Removal of Reverse-fluxed Ammonium by Anammox in a Forward Osmosis System Using Ammonium Bicarbonate as a Draw Solute

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Abstract

Reverse flux of ammonium draw solute is a serious problem for applying forward osmosis (FO) in water/wastewater treatment. In this study, anaerobic ammonium oxidization (anammox) was synergistically linked to FO for removal of reverse-fluxed ammonium, thereby creating an osmotic anammox system. The feasibility of this system was demonstrated through both batch and continuous operation, and the anammox process was developed in two stages: sole anammox and nitrification-anammox. With addition of nitrite, the sole anammox process achieved an effluent ammonium concentration of at $9.9 \pm 9.5 \text{ mg N L}^{-1}$. The nitrification-anammox maintained an ammonium concentration of $3.1 \pm 4.2 \text{ mg N L}^{-1}$, and increased the water flux to $2.46 \pm 0.24 \text{ LMH}$ ($\text{L m}^{-2} \text{ h}^{-1}$) compared with the sole anammox ($1.90 \pm 0.14 \text{ LMH}$). The nitrification-anammox process exhibited advantages over anammox process in assisting the FO with respect to water flux improvement and chemical savings. The osmotic anammox system can be linked to previously developed microbial electrolysis cells that recover ammonium from high-strength wastes as a draw solute for FO operation. The results encourage further investigation of this system for effect of organic residues, decreasing nitrate accumulation, understanding biofilm on the FO membrane, and long-term performance with actual waste.

Keywords: Forward osmosis; anammox; ammonium bicarbonate; reverse salt flux; wastewater treatment

1. Introduction

Wastewater reclamation and reuse represents a promising way to sustainable water resource management. To achieve a high-quality effluent, newly developed membrane technologies have been studied and applied extensively [1]. Among them, forward osmosis (FO) is of strong interest because of its reduced energy consumption and membrane fouling [2-4]. In an FO process, an osmotic pressure created by water potential difference drives water to permeate across a semipermeable membrane from a low concentration solution (feed solution) side to a concentrated solution (draw solution) side [5-7], resulting in a concentrated feed solution and a diluted draw solution. Draw solute, which should be highly soluble, easily separable and recoverable, non-toxic, nonreactive with membranes, and economically feasible, plays a key role in a successful FO system [8]. Recovery of draw solute accounts for most of the energy consumption in an FO process [5, 8]. In addition, reverse salt flux causes the loss of draw solute, which results in increased operating cost due to draw solute replenishment, and creates potential environmental concerns as draw solute is released into the feed solution.

In the past decade, much effort as well as significant progress has been made in the development of draw solutes for various potential applications that can generate a high osmotic pressure with low reverse salt permeation [9]. The thermolytic ammonium bicarbonate ($\text{NH}_3\text{-CO}_2$) is considered as an effective draw solute because of its high solubility, osmotic efficiency, and circulation capacity [10]. More importantly, the diluted ammonium bicarbonate draw solution can be decomposed into ammonia and carbon dioxide at a temperature as low as 60 °C, thereby achieving a low-energy recovery process for draw solute recycle [10]. The application of ammonium bicarbonate draw solute has been widely investigated at the lab scale [5, 10-14], and

also demonstrated in a pilot-scale desalination system for treating the produced water from natural gas extraction [15]. However, the loss of ammonium draw solute via reverse salt flux (RSF) can hardly be avoided, and the ammonium migrated into the feed solution may require further treatment because it is an important inorganic contaminant to water body.

Recently, we have demonstrated that ammonium recovered from a synthetic organic solution by a microbial electrolysis cell (MEC) can be applied as a draw solute in an FO system that extracted water from the MEC anode effluent [16]. It was observed that due to the reduced liquid volume and RSF, the ammonium concentration in the feed solution increased from 0.24 ± 0.03 to 1.66 ± 0.15 g L⁻¹. Although this concentrated feed solution was returned to the MEC for further treatment, it reduced the treatment capacity of the MEC, which could receive only 50% of fresh medium in each batch due to the need of treating the returning solution. To avoid such a reduction in MEC treatment capacity, the reverse-fluxed ammonium should be removed or recovered in the FO.

Ammonium removal can be accomplished by biological reactions such as anaerobic ammonium oxidation (anammox), where anammox bacteria convert ammonium to N₂ with nitrite as a terminal electron acceptor under an oxygen-limited condition [17]. Nitrification by ammonium oxidizing bacteria (AOB) is required to oxidize part of ammonium to nitrite [18]. Thus, the cooperation of ammonium-oxidizing bacteria (AOB) and anammox bacteria is essential to achieve completely autotrophic nitrogen removal. Typically, two methods can be applied to start up nitrification-anammox process, either by inoculating nitrifying sludge into anammox reactors [19, 20] or by inoculation of anammox biomass into nitrification reactors [21,

22]. The nitrification-anammox process represents an efficient and cost-effective approach for biological nitrogen removal with significantly reduced demand for oxygen and organic carbon.

Given the challenges of reverse-fluxed ammonium in the FO and the advantage of an anammox process in ammonia removal, in this study we have synergistically linked anammox to FO, and created an osmotic anammox system to remove the reverse-fluxed ammonium during the FO process. As a proof-of-concept study, the key objectives are to: (1) demonstrate the feasibility of the osmotic anammox system; and (2) develop a nitrification–anammox process associated with FO. Although the osmotic anammox is designed to be connected to an MEC that provides ammonium as draw solute, this study focused only on the osmotic anammox, and the MEC performance has been previously reported [16] and thus was not included here.

2. Materials and Methods

2.1. Osmotic anammox setup

The schematic of a lab-scale osmotic anammox system is shown in Figure 1. The system consisted of two units, an upflow anammox reactor and an FO unit, which were linked through the feed solution that was recirculated between the anammox reactor and the FO feed side at a recirculation flow rate of 34 mL min^{-1} , resulting in an upflow velocity of 1.04 m h^{-1} . The anammox reactor had a working volume of 1.5 L (height 0.75 m, diameter 0.05 m), and a plastic funnel was placed on its top to separate gas and liquid while reducing biomass loss. The pH inside the anammox reactor was maintained between 7 and 8 by adding HCl or NaOH solution when necessary. The feed side of the FO unit had a working volume of 2 L. The cellulose triacetate (CTA) membrane with a surface area of 0.01 m^2 (Hydration Technologies Inc., Albany,

OR, USA) was installed with its active layer facing the feed solution [16]. A heating rod was used to maintain the temperature of 30 ± 1 °C in the feed side.

Figure 1. The schematic of the osmotic anammox system.

2.2. System operation

The anammox reactor was initially inoculated with a mixed biomass mainly containing anammox granules obtained from another anammox reactor (5 L) in our lab; fluorescent *in situ* hybridization (FISH) indicated that the anammox bacteria accounted for ~ 80% enrichment. The sole source of ammonium into the anammox reactor was the reverse-fluxed ammonium ions from the draw side of the FO to its feed side. The extracted water from the anammox reactor was compensated by a mineral solution ($480\text{--}580$ mL d⁻¹) prepared according to a previous study [23]: NaHCO₃ 0.42 g L⁻¹, KH₂PO₄ 0.0272 g L⁻¹, MgSO₄ 0.059 g L⁻¹, CaCl₂•2H₂O 0.18 g L⁻¹ and 1 mL L⁻¹ trace elements solution I and 1 mL L⁻¹ trace elements solution II. The trace elements

solution I contains (g L⁻¹): EDTA, 5 and FeSO₄, 5. The trace elements solution II is composed of (g L⁻¹): EDTA-2Na 15, CuSO₄•5H₂O 0.25, ZnSO₄•7H₂O 0.43, NaMoO₄•2H₂O 0.22, MnCl₂•4H₂O 0.99, NiCl₂•6H₂O 0.19, CoCl₂•6H₂O 0.24, NaSeO₄•10H₂O 0.21, and H₃BO₄ 0.014 [23]. The draw solution (0.5 M ammonium bicarbonate, 29.7 ± 1.7 mS cm⁻¹) was fed to the draw side of the FO continuously at a rate of 228 mL d⁻¹ and was recirculated at 100 mL min⁻¹. The experiment started in a batch mode and then was changed to a continuous mode. Each batch cycle used 200 mL of 0.5 M NH₄HCO₃ as the draw solution, and the synthetic solution contained 25 mM nitrite to support anammox bacteria growth; each cycle was operated for 1 to 2 days, depending on the changes of water flux and ammonium concentration in the feed side. The continuous operation had two stages (Table 1): in the stage I (39 days), only anammox process was examined and nitrite was externally added; and in the stage II (45 days), a nitrification-anammox process was developed by limiting aeration in the feed side while gradually decreasing nitrite supply. Aeration was controlled by a gas flow meter based on dissolved oxygen (DO) monitoring data and reactor performance. The hydraulic retention time (HRT) of the anammox reactor in the stage I and II was 2.66 ± 0.42 d and 3.12 ± 0.06 d, respectively.

Table 1 Operation duration for Stage I and Stage II

Stage	Period	Nitrite addition mg N L ⁻¹	Operation duration day
I	A	280, 350, 420	1-16
	B	350	17-39
II	A(transitional)	280 to 140, 112, 70, 35 to 0	40-52
	B (stable)	0	53-84

2.3. Measurement and analysis

The concentration of ammonium ($\text{NH}_4^+\text{-N}$) was measured by a standard ammonia ion selective electrode (Fisher Scientific, Pittsburgh, PA, USA). The concentrations of nitrite ($\text{NO}_2^-\text{-N}$) and nitrate ($\text{NO}_3^-\text{-N}$) were determined by a spectrophotometer (DR 890, Hach Company, Loveland, CO, USA). The pH was measured by a benchtop pH meter (Oakton Instruments, Vernon Hills, IL, USA). Conductivity was measured with a benchtop conductivity meter (Mettler-Toledo, Columbus, OH, USA). Water flux ($\text{L m}^{-2} \text{h}^{-1}$, LMH) in the FO was calculated by the change of weight recorded on the balance (Scort Pro, Ohaus, Columbia, MD, USA). The reverse salt flux (RSF, $\text{g N m}^{-2} \text{h}^{-1}$) was calculated based on the ammonium mass balance. The online pH/ORP control system (Milwaukee Instruments, Inc., Rocky Mount, NC, USA) was employed to monitor the environment in the reactor. Dissolved oxygen (DO) was measured regularly by a portable DO meter (Hanna Instruments Inc., Woonsocket, RI, USA).

3. Results and discussion

3.1 System startup

Before coupling the FO with the anammox reactor, the water flux and RSF characteristics of the FO were evaluated under an abiotic condition (Figure 2). Using 200 mL 1 M NH_4HCO_3 and tap water as the draw and the feed solutions, respectively, the average water flux decreased from 5.7 to 1.8 LMH within 24 h, and the draw solution conductivity decreased from 57.3 to 16.0 mS cm^{-1} . Meanwhile, the RSF reached $4.0 \pm 0.5 \text{ g N m}^{-2} \text{h}^{-1}$, resulting in an increase of the conductivity and ammonium concentration in the feed side to 1.6 mS cm^{-1} and 410 mg N L^{-1} , respectively. Thereafter, the anammox process was introduced and anticipated to maintain a low ammonium concentration in the feed side by oxidizing the reversed-flux ammonium from the draw side.

Figure 2. The performance of the FO under an abiotic condition: (A) changes of conductivity and ammonium concentration in the feed solution, and (B) changes of conductivity in the draw effluent versus water flux.

Figure 3 showed the system performance from the batch experiment. During one cycle (48 hours), the water flux decreased by 64% in the first 24 hours, and then exhibited a relative stable period before dropping dramatically at the final moment; the decrease in water flux followed the decrease in the conductivity of the draw solution (Figure 3A). The ammonium concentration in the feed side increased rapidly due to the large amount of reverse-fluxed ammonium at the beginning, and then started to decrease because of ammonium removal by anammox. Despite the

increased ammonium concentration, the conductivity on the feed side had no obvious change. Figures 3B and 3C show the system performance of six batch cycles. The evolution of water flux exhibited similar downtrend in each cycle (Figure 3B). However, the ammonium concentration fluctuated, likely affected by the factors such as biofilm formed on the FO unit and microbial activities (Figure 3C). The results of the batch experiment have provided an initial demonstration of the system feasibility and also a good foundation for continuous operation that will be described in the following.

Figure 3. The system performance in the batch mode: (A) the system performance in a cycle; (B) the evolution of water flux during the six cycles; and (C) the ammonium concentration and conductivity in the feed side for each cycle.

3.2 Anammox process coupled with FO

With 0.5 M ammonium draw solute, the conductivity of draw effluent was maintained at $15.0 \pm 0.7 \text{ mS cm}^{-1}$ (0.2 M ammonium) and the FO achieved a water flux of $1.9 \pm 0.1 \text{ LMH}$ (Figure 4A). This observation was similar to a previous study where 2.1 LMH was reported with 1 M ammonium bicarbonate and 0.5 M NaCl as draw and feed solutions, respectively [24]. The RSF was determined as $1.2 \pm 0.2 \text{ g N m}^{-2} \text{ h}^{-1}$ (Figure 4A), which is twice as high as that reported in our previous study ($\sim 0.5 \text{ g N m}^{-2} \text{ h}^{-1}$) [16], likely due to a relatively high salt gradient with a constant ammonium concentration maintained in the draw effluent. The RSF of ammonium resulted in an ammonium loading rate in the anammox reactor of $0.19 \pm 0.04 \text{ kg N m}^{-3} \text{ d}^{-1}$.

Figure 4. The system performance of anammox coupling with FO process in the Stage I: (A) water flux and RSF in the FO process, (B) the profiles of ammonium, nitrite, and nitrate in the anammox reactor, (C) the profiles of ammonium, nitrite, and nitrate in the feed side of FO unit, and (D) the conductivity profiles.

In the Stage I, only anammox was expected to function and thus nitrite needed to be added externally. The concentration of nitrite was adjusted according to the anammox performance (Table 1). The concentrations of ammonium, nitrite and nitrate nitrogen in the anammox reactor effluent are shown in Figure 4B. When nitrite was added with increasing concentrations from 280 to 350 mg L⁻¹, the anammox reactor could maintain the NH₄⁺-N below 10 mg N L⁻¹. On day

9 when a sudden increase of the ammonium concentration from 7.7 to 57.1 mg N L⁻¹ was observed, the nitrite concentration was further increased to 420 mg N L⁻¹. The increased nitrite addition resulted in a very low concentration of ammonium (0.4 mg N L⁻¹) but elevated concentrations of both nitrite and nitrate (34 mg N L⁻¹ and 109 mg N L⁻¹, respectively, on day 10), indicating that the nitrite input might have been excessive for anammox reaction. The occurrence of nitrate was likely due to nitrite oxidation by nitrite oxidizing bacteria (NOB) when oxygen was available (possibly intruded from the draw side and due to the mixing of the feed solution of the FO) [25]. A similar trend of increased nitrite and nitrate concentrations was also observed on day 15. After lowering the nitrite concentration to 350 mg N L⁻¹ on day 16, the ammonium, nitrite and nitrate concentrations in the anammox reactor were maintained at 9.9 ± 9.5 mg N L⁻¹, 1.3 ± 3.2 mg N L⁻¹, 13.9 ± 7.9 mg N L⁻¹, respectively, during the remaining period of the stage I (Figure 4B). With the assistance of anammox reactor, the accumulation of ammonium was not observed in the feed side of the FO (Figure 4C), and the conductivity of the feed solution was not obviously increased (Figure 4D), thereby creating a desirable condition for continuously operating FO with a constant water flux (Figure 4A).

3.3 Nitritation-anammox process coupled with FO

Supplementing nitrite to anammox is not practical, and thus nitrite production via partial nitrification (nitritation) will be necessary. In the Stage II, a nitritation-anammox process was developed through decreasing nitrite input and supplying limited DO to stimulate AOB growth and prevent NOB activities.

Figure 5. The system performance of nitrification-anammox coupling with FO process in the Stage II: (A) the profiles of ammonium, nitrite, and nitrate in the nitrification-anammox reactor, (B) water flux and RSF of the FO process, (C) the profiles of ammonium, nitrite, and nitrate in the feed side of FO unit, and (D) the conductivity profiles.

During the transitional period (day 40-52), addition of 280 mg N L⁻¹ nitrite in the anammox influent led to the accumulation of nitrite and nitrate in both anammox reactor and the feed solution of the FO (Figures 5A and 5C), which decreased when the influent nitrite decreased to 140 mg N L⁻¹. As the nitrite addition continued to decrease, air supply was increased slightly to improve the conversion of ammonium to nitrite by AOB. After Day 53, nitrite addition was

completely removed from the influent (Figure 5A). The ammonium concentrations of $3.1 \pm 4.2 \text{ mg N L}^{-1}$ and $12.8 \pm 6.4 \text{ mg N L}^{-1}$ were achieved in the anammox reactor effluent and the FO feed side, respectively (Figures 5A and 5C). In addition, a very low nitrite concentration was observed while $41.6 \pm 12.6 \text{ mg L}^{-1}$ of nitrate was retained in the feed solution (Figure 5C), much higher than $21.2 \pm 10.8 \text{ mg N L}^{-1}$ obtained in the Stage I (Figure 4C), suggesting that aeration has stimulated the complete nitrification. Nevertheless, nitrate did not increase cumulatively, likely due to the occurrence of other processes, such as denitrification under a low oxygen condition and moving across the FO membrane to the draw side (where the nitrate concentration was $15.2 \pm 5.1 \text{ mg N L}^{-1}$).

The DO concentrations in the nitrification-anammox reactor and the feed side were $0.8 \pm 0.1 \text{ mg O}_2 \text{ L}^{-1}$ and $1.4 \pm 0.4 \text{ mg O}_2 \text{ L}^{-1}$, respectively (Figure 6), and such difference was caused by microbial activities in the anammox reactor and incomplete mixing between the feed side and the anammox reactor by recirculation. The suitable DO conditions were intended to promote the co-existence of AOB and anammox bacteria but suppress NOB activities. Previous studies suggested that AOB could be predominant over NOB due to their higher affinity for oxygen under low DO conditions [26]. NOB also exhibited a lower affinity to nitrite than anammox bacteria when both nitrite and O_2 were limited [27, 28]. Further microbial analysis is necessary to confirm the microorganism compositions in the reactor. In addition, during the stable period (day 53-84), the pH in the reactor was able to stay in a suitable range of 7-8 without base addition. Such pH changes did not agree that the nitrification-anammox system is expected to decrease due to the net H^+ production [19], possibly due to pH buffering by alkalinity input from reverse salt flux and CO_2 diffusion from air.

Figure 6. The DO profiles in the nitrification-anammox reactor and the feed side in the Stage II.

The FO achieved a maximum water flux of 3.2 LMH (average 2.3 ± 0.4 LMH) with the RSF of 0.8 ± 0.5 g N m⁻² h⁻¹ (Figure 5B), which resulted in the ammonium loading rate of 0.14 ± 0.08 kg N m⁻³ d⁻¹ for the nitrification-anammox reactor. The abrupt decrease in water flux on day 67 and day 76 occurred because of the exhaustion of the concentrated draw solution. Compared to the stage I, the stage-II FO achieved a higher water flux of 2.5 ± 0.2 LMH (Figure 7A), benefiting from a lower conductivity (2.39 ± 0.68 mS cm⁻¹ versus 3.36 ± 0.30 mS cm⁻¹, Figures 4D and 5D) of the feed solution due to elimination of nitrite addition. The RSF declined by 39.0% while the salt rejection increased by 8.5% in the Stage II (Figure 7A), likely related to that a decrease of the ammonium concentration in the draw effluent (2.45 ± 0.27 g N L⁻¹ versus 2.75 ± 0.11 g N L⁻¹, $p < 0.05$, Figure 7B) and the similar concentration in the feed solution (Figures 4C and 5C) increased water flux.

Figure 7. Comparison of the FO performance between the Stage I (the Period B) and II (the stable period): (A) compare water flux and RSF, and (B) compare draw effluent conductivity and salt rejection.

3.4 Perspectives

The proposed osmotic anammox system has several potential benefits. First, it decreases the ammonium concentration in the feed and thus helps maintain a large osmotic pressure for achieving desired water flux. Second, it prevents the release of ammonium contaminants into the water body. Third, when being linked to an MEC for wastewater, it increases the treating

capacity of the MEC. Future applications of this system are to be explored, and we propose a few that can be further investigated: (1) the osmotic anammox can be linked to MECs for treating concentrated liquid waste, as described in the Introduction section; (2) the system can be used to effectively retain anammox biomass (and then the focus of the process will be on anammox); and (3) it may be used for desalination of either seawater or brackish water by FO with ammonium bicarbonate as a draw solute, and to achieve that, anammox under a high-salinity condition needs to be studied.

The results of this study encourage further investigation to address several issues: (1) analysis of biofilm formed on the FO membrane to reveal their functions in nitrogen transformation; (2) investigation of the effect of organic residues on both anammox and FO; (3) removal of nitrate that is produced from anammox; and (4) examination of the system with actual wastewater for long-term stability.

4. Conclusions

This study has demonstrated that anammox can be applied to remove reverse-fluxed ammonium during forward osmosis, and this osmotic anammox system may be applied to treat waste liquid that has been treated for organic removal and ammonium recovery. This system is functioning under either sole anammox or nitrification-anammox condition. Such removal helps maintain a stable water flux and prevents the release of ammonium into water body. The findings of this study encourage further investigation of the proposed system to address reverse-fluxed ammonium and thus to make the FO using ammonium as draw more sustainable and practical. Application niches for this osmotic anammox should also be explored.

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References

- [1] A.D. Khawaji, I.K. Kutubkhanah, J.-M. Wie, Advances in seawater desalination technologies, *Desalination*, 221 (2008) 47-69.
- [2] T.-S. Chung, X. Li, R.C. Ong, Q. Ge, H. Wang, G. Han, Emerging forward osmosis (FO) technologies and challenges ahead for clean water and clean energy applications, *Curr. Opin. Chem. Eng.*, 1 (2012) 246-257.
- [3] K. Luttmiah, A.R.D. Verliefde, K. Roest, L.C. Rietveld, E.R. Cornelissen, Forward osmosis for application in wastewater treatment: A review, *Water Res.*, 58 (2014) 179-197.
- [4] T.S. Chung, S. Zhang, K.Y. Wang, J.C. Su, M.M. Ling, Forward osmosis processes: Yesterday, today and tomorrow, *Desalination*, 287 (2012) 78-81.
- [5] R.L. McGinnis, M. Elimelech, Energy requirements of ammonia-carbon dioxide forward osmosis desalination, *Desalination*, 207 (2007) 370-382.
- [6] F. Zhang, K.S. Brastad, Z. He, Integrating forward osmosis into microbial fuel cells for wastewater treatment, water extraction and bioelectricity generation, *Environ. Sci. Technol.*, 45 (2011) 6690-6696.
- [7] M. Xie, W.E. Price, L.D. Nghiem, M. Elimelech, Effects of feed and draw solution temperature and transmembrane temperature difference on the rejection of trace organic contaminants by forward osmosis, *J. Membr. Sci.*, 438 (2013) 57-64.
- [8] A. Achilli, T.Y. Cath, A.E. Childress, Selection of inorganic-based draw solutions for forward osmosis applications, *J. Membr. Sci.*, 364 (2010) 233-241.
- [9] L. Chekli, S. Phuntsho, H.K. Shon, S. Vigneswaran, J. Kandasamy, A. Chanan, A review of draw solutes in forward osmosis process and their use in modern applications, *Desalin. Water Treat.*, 43 (2012) 167-184.
- [10] J.R. McCutcheon, R.L. McGinnis, M. Elimelech, A novel ammonia-carbon dioxide forward (direct) osmosis desalination process, *Desalination*, 174 (2005) 1-11.
- [11] J.R. McCutcheon, R.L. McGinnis, M. Elimelech, Desalination by ammonia-carbon dioxide forward osmosis: influence of draw and feed solution concentrations on process performance, *J. Membr. Sci.*, 278 (2006) 114-123.
- [12] X.L. Lu, C. Boo, J. Ma, M. Elimelech, Bidirectional Diffusion of Ammonium and Sodium Cations in Forward Osmosis: Role of Membrane Active Layer Surface Chemistry and Charge, *Environ. Sci. Technol.*, 48 (2014) 14369-14376.
- [13] P. Liu, B.Y. Gao, H.K. Shon, D.F. Ma, H.Y. Rong, P. Zhao, S. Zhao, Q.Y. Yue, Q. Li, Water flux behavior of blended solutions of ammonium bicarbonate mixed with eight salts respectively as draw solutions in forward osmosis, *Desalination*, 353 (2014) 39-47.
- [14] R.L. McGinnis, J.R. McCutcheon, M. Elimelech, A novel ammonia-carbon dioxide osmotic heat engine for power generation, *J. Membr. Sci.*, 305 (2007) 13-19.
- [15] R.L. McGinnis, N.T. Hancock, M.S. Nowosielski-Slepowron, G.D. McGurgan, Pilot demonstration of the NH₃/CO₂ forward osmosis desalination process on high salinity brines, *Desalination*, 312 (2013) 67-74.
- [16] M. Qin, Z. He, Self-Supplied Ammonium Bicarbonate Draw Solute for Achieving Wastewater Treatment and Recovery in a Microbial Electrolysis Cell-Forward Osmosis-Coupled System, *Environ. Sci. Technol. Lett.*, 1 (2014) 437-441.
- [17] A. Mulder, A.A. Vandegraaf, L.A. Robertson, J.G. Kuenen, Anaerobic ammonium oxidation discovered in a denitrifying fluidized bed reactor, *FEMS Microbiol. Ecol.*, 16 (1995) 177-183.

- [18] Z. Hu, T. Lotti, M. de Kreuk, R. Kleerebezem, M. van Loosdrecht, J. Kruit, M.S. Jetten, B. Kartal, Nitrogen removal by a nitrification-anammox bioreactor at low temperature, *Appl. Environ. Microbiol.*, 79 (2013) 2807-2812.
- [19] K.A. Third, A.O. Sliekers, J.G. Kuenen, M.S.M. Jetten, The CANON system (completely autotrophic nitrogen-removal over nitrite) under ammonium limitation: Interaction and competition between three groups of bacteria, *Syst. Appl. Microbiol.* , 24 (2001) 588-596.
- [20] A.O. Sliekers, K.A. Third, W. Abma, J.G. Kuenen, M.S.M. Jetten, CANON and Anammox in a gas-lift reactor, *FEMS Microbiol. Lett.* , 218 (2003) 339-344.
- [21] Z. Gong, S.T. Liu, F.L. Yang, H. Bao, K. Furukawa, Characterization of functional microbial community in a membrane-aerated biofilm reactor operated for completely autotrophic nitrogen removal, *Bioresour. Technol.* , 99 (2008) 2749-2756.
- [22] J.R. Vazquez-Padin, M.J. Pozo, M. Jarpa, M. Figueroa, A. Franco, A. Mosquera-Corral, J.L. Campos, R. Mendez, Treatment of anaerobic sludge digester effluents by the CANON process in an air pulsing SBR, *J. Hazard. Mater.* , 166 (2009) 336-341.
- [23] U. Imajo, T. Tokutomi, K. Furukawa, Granulation of Anammox microorganisms in up-flow reactors, *Water Sci. Technol.*, 49 (2004) 155-163.
- [24] B. Chanukya, S. Patil, N.K. Rastogi, Influence of concentration polarization on flux behavior in forward osmosis during desalination using ammonium bicarbonate, *Desalination*, 312 (2013) 39-44.
- [25] Y. Peng, G. Zhu, Biological nitrogen removal with nitrification and denitrification via nitrite pathway, *Appl. Microbiol. Biotechnol.* , 73 (2006) 15-26.
- [26] N. Bernet, P. Dangcong, J.-P. Delgenès, R. Moletta, Nitrification at low oxygen concentration in biofilm reactor, *J. Environ. Eng.-ASCE*, 127 (2001) 266-271.
- [27] R. Blackburne, Z.G. Yuan, J. Keller, Partial nitrification to nitrite using low dissolved oxygen concentration as the main selection factor, *Biodegradation*, 19 (2008) 303-312.
- [28] A. Schramm, D. De Beer, A. Gieseke, R. Amann, Microenvironments and distribution of nitrifying bacteria in a membrane - bound biofilm, *Environmental Microbiology*, 2 (2000) 680-686.