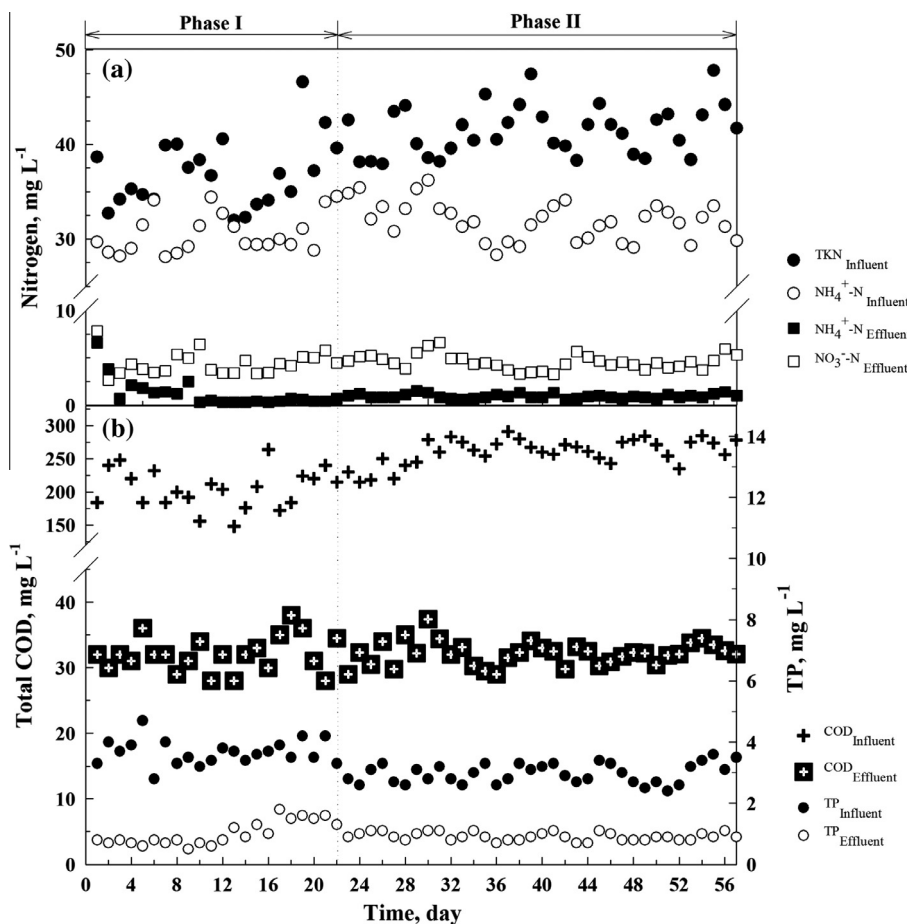


Fig. 5. Overall performance of MB-A²O system.

3. Results and discussions

3.1. Overall performance for ABA² system

The system had been running for 90 d, and then the air on/off cycle of 60 min/45 min ($f_{a,t}$ was set at 0.57) was implemented. The results (Table 1) demonstrate good performance with relatively short HRT (5.5 h) despite fluctuating influent concentrations (Fig. 2). The removal efficiencies for COD, TN, TKN, NH_4^+ -N and TP were 90%, 67%, 87%, 87% and 62%, respectively. The effluent COD, TN, NH_4^+ -N and TP were 20, 11, 3.7 and 1.1 mg L^{-1} , respectively.

The results of nutrient track study for the 3rd tank of alternating aerobic/anoxic are shown in Fig. 3. As shown in the figure, NH_4^+ is oxidized to NO_3^- during aeration periods, while NO_3^- is reduced during the subsequent anoxic stage, achieving both energy saving for aeration and total nitrogen reduction. The zero-order nitrification and denitrification rates are $1.4 \text{ mg g}^{-1} \text{ VSS h}^{-1}$ NO_3^- -N produced and $1.9 \text{ mg g}^{-1} \text{ VSS h}^{-1}$ NO_3^- -N reduced, respectively; values are comparable with those of others (Hao and Huang, 1996). As for P level, P reduction in aerobic cycle is observed with P concentration increase during anoxic cycle due to dilution of lower P at the end of aerobic cycle and high influent P level.

To better understand the role of each reactor in the ABA² system, the concentrations of inlet and outlet of different nitrogen species and PO_4^{3-} were monitored with results shown in Fig. 4. There are well known biological reactions observed in this figure, e.g., P release occurs in the 1st anaerobic tank and subsequent P uptake in the alternating aerobic/anoxic tank; nitrification occurs in the alternating aerobic/anoxic tank and in the last aerobic tank;

and denitrification occurs both in the buffer and alternating aerobic/anoxic tanks. Due to cold season (wastewater temp ca 10 °C) along with short HRT of 5.5 h, the overall performance is acceptable but not excellent. It should be noted that significantly less energy (about half) was required by the ABA² process, comparing to the conventional AS system. In addition, a better effluent quality could be obtained with an increased $f_{a,t}$ ratio, e.g., in winter time, albeit it requires more energy.

3.2. Overall performance for MB-A²O system

The results (Table 2) clearly demonstrate similar excellent effluent quality in both cases of $f_{a,s}$ ratio at 0.58 and 0.42; the effluent COD, TN, TKN and TP concentrations are about 30, 7.0, 2.6 and 1.0 mg L^{-1} , respectively (Fig. 5). In addition to providing excellent effluent quality, the energy saving is about 28% if the operation is changed from $f_{a,s}$ of 0.58–0.42. Again, the in-out of nutrient concentrations for each tank (Fig. 6) indicates P release in the 1st anaerobic tank and subsequently P uptake in the anoxic/aerobic system; NH_4^+ oxidation and NO_3^- generation in the anoxic/aerobic system. To the best of our knowledge, this is the 1st attempt to adjust aeration volume to save aeration energy. In actual plants, several baffle slots can be installed so that volume of aerobic to anoxic can be easily adjusted. The mixing intensity at the latter part of anoxic portion should be designed higher to handle additional volume where it is changed to anoxic conditions. For comparison, the effluent weir in oxidation ditch can be adjusted to reduce oxidation ditch volume which in turn can save brush aeration energy due to lower submergence (USEPA, 2010).

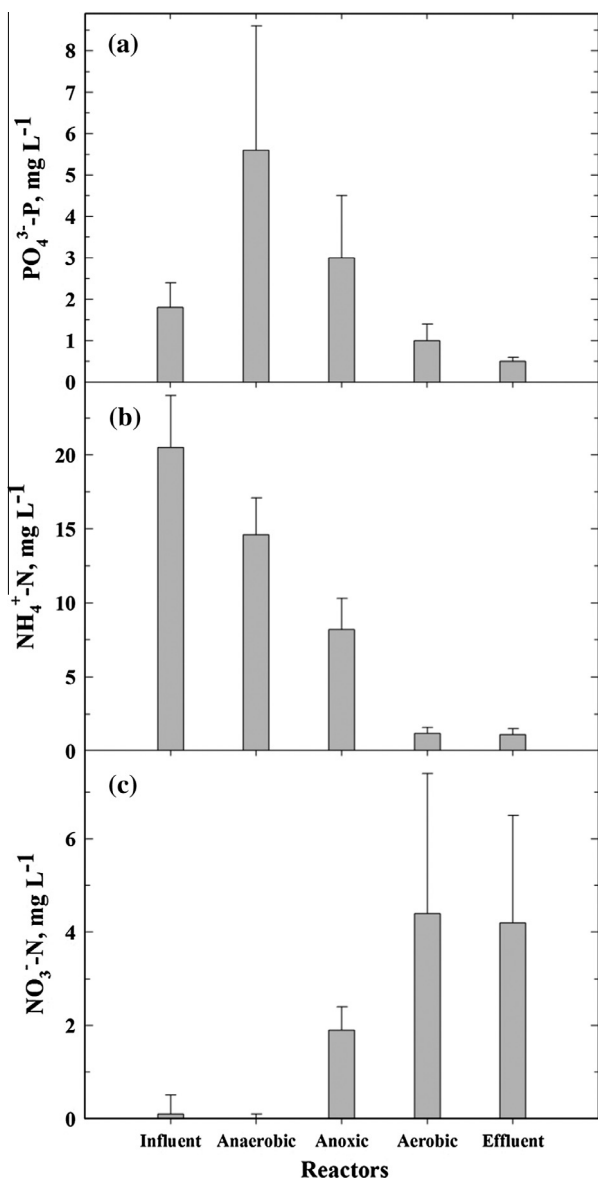


Fig. 6. Nutrient concentrations at each unit process of MB-A²O system.

4. Conclusions

For the newly developed two modified AS processes, the results of the present study clearly demonstrate energy saving by either reducing aeration period in the ABA² process (temporal) or adjusting volume ratio between aerobic and anoxic tanks (spatial) while maintaining acceptable effluent quality. From the results, it was concluded that the ABA² and the MB-A²O systems are potentially promising, since they can be easily implemented in a conventional AS or an A²O system to save energy for aeration. While the fixed ratios of $f_{a,t}$ and $f_{a,s}$ were used in the present study to demonstrate the performance of these two processes along with the extent of energy saving, process control to adjust $f_{a,t}$ and $f_{a,s}$ could be easily implemented by either using sensor- or model-based control scheme. However, if operators do not have capability for process control, the $f_{a,t}$ and $f_{a,s}$ ratios can also be manually adjusted to accommodate temperature changes between summer and winter seasons. By the same token, the volume of the anaerobic stage can be adjusted to accommodate P release.

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References

- Al-Ghusain, I., Hao, O.J., 1995. Use of pH as control parameter for aerobic/anoxic sludge digestion. *J. Environ. Eng. ASCE* 121, 225–235.
- APHA, 2005. Standard Methods for the Examination of Water and Wastewater, 21th ed. American Public Health Association, Washington, DC.
- Balku, S., Berber, R., 2006. Dynamics of an activated sludge process with nitrification and denitrification: start-up simulation and optimization using evolutionary algorithm. *Comput. Chem. Eng.* 30, 490–499.
- Barat, R., Montoya, T., Seco, A., Ferrer, J., 2011. Modelling biological and chemically induced precipitation of calcium phosphate in enhanced biological phosphorus removal systems. *Water Res.* 45, 3744–3752.
- Bournazou, M.N., Hooshiar, K., Arellano-Garcia, H., Wozny, G., Lyberatos, G., 2013. Model based optimization of the intermittent aeration profile for SBRs under partial nitrification. *Water Res.* 47, 3399–3410.
- Ferrer, J., Rodrigo, M.A., Seco, A., Penya-roja, J.M., 1998. Energy saving in the aeration process by fuzzy logic control. *Water Sci. Technol.* 38 (3), 209–217.
- Fiter, M., Güell, D., Comas, J., Colprim, J., Poch, M., Rodríguez-Roda, I., 2005. Energy saving in a wastewater treatment process: an application of fuzzy logic control. *Environ. Technol.* 26, 1263–1270.
- Guo, J.H., Peng, Y.-Z., Peng, C.-Y., Wang, S.-Y., Chen, Y., Huang, H.-J., Sun, Z.-R., 2010. Energy saving achieved by limited filamentous bulking sludge under low dissolved oxygen. *Bioresour. Technol.* 101, 1120–1126.
- Hao, O.J., Chen, J.M., 1994. Factors affecting nitrite buildup in submerged filter system. *J. Environ. Eng. ASCE* 120, 1298–1307.
- Hao, O.J., Huang, J., 1996. Alternating aerobic-anoxic process for nitrogen removal: process evaluation. *Water Environ. Res.* 68, 83–93.
- Holenda, B., Domokos, E., Rédey, A., Fazakas, J., 2008. Dissolved oxygen control of the activated sludge wastewater treatment process using model predictive control. *Comput. Chem. Eng.* 32, 1270–1278.
- Huang, J., Hao, O.J., 1996. Alternating aerobic-anoxic process for nitrogen removal: dynamic modeling. *Water Environ. Res.* 98, 93–104.
- Insel, H.G., Görgün, E., Artan, N., Orhon, D., 2009. Model based optimization of nitrogen removal in a full scale activated sludge plant. *Environ. Eng. Sci.* 26, 471–480.
- Jolly, M., Pöpel, S., Wallis-Lage, C., Buchanan, A., 2010. Energy saving in activated sludge plants by the use of more efficient fine bubble diffusers. *Water Environ. J.* 24, 58–64.
- Kim, H., Hao, O.J., 2001. PH and oxidation–reduction potential control strategy for optimization of nitrogen removal in an alternating aerobic–anoxic system. *Water Environ. Res.* 73, 95–102.
- Kim, J.-H., Chen, M., Kishida, N., Sudo, R., 2004. Integrated real-time control strategy for nitrogen removal in swine wastewater treatment using sequencing batch reactors. *Water Res.* 38, 3340–3348.
- Leu, S.-Y., Rosso, D., Larson, L.E., Stenstrom, M.K., 2009. Real-time aeration efficiency monitoring in the activated sludge process and methods to reduce energy consumption and operating costs. *Water Environ. Res.* 81, 2471–2481.
- Liu, X.-W., Wang, Y.-P., Huang, Y.-X., Sun, X.-F., Sheng, G.-P., Zeng, R.J., Li, F., 2011. Integration of a microbial fuel cell with activated sludge process for energy-saving wastewater treatment: taking a sequencing batch reactor as an example. *Biotechnol. Bioeng.* 108, 1260–1267.
- Martín de la Vega, P.T., Martínez de Salazar, E., Jaramillo, M.A., Cros, J., 2012. New contributions to the ORP & DO time profile characterization to improve biological nutrient removal. *Bioresour. Technol.* 114, 160–167.
- McCarty, P.L., Bae, J., Kim, J., 2011. Domestic wastewater treatment as a net energy producer – Can this be achieved? *Environ. Sci. Technol.* 45, 7100–7106.
- Metcalf and Eddy, 2004. *Wastewater Engineering: Treatment & Reuse*, 4th ed. McGraw-Hills, New York.
- Meyer, U., Pöpel, H.J., 2003. Fuzzy-control for improved nitrogen removal and energy saving in WWT-plants with pre-denitrification. *Water Sci. Technol.* 47 (11), 69–76.
- Pollice, A., Tandoi, V., Lestingi, C., 2002. Influence of aeration and sludge retention time on ammonium oxidation to nitrite and nitrate. *Water Res.* 36, 2541–2546.
- Puig, S., Corominas, L., Vives, M.T., Balaguer, M.D., Colprim, J., Colomer, J., 2005. Development and implementation of a real-time control system for nitrogen removal using OUR and ORP as end points. *Ind. Eng. Chem. Res.* 44, 3367–3373.
- Rieger, L., Takács, I., Siegrist, H., 2012. Improving nutrient removal while reducing energy use at three Swiss WWTPs using advanced control. *Water Environ. Res.* 88, 170–188.
- Sharma, A.K., Guildal, T., Thomsen, H.R., Jacobsen, B.N., 2011. Energy savings by reduced mixing in aeration tanks: results from a full scale investigation and long term implementation at Avedoere wastewater treatment plant. *Water Sci. Technol.* 64, 1089–1095.
- USEPA, 2010. Evaluation of Energy Conservation Measures for Wastewater Treatment Facilities. US Environmental Protection Agency, Washington, DC. 20460.

Wang, J., Yang, N., 2004. Partial nitrification under limited dissolved oxygen conditions. *Process Biochem.* 39, 1223–1229.

Zhou, Y., Oehmen, A., Lim, M., Vadivelu, V., Ng, W.J., 2011. The role of nitrite and free nitrous acid (FNA) in wastewater treatment plants. *Water Res.* 45, 4672–4682.

Zimmerman, W.B., Hwakandamby, B.N., Tesar, V., Bandulasena, H.C., Omotowa, O.A., 2010. On the design and simulation of an airlift loop bioreactor with microbubble generation by fluidic oscillation. *Int. Sugar J.* 112, 90–103.