

# 11<sup>th</sup> International Desalination Workshop

*Membranes and Membrane Processes  
for Water Applications*

## **ABSTRACT BOOK**

**JULY 12-13, 2018**

**Singapore**



## Program

### Thursday, July 12 (Morning Session)

Time	Venue: NEC Auditorium	
08:00 ~ 9:15	Morning Reception and Registration	
9:15 ~ 9:30	<p><b>Welcoming remark: Prof. Seungkwan Hong</b> Chairman of IDW2018</p> <p><b>Congratulatory remark: Prof. Rong Wang</b> President of Membrane Society in Singapore (MEMSIS)</p> <p><b>Opening remark: Eunkyung Kim</b> Ministry of Environment, Korea Korean Environmental Industry &amp; Technology Institute (KEITI)</p>	
9:30 ~ 10:30	<p><b>Plenary Talk 1: Beyond 10 years of IDW</b> <i>Prof. In S. Kim</i> Gwangju Institute of Science and Technology, Korea</p> <p><b>Plenary Talk 2: Recent Developments in Desalination Related Technology</b> <i>Prof. Rong Wang</i> Singapore Membrane Technology Centre (SMTC), Singapore</p>	
10:30 ~ 10:40	Photo Time	
10:40 ~ 11:00	Coffee Break	
Session	<p><b>Venue: Lecture Room 1</b></p> <p><b>Session A</b></p> <p><b>Expanding FO Applications</b></p> <p><i>Chair: Hokyong Shon, Jinsik Sohn</i></p>	<p><b>Venue: Lecture Room 2</b></p> <p><b>Session B</b></p> <p><b>Management and Utilization of RO Brine</b></p> <p><i>Chair: Seung-Hyun Kim, Dong suk Han</i></p>
11:00 ~ 11:30	<p><b>Keynote (A)</b> <b>Osmotically driven processes for current and potential niche applications</b> <i>Hokyong Shon</i> (University of Technology Sydney, Australia)</p>	<p><b>Keynote (B)</b> <b>Brine solution in seawater desalination</b> <i>Seunghyun Kim</i> (Kyungnam Univeristy, Korea)</p>
11:30 ~ 11:50	<p><b>(A-1)</b> <b>Pilot-scale feasibility study of seawater desalination based on FO-RO hybrid system</b> <i>Sunkyung Kim, Marc Petry, Sanghyun Kim</i> (Hyundai Engineering &amp; Construction)</p>	<p><b>(B-1)</b> <b>Electro-membrane processes for reverse osmosis concentrate recovery</b> <i>V.V. Waghlikar, D. Zhao, L.Y. Lee, S.L. Ong, H. Zhuang, N. E. Moe, J. Barber and H.Y. Ng</i> (National University of Singapore, Singapore)</p>
11:50 ~ 12:10	<p><b>(A-2)</b> <b>Desalination of highly saline water using osmotically enhanced dewatering (OED): experimental and theoretical analysis</b> <i>Jungwon Kim, Inhyuk David Kim, Jungbin Kim, Junghyun Kim, Seungkwan Hong</i> (Korea University, Korea)</p>	<p><b>(B-2)</b> <b>Electrochemical lithium recovery in RO-MD brine</b> <i>Jeyong Yoon, Seoni Kim, Hwajoo Joo</i> (Seoul National University, Korea)</p>
12:10 ~ 12:30	<p><b>(A-3)</b> <b>Forward osmosis module arrangement to enhance recovery rate</b> <i>Suhan Kim, Jongmin Jeon, Jaehak Jung, Jonnyoung Choi</i> (Pukyong National University, Korea)</p>	<p><b>(B-3)</b> <b>SWRO-PRO hybrid desalination for water &amp; energy production</b> <i>Yonggyun Park, Inho Yeo, Wonil Lee, Taeshin Park</i> (GS E&amp;C, Korea)</p>
12:30 ~ 14:00	Lunch Break and Poster Session (Lobby)	

**Thursday, July 12 (Afternoon Session)**

Session	<b>Venue: Lecture Room 1</b> <b>Session C</b> <b>SWRO Optimization &amp; Advancement</b> <i>Chair: Tzzy Haur Chong, Jaelim Lim</i>	<b>Venue: Lecture Room 2</b> <b>Session D</b> <b>Scaling-up New Desalination Technology</b> <i>Chair: Sangho Lee, Jaeyong Yoon</i>
14:00 ~ 14:30	<b>Keynote (C)</b> <b>Improved recovery of seawater desalination by energy-efficient reverse osmosis (EERO) process</b> <i>Tzzy Haur Chong, Seonki Lee, Kwanho Jeong, Shuwen Goh, S.R. Suwarno, W.B Krantz</i> (Nanyang Technological University, Singapore)	<b>Keynote (D)</b> <b>Design and operation of hollow fiber membrane distillation process</b> <i>Sangho Lee, Yongjun Choi, Younghyun Shin, Jihyeok Choi, Junseok Choi</i> (Kookmin University)
14:30 ~ 14:50	<b>(C-1)</b> <b>K-water's efficient operation strategy for desalination plant</b> <i>Jihye Kim, Boungsu Kwon, Chunghwan Kim, Kyunghyuk Lee, Jaelim Lim</i> (K-water Institute of Water & Environment, Korea)	<b>(D-1)</b> <b>Novel modification method for membranes used in membrane distillation</b> <i>Nick Guan Pin Chew, Shanshan Zhao, Chandresh Malde, Rong Wang</i> (Nanyang Technological University, Singapore)
14:50 ~ 15:10	<b>(C-2)</b> <b>Improvements of 10MIGD Busan SWRO plant by low energy consumption and O&amp;M simulation tools</b> <i>Seokho Choi, Jungwon Park, Jungjune Lee, Younggeun Lee, Kwanghee Shin, Hyungkeun Roh</i> (Corporate R&D Institute in Doosan Heavy Industries & Construction, Korea)	<b>(D-2)</b> <b>Hydrogen production and water purification using photoelectrocatalytic desalination process</b> <i>Dong suk Han, Seunghyun Kim, Guangxiao Piao, Ho Kyung Shon, Hyunwoong Park</i> (Texas A&M at Qatar)
15:10 ~ 15:30	<b>(C-3)</b> <b>Desalination by resilient energy-efficient, and advanced mobile systems (DREAMS): A step toward sustainability</b> <i>Joon Seok Choi, Sangho Lee, Moonhyun Hwang</i> (Korean Institute of Construction Technology)	<b>(D-3)</b> <b>Development of low energy consumption CDI system and its applications</b> <i>Namsoo Park, Kyungseok Kang, Hyunwoo Yoo</i> (SIONTECH Co. Ltd, Korea)
15:30 ~ 15:50	<b>(C-4)</b> <b>Cost analysis of small scale SWRO plants</b> <i>Seongpil Jeong, Hien Thi Nguyen, Jooyoung Park</i> (Korea Institute of Science and Technology)	<b>(D-4)</b> <b>Theoretical and experimental approaches of liquid entry pressure determination in membrane distillation processes</b> <i>Changkyu Lee, Chansoo Park, Dongsoo Shin, Junseok Choi, Jongoh Kim</i> (R.E.D., Korea)
15:50 ~ 16:10	Coffee Break	

**Thursday, July 12 (Afternoon Session): Continued**

Session	<b>Venue: Lecture Room 1</b> <b>Session E</b> <b>Fouling Characterization and Control</b> <i>Chair: Am Jang, How Yong Ng</i>	<b>Venue: Lecture Room 2</b> <b>Session F</b> <b>Desalination Technology Integrating with Water Reuse</b> <i>Chair: Masaru Kurihara, Suhan Kim</i>
16:10 ~ 16:40	<b>Keynote (E)</b> <b>Role of fouling control in expanding FO applications</b> <i>Seungkwan Hong, Gimun Gwak, David Inhyuk Kim</i> (Korea University, Korea)	<b>Keynote (F)</b> <b>Further Progress in Megaton project in Japan</b> <i>Masaru Kurihara</i> (Toray Inc. Japan)
16:40 ~ 17:00	<b>(E-1)</b> <b>Novel biofouling control and detection using Electrical Impedance Spectroscopy (EIS)</b> <i>Jia Shin Ho, Lee Nuang Sim, Tzyy Haur Chong, H.G.L. Coster, Hideyuki Komori, Akihiro Fujii, Kunihiro Hayakawa</i> (Nanyang Technological University, Singapore)	<b>(F-1)</b> <b>Application of novel outer selective thin film composite hollow fiber forward osmosis membrane in osmotic membrane bioreactor treating municipal wastewater</b> <i>Van Huy Tran, Sungil Lim, Nirenkumar Pathak, Nawshad Akther, Sherub Phuntsho, Dong Suk Han and Hokyoung Shon</i> (University of Technology Sydney, Australia)
17:00 ~ 17:20	<b>(E-2)</b> <b>Evaluating membrane fouling potentials of dissolved organic matter in brackish water</b> <i>Jongkwan Park, Sanghun Park, Jeongyeop You, Kyung Hwa Cho</i> (Ulsan National Institute of Science and Technology, Korea)	<b>(F-2)</b> <b>Performance evaluation and fouling characterization of element-scale FO process</b> <i>Sanghyun Jeong, Am Jang</i> (Sungkyunkwan University, Korea)
17:20 ~ 17:40	<b>(E-3)</b> <b>Novel membranebased spectrophotometric method for quantifying of transparent exopolymer particles (TEP)</b> <i>Lee Nuang Sim, Stanislaus Raditya Suwarno, Tzyy Haur Chong, Emile R. Cornelissen Anthony G. Fane</i> (Nanyang Technological University, Singapore)	<b>(F-3)</b> <b>Nanowires versus Nanosheets – Effect of NiCo2O4 Nanostructures on Ceramic Membrane Filterability and Fouling Potentia</b> <i>Zhiyang Lyu, Tze Chiang Albert Ng, Qilin Gu, Lei Zhang, Zeming He, Weijie Poh, How Yong Ng, John Wang</i> (National University of Singapore)
17:40 ~ 18:00	<b>(E-4)</b> <b>Immobilization of antimicrobial chemicals on RO membrane surfaces for in-situ biofouling control</b> <i>Taek-Seung Kim Seok Tae Kang</i> (Korea Advanced Institute of Science and Technology, Korea)	<b>(F-4)</b> <b>Improving energy efficiency of pretreatment against algal bloom for seawater desalination by novel meshed tube filtration</b> <i>Jihun Lim, Gyuhyon Cha, Soohoon Choi, Hyunkyung Lee, Kwangse Kim, Sangjun Ahn, and Seungkwan Hong</i> (Korea University, Korea)
18:30 ~ 20:30	<b>Banquet Dinner</b> <b>Awarding Ceremony</b> Peach Garden Chinese Restaurant, NTU campus	

**Thursday, July 12**

NO	Title
(P-1)	<p><b>Application of MFI-UF to manage reverse osmosis (RO) process: a pilot study in ultrapure water (UPW) production system</b></p> <p>Hyunkyung Lee, Min Zhan, Yongxun Jin, Seungkwan Hong</p> <p>School of Civil, Environmental and Architectural Engineering, Korea University</p>
(P-2)	<p><b>Preparation and characterization of superhydrophobic co-axial electrospun nanofiber membranes</b></p> <p>Yun Chul Woo, June-Seok Choi</p> <p>Department of Land, Water and Environment Research, Korea Institute of Civil Engineering and Building Technology</p>
(P-3)	<p><b>Study on prediction of water quality of produced water considering characteristics of individual process design factors for ultrapure water</b></p> <p>Boungsu Kwon, Kyoung Wan Kim, Jihye Kim, Kyunghyuk Lee, Jaelim Lim</p> <p>Water Works Research Center, K-water Institute</p>
(P-4)	<p><b>Study of the optimization process combination on the ultrapure water treatment system</b></p> <p>Boungsu Kwon, Kyoung Wan Kim, Jihye Kim, Kyunghyuk Lee, Jaelim Lim</p> <p>Water Works Research Center, K-water Institute</p>
(P-5)	<p><b>Effect of Pressure on Feed Solution at hollow Fiber FO Process</b></p> <p>Bongchul Kim, Yun-chul Woo, Juneseok Choi</p> <p>Korea Institute of Civil Engineering and Building Technology (KICT)</p>
(P-6)	<p><b>Long-term evaluation of element-scale plate-frame forward osmosis process</b></p> <p>Sehyun Ban, Sung Ju Im, Am Jang</p> <p>Graduate School of Water Resources, Sungkyunkwan University (SKKU)</p>
(P-7)	<p><b>The effect of TFC-PRO membrane performance parameters and optimization of operating conditions for spiral wound PRO modules</b></p> <p>Yeonju Sim, Manjae Han, Jonghwa Lee</p> <p>Toray Chemical Korea Inc</p>
(P-8)	<p><b>Investigation of fouling and cleaning behavior in a pilot-scale forward osmosis process</b></p> <p>Duksoo Jang, Seungju Choi, Dongkyu Park, Yunho Kim, Seoktae Kang</p> <p>Department of Civil and Environmental Engineering, Korea Advanced Institute of Science and Technology (KAIST)</p>
(P-9)	<p><b>Direct observation of oil droplets attached on polyamide membrane surface</b></p> <p>Pattarasiri Fagkaew, Seoktae Kang</p> <p>Department of Civil and Environmental Engineering, Korea Advanced Institute of Science and Technology (KAIST)</p>
(P-10)	<p><b>Prediction of long-term performance in a reverse osmosis desalination plant</b></p> <p>Kwanghee Shin, Yongjun Choi, Younggeun Lee, Hyungkeun Roh, Sangho Lee</p> <p>Corporate R&amp;D Institute in Doosan Heavy Industries &amp; Construction</p>
(P-11)	<p><b>Comparison of Vacuum Membrane Distillation and Reverse Osmosis in Water Reuse Application</b></p> <p>Younghoon Ko, Yongjun Choi, Hyeongrak Cho, Yongsun Jang, Jihyeok Choi, Sangho Lee</p> <p>Civil and Environmental Engineering, Kookmin University</p>

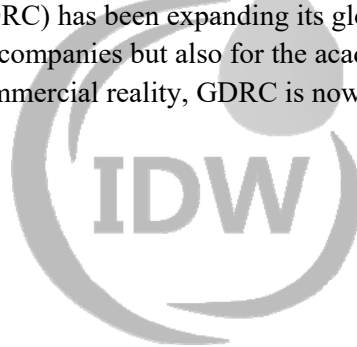
## Beyond 10 Years of IDW

In S. Kim

Global Desalination Research Center (GDRC), Gwangju Institute of Science and Technology, Korea

As the International Desalination Workshop (IDW) celebrates its 11<sup>th</sup> anniversary, this conference of intercultural academic heritage is now ready to further expand its horizon. IDW has become more successful as years passed by thanks to tremendous efforts of desalination professionals in and out of academia around the globe.

Being part of the International Desalination Association (IDA), Korea Desalination Plant Association (KDPA) has driven the Korean desalination technologies toward commercial reality to relay such efforts. KDPA is a group of Korean companies from various industries that has nurtured its solidarity aiming at the materialization of Korean desalination technologies into a global standard. Starting from the 11<sup>th</sup> IDW this year, KDPA is now ready to lead the motivations for the field applications of desalination technologies with the support of the academia. Since its commencement in 2013, Global Desalination Research Center (GDRC) has been expanding its global network by functioning as the hub not only for the multinational companies but also for the academic institutions in the global scale. As KDPA departed toward the commercial reality, GDRC is now ready to fully support ever more.



## Recent Developments in Desalination Related Technology

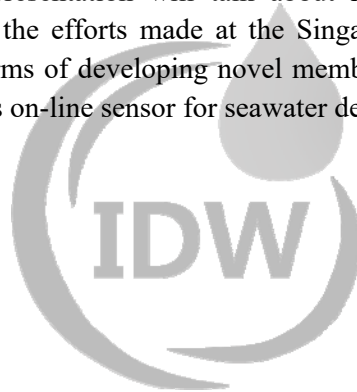
Rong Wang

Singapore Membrane Technology Centre, Singapore

School of Civil and Environmental Engineering, Nanyang Technological University, Singapore

Membrane technologies have been widely used for seawater desalination. However, the key membrane process of reverse osmosis (RO) is energy-intensive. Developing energy-efficient membranes and membrane processes have been research topics of interest in global water and membrane communities. Various highly-effective membranes and new processes are being developed to address the challenge imposed by the water-energy nexus.

As a nation with limited natural resources, Singapore has been active in developing advanced desalination technologies. This presentation will talk about recent developments in desalination related technology. In particular, the efforts made at the Singapore Membrane Technology Centre (SMTC) will be highlighted in terms of developing novel membranes and membrane processes such as membrane distillation as well as on-line sensor for seawater desalination applications, etc.



---

# Expanding FO Applications

(Session A)

---

- Room 1 -





## **Osmotically driven processes for current and potential niche applications**

Ho Kyong Shon

Center for Technology in Water and Wastewater, School of Civil and Environmental Engineering,  
University of Technology Sydney (UTS), Australia.

Forward osmosis (FO) and pressure retarded osmosis (PRO) are osmotically driven membrane processes and emerging as viable methods for producing fresh water from saline water and capturing clean energy, respectively. This presentation will probe various opportunities to extend potential commercialization of FO and PRO into new niches and applications, identifying key technology constraints.

The FO process is a promising and emerging low energy desalination technology that works on the principles of natural osmotic process. FO membranes have been available for over 40 years, but the applications have still been a niche with water purification. Recently, FO has been investigated for a wide range of applications including desalination, wastewater treatment, reverse osmosis concentrate treatment, food processing, emergency nutritious drinks, pharmaceutical industries, etc. However, the application of the FO process for potable water desalination is still a challenge due to lack of an ideal draw solution that can be easily separated from the pure water and recover for regeneration and reuse. It irrefutably requires an additional process, which could consume extra energy. However, FO has been found to be ideal for those applications where the separation of draw solute and the water is not essential such as fertigation, emergency drink, etc. Advancements in FO technologies and changes in target niche markets are rapidly changing the FO landscape. The total addressable markets for FO systems are now estimated to be continuously growing as a result of innovations in FO membranes, elements, and draw solutions that reduce cost and footprint, marketing FO for reuse, food and beverage, oil and gas, and high salinity instead of desalination, regulations that promote near zero liquid discharge and industrial reuse and increased interest in potable reuse and emerging contaminant removal. Finally, PRO as a salinity gradient energy extension of FO, emphasizing membrane properties, membrane fouling, draw/feed solution considerations, pilot demonstration will be discussed.

This presentation will provide latest information on overall pros and cons of FO and PRO demonstrations and share main results of our recent FO and PRO activities.

## **Pilot scale feasibility study of seawater desalination based on FO – RO hybrid system**

Sunkyu Kim, Marc Petry, Junghoon Choi, Sanghyun Kim<sup>†</sup>

Water & Environment Team, Research and Development Division,  
Hyundai Engineering & Construction, Korea

Desalination has been considered as an important technology in alleviating water shortage, a serious challenge that we face globally. Pressure-driven membrane-based processes, such as Reverse Osmosis (RO), is gaining worldwide acceptance in the desalination market due to their energy efficiency compared to other desalination processes such as thermal distillation. However, pressure-driven processes require energy input in the form of hydraulic pressure to drive the process, and the driving force also accelerates fouling issues. Forward Osmosis (FO), on the other hand, utilizes an osmotic gradient as driving force for water flux, and presents a solution that consumes less energy and has a lower fouling propensity. In this study done in collaboration between Hyundai Engineering & Construction (HDEC) and Nanyang Technological University (NTU), a hybrid FO system is conceptualized and developed to study and review various FO hybrid processes. After verification of commercial FO membranes performances with a variety of application scenarios such as municipal water or industrial wastewater, the further study on FO application will be confirmed through pilot scale test. Currently the pilot plant is installed in PUB testbedding site and in operation for pilot scale study. This study aims to find the most feasible process application of FO based on the lab scale performance test. The feasibility study will be evaluated through key operational parameters to be able to make competitive costs in terms of OPEX/CAPEX.

Through pilot scale study, energy saving from FO-RO process will be verified with operation data. FO-RO pilot plant is constructed in Singapore PUB testbedding site after going through required process from PUB. Main feature of pilot plant is it has implemented high performance FO membrane, the system design is optimized for research study under cooperation with membrane supplier, and it has energy consumption comparison system to verify FO-RO process is spends less power than conventional RO. This pilot plant will produce and provide technical data for economic feasibility study of FO-RO application on seawater desalination industry.

## **Desalination of highly saline water using osmotically enhanced dewatering (OED) : experimental and theoretical analysis**

Jungwon Kim, Inhyuk David Kim, Jungbin Kim, Junghyun Kim, Seungkwan Hong<sup>†</sup>

School of Civil, Environmental and Architectural Engineering, Korea University, Korea

### **1. Introduction**

A newly developed osmotic enhanced dewatering (OED) process was proposed and investigated for enhancement of water recovery from shale gas produced water by supporting the hydraulic driving force with a draw solution (DS). The DS produces an osmotic pressure on the permeate side which is lower or equal to that of the feed solution (FS), neutralizing the overall osmotic pressure difference and allowing much more water extraction than RO.

### **2. Methods**

The efficiency of the OED process was first examined by verifying its performance based on the experimental and simulation results. In addition, this study systematically explored the applicability of OED process for dewatering of shale gas produced water.

### **3. Results and Discussion**

The simulation results first showed that OED achieved higher water recovery over forward osmosis (FO) due to less internal concentration polarization (ICP). Water recovery could be higher with decreasing feed flow fraction, increasing normalized membrane area, and increasing hydraulic driving force fraction.

### **4. Conclusions**

Our modelled and experimental observations suggest that the OED-RO process can be an energy-efficient process in concentrating high salinity wastewater.

### **5. References**

Kim, Jungwon, et al. "Osmotically enhanced dewatering-reverse osmosis (OED-RO) hybrid system: Implications for shale gas produced water treatment." *Journal of Membrane Science* 554 (2018): 282-290.

## Forward osmosis module arrangement to enhance recovery rate

Jongmin Jeon<sup>a</sup>, Jaehak Jung<sup>a</sup>, Joon Young Choi<sup>b</sup>, Suhan Kim<sup>a†</sup>

<sup>a</sup>Department of Civil Engineering, Pukyong National University, Korea

<sup>b</sup>Hyorim industries, Inc., Institute of Technology, Korea

### 1. Introduction

Forward osmosis (FO) is a separation process using salinity gradient as a driving force. Draw solution (DS) with higher salinity extracts pure water part of feed solution (FS) with lower salinity through semi-permeable membrane. In a module-scale of FO system operation, DS is diluted and FS is concentrated while they flow through the FO module. If FO modules are connected in series to increase recovery rate, DS is more diluted and FS is more concentrated, which makes the osmotic pressure drop smaller. Thus, the serial arrangements of FO modules are not very effective to increase the recovery rate of FO systems. In this work, a new combination of serial and parallel arrangement method for FO modules are suggested. In this FO module arrangement, DS channels are connected in parallel and FS channels are connected in series.

### 2. Methods

The performance of the new FO module arrangement is tested using the FO module modelling approach developed by our research group (Jeon et al., 2018) and an FO module experimental setup. The recovery rate of FO system is expressed as the concentration rate of FS, which is the ratio of FS to concentrated FS.

### 3. Results and Discussion

When DS is seawater (600 mM as NaCl) and FS is a brackish water (10 mM as NaCl), the concentration rate of FS is 3.3 with the serial FO module arrangement while the new FO arrangement exhibits 5.4 of the concentration rate.

### 4. Conclusions

The new FO module arrangement where DS channels are connected in parallel and FS channels are connected in series, turns out to be more efficient to concentrate FS than the serial arrangement.

### 5. References

J. Jeon, J. Jung, J.Y. Choi, S. Kim, A simple modelling approach for a forward osmosis system with a spiral wound module. *Desalination* 433 (2018) 120-131.

---

# Management and Utilization of RO Brine

(Session B)

---

- Room 2 -



## **Brine Solution in Seawater Desalination**

Seung-Hyun Kim

Civil Engineering Department, Kyungnam University, Korea

There are two challenges in seawater desalination; energy efficiency and brine management. Although the brine management has received less attention so far from the desalination community, it will soon change as the awareness of environmental impact increases. The brine solution will be discussed in this presentation, especially focusing on results of the Korean research group called, Global MVP (GMVP), who have a vision to make the seawater desalination plant more environment friendly. They proposed two brine solutions: dilution and zero liquid discharge (ZLD). The GMVP attempt to dilute the brine's high salinity level with secondary effluent from nearby wastewater treatment plant. They also attempt to recover the salinity gradient energy (SGE) by applying pressure retarded osmosis (PRO). This approach allows to eliminate or at least minimize the environmental concern from the brine's ocean discharge as well as to reduce the energy consumption of seawater desalination. In the ZLD approach, they first attempt to reduce the brine volume using membrane distillation (MD), and then to recover valuable resources (Li and Sr) from the MD brine. The remaining MD brine was used to produce the brick. The GMVP have built the pilot plants of SWRO-PRO and SWRO-MD.

## Applications of Electro-Membrane Processes for Reverse Osmosis Concentrate Recovery

V.V. Wagholikar<sup>a,b</sup>, D. Zhao<sup>a,b</sup>, L.Y. Lee<sup>a,b</sup>, S.L. Ong<sup>a,b</sup>, H. Zhuang<sup>c</sup>,  
N. E. Moe<sup>d</sup>, J. Barber<sup>c</sup> and H.Y. Ng<sup>\*a,b</sup>

\*<sup>a</sup> Sembcorp-NUS Corporate Laboratory, National University of Singapore; <sup>b</sup> Centre for Water Research, Department of Civil & Environmental Engineering, Faculty of Engineering, National University of Singapore; <sup>c</sup> SUEZ Water Technologies & Solutions Singapore Pte. Ltd.; <sup>d</sup> SUEZ Water Technologies & Solutions, USA; <sup>e</sup> SUEZ Water Technologies & Solutions, Canada

### 1. Introduction

Electro-membrane processes are advanced electrical separation processes, where the migration of ions in the feed streams are driven by potential difference and/or the salinity gradient between the two streams that are separated by ion-exchange membranes. This presentation comprises of two electro-membrane separation process research projects. Project 1 investigated the modeling of cell pair resistances in electro-membrane separation processes, while Project 2 evaluated the scaling potential of electrodialysis reversal (EDR) process for industrial RO concentrate treatment.

### 2. Methods

A non-contact resistance characterization method was employed in Project 1 to determine the resistances of individual spacers, membranes and sandwiched cell pairs in NaCl solutions with two different concentrations using 1000 Hz AC. Shadow factors of four different spacer meshes were experimentally determined as the ratio of spacer resistance to the resistance of the meshless channel of the same thickness. A lab-scale EDR system for water recovery from petrochemical industrial RO concentrate was used in Project 2. This RO concentrate contained hardness, bicarbonate and sulfate ions. Based on theoretical saturation index (SI) calculations for CaCO<sub>3</sub> and CaSO<sub>4</sub> salts, this RO concentrate was of high scale formation potential in the EDR system. The effect of varying anti-scalant residual dosage in the RO concentrate on the EDR process was also evaluated.

### 3. Results and Discussion

In Project 1, the additivity of cell pair resistances was confirmed and the most suitable functional form of the resistances in series (RIS) model was obtained. Shadow factors calculated from the mesh geometry showed a reasonable agreement with the experimental values. In Project 2, insignificant scaling was observed in the lab-scale EDR experiment runs. This could be due to the presence of anti-scalant residuals in the RO concentrate (originated from the anti-scalant dose applied to the upstream full-scale RO process) which may have inhibited the scale formation in the dilute and concentrate EDR streams. The results from the varying anti-scalant residual dosage study showed that the presence of anti-scalant in the RO concentrate was effective in limiting the scale formation during the EDR process.

### 4. Conclusions

This study validates the theory for systematically modeling the resistances of large industrial stacks for use in commercial operations. It can expedite the process of selection of low resistance spacer meshes and membranes for optimizing the power consumption in electro-membrane processes. The findings of the EDR study suggested that additional anti-scalant dosing would not be required for the EDR process treating RO concentrate which contains residual anti-scalant from the upstream RO process. This would provide significant operational cost savings in concentrate management using EDR process.

## Electrochemical lithium recovery in RO-MD brine

Jeyong Yoon<sup>\*</sup>, Seoni Kim, Hwajoo Joo

School of Chemical and Biological Engineering and Institute of Chemical Processes (ICP),  
Seoul National University, Korea

Seawater desalination have attracted a lot of attention, and various kinds of processes have been developed to an industrial level. Desalination plants inevitably generates and discharges 2-3 times concentrated seawater (desalination brine). Although there have been a lot of environmental concerns on discharge of desalination brine, the processes for treatment and utilization of desalination brine have not been intensively studied. In order to eliminate the environmental concerns on desalination brine and generate additional economic profit, our team in GMVP project designed a valuable resource recovery (VRR) process. VRR process is consist of four consecutive unit processes; lithium recovery, strontium recovery, sodium hydroxide (NaOH) production, and brick fabrication. Precious metal ions are extracted from desalination brine at the first two unit processes, and the residual brine is converted to NaOH solution by electrolysis at the third unit process. By mixing the generated NaOH solution and slag powder, bricks were fabricated at the last unit process. Through this VRR process, not only valuable resources were recovered including lithium, strontium and bricks, but also desalination brine was completely utilized. In this presentation, we will focus on the first unit process, lithium recovery. Lithium is included in desalination brine with 0.4-0.5 mg/L of concentration, and the demand for lithium has shown a rapid growth due to the wide usage of energy storage devices. In this study, an electrochemical system composed of  $\lambda$ -MnO<sub>2</sub> and silver electrodes was utilized for rapid and selective Li<sup>+</sup> recovery from the desalination brine. By using this system, Li<sup>+</sup> was selectively recovered from the desalination brine within one day without usage of harmful chemicals. Furthermore, we constructed a scaled-up lithium recovery system which can treat 6 ton of desalination brine in one day, and the experimental results obtained from the system operation will be introduced.



## **SWRO-PRO hybrid desalination for water & energy production**

Yong-Gyun Park<sup>†</sup>, In-Ho Yeo, Wonil Lee, Taeshin Park

Environment Process Engineering Team, GS Engineering & Construction (GS E&C), Korea

Seawater Reverse Osmosis (SWRO) desalination technology covers 70 to 80 % of annual new contracted desalination capacity owing to its lower electrical power consumption (3-5 kWh/m<sup>3</sup>) compared to thermal desalination technologies (up to 18 kWh/m<sup>3</sup>) such as MSF, MED, etc. However, conventional SWRO desalination systems are still required to be further improved to lower their energy consumption rate. Recently, a novel hybrid SWRO desalination system utilizing Pressure Retarded Osmosis (PRO) technology has been studied, which can recover a large amount of osmotic power from concentrated brine with 60,000 to 80,000 ppm of TDS. The advanced SWRO-PRO hybrid process developed by GS E&C (Seoul, Korea) can make the PRO technology economically coupled with a general SWRO desalination process. To investigate a SWRO-PRO process, a pilot plant (20 m<sup>3</sup>/d) and a demonstration plant (240 m<sup>3</sup>/d) utilizing SWRO brine as a PRO draw solution and treated waste water as a PRO feed solution have been constructed and operated with different types of TFC spiral-wound PRO membrane modules (8-inch). And the various operation conditions of the plants have been investigated for obtaining the optimal design and operation parameters to design a large-scale SWRO-PRO hybrid desalination plant. According to the pilot study results obtained, the SWRO-PRO hybrid desalination technology has great potential to reduce the large amount of energy required for desalination and to minimize the brine's negative impacts on the marine environment.

---

# SWRO Optimization & Advancement

(Session C)

---

- Room 1 -



## Improved Recovery of Seawater Desalination by Energy-Efficient Reverse Osmosis (EERO) Process

Tzyy Haur Chong<sup>a,b</sup>, Seonki Lee<sup>b</sup>, Kwanho Jeong<sup>b</sup>, Shuwen Goh<sup>b</sup>, S.R. Suwarno<sup>b</sup>, W.B Krantz<sup>c</sup>

<sup>a</sup> School of Civil and Environmental Engineering, Nanyang Technological University, Singapore.

<sup>b</sup> Singapore Membrane Technology Centre, Nanyang Environment and Water Research Institute, Nanyang Technological University, Singapore.

<sup>c</sup> Department of Chemical and Biological Engineering, University of Colorado, USA

Typical recovery of conventional single-stage reverse osmosis (SSRO) process for seawater desalination is  $\leq 50\%$  due to the osmotic pressure limitation. The novel energy-efficient reverse osmosis (EERO) process that combines SSRO and a counter-current membrane cascade with recycling (CMCR) was used to achieve high recovery i.e.  $> 50\%$  at modest energy consumption<sup>1,2</sup>. The CMCR consists of a terminal RO stage and a nanofiltration stage in series. A counter-current configuration implies that the retentate and permeate move in opposite directions. At the mixing point between CMCR stages, SSRO brine is blended with retentate that recycled from terminal RO to increase the recovery; and this blended stream is the feed to NF. The permeate from NF is further processed by terminal RO and the retentate of NF (i.e., final retentate of EERO) is a highly concentrated brine. The final product water of EERO is the combined permeate from SSRO and terminal RO. The required pressure to achieve high water recovery in the EERO process can be significantly reduced because it combines the advantage of SSRO with the ability of CMCR to reduce osmotic pressure differential across the NF membrane by allowing partial passage of salts as well as retentate recycling and multi-pass processing of permeate. The process modeling as well as the pilot trial of EERO will be presented. Briefly, an overall recovery of 65% can be achieved at operating pressure of  $\sim 50$  bar and energy consumption of  $2.8 \text{ kWh/m}^3$  based on pump efficiency of 85% and ERD efficiency of 90%.

### References

Chong T.H., Loo S.-L., Krantz W.B., J. of Membrane Science, 473, 177-188, 2015.

Chong T.H., Loo S.-L., Krantz W.B., Desalination, 366, 15-31, 2015.

## Efficient operation strategy for SWRO desalination plant

Jihye Kim, Bounsu Kown, Chunghwan Kim, Kyunghyuk Lee, Jaelim Lim<sup>†</sup>

Water Works Research Center, K-water Institute, Korea

Climate change has affected the global hydraulic cycle and thus aggravate the regional freshwater accessibility. Membrane-based desalination technology typified by reverse osmosis (RO) is widely recognized as a promising solution for water shortage and already utilized worldwide. Desalinated water cost is varied by the plant location, energy cost, and other site-specific characteristics, however, mostly more expensive than conventional-treated water. The operation and maintenance (O&M) costs hold 35-65% of the total necessary expense indicates that development of O&M cost-saving technologies is key factor to enhance the feasibility. To do so, K-water has been developing the efficient operation strategies for SWRO desalination plants and making a package program for the 1,000 m<sup>3</sup>/d pilot plant which will be constructed in UAE as a mission of the KORAE research team. The program includes the following functions; suggestion of the optimal dissolved air flotation process operating conditions such as coagulant dosing rate, saturator pressure, and recycling ratio according to the change of raw water conditions, determination of the optimal cleaning-in-place (CIP) timing for ultrafiltration process by data-based transmembrane pressure prediction, optimization of CIP and membrane replacement timing RO process, and energy monitoring/mapping of total plant. By utilizing these techniques, improvement of efficiency and stability of the desalination plant is expected; subsequently, it would be possible to keep the increase of annual energy consumption and O&M cost less than 5%.

## **Improvements of 10MIGD Busan SWRO plant by low energy consumption and O&M simulation tools**

Seokho Choi<sup>†</sup>, Jungjune Lee, Younggeun Lee, Kwanghee Shin and Hyungkeun Roh

Water Technology Development Team, Doosan Heavy Industries & Construction, Korea

### **1. Introduction**

Recently, RO project is developed as build-operate-transfer (BOT) model which is preferred by client due to reliability, stability, etc. 10 MIGD SWRO desalination plant located in Busan Korea is initially supposed to be used as trial Test Bed to apply and optimize the innovative technologies. After construction and commissioning, it is optimized for less energy consumption and improved by O&M software tool. The plant is originally designed as low energy consumption of 4 kWh/m<sup>3</sup>, but more aggressive energy consumption of 3.6 kWh/m<sup>3</sup> is targeted and expected to be achieved mainly by process modification and flexible operation. And O&M ICT simulation tool is developed and optimized

### **2. Process modification for low energy and flexible operation**

For the purpose of both energy consumption reduction and flexible operation, VFD(Variable Frequency Drive) is applied to high pressure pump and RO membrane vessels is sufficiently added to increase maximum production capacity. Therefore, the flow rate from process pumps is able to be changed flexibly considering the variation of time dependent electricity unit cost. For less energy consumption, some process pumps are minimized. The flow from DAF recycle pump is replaced with that from the seawater supply pump so that DAF recycle pumps are not needed to be operated at less production condition. And, the filtrate from UF membrane is directly fed to HP pump without using UF filtered water tank and pump. Consequently, the targeted energy consumption of 3.6 kWh/m<sup>3</sup> is simulated and demonstrated.

### **3. SWRO O&M simulation tool developments**

O&M software tools are developed such as RMS(Remote Monitoring System), EMS(Energy Monitoring System), MMO(Membrane Maintenance Optimizer), CMMS(Computerized Maintenance Management System) and RAM(Reliability Availability Maintainability). The operation data is monitored in real time and analyzed at the remote head office through RMS. Energy consumption is monitored with the time based electric cost by EMS. MMO monitors the status of membranes and provides the appropriate time for CIP and RO membrane replacement. CMMS provides the plant management services and documents related to maintenance activities. RAM calculates realistic plant availability and informs the optimum overhaul time, the expected maintenance schedule & costs.

### **4. References**

Sungwoo Woo, et al. IDA World Congress, Perth, Western Australia Sep. 4-9, 2011

F.Y. Wang, et al. IDA World Congress, Dubai, UAE Nov. 7-12, 2009.

## **Desalination by Resilient, Energy-Efficient, and Advanced Mobile Systems (DREAMS): A Step toward Sustainability**

Juneseok Choi<sup>a†</sup>, Sangho Lee<sup>b</sup>, Moonhyun Hwang<sup>c</sup>

<sup>a</sup>Civil and Environmental Engineering, Kookmin University, Korea

<sup>b</sup>Korea Institute of Civil Engineering and Building Technology, Korea

<sup>c</sup>School of Civil, Environmental and Architectural Engineering, Korea University, Korea

The problem of water scarcity is increasingly acute and prominent as the effect of climate change becomes more severe. This results in a critical issue on sustainable water supply in off-grid regions located in islands and coastal regions. One of the main challenges is the variation in water scarcity over time and space, which requires highly resilient technologies for water supply. A novel approach that holds promise is the mobile desalination technology aboard ships (or the desalination ship). However, there are only limited cases of such systems for practical applications in pilot- or full-scales.

In this context, this paper presents technologies required for design and operation of desalination ships, such as SWRO process for variable throughput and intermittent operation, design optimization for compact and lightweight desalination unit, smart operation and maintenance, hybrid energy supply, and management on the ship, etc. This paper also introduces a new research project aiming at the development of technologies for desalination ships, which is named DREAMS (Desalination by Resilient, Energy-Efficient, and Advanced Mobile Systems) supported by the Korean Government between 2018 and 2023.

### **References**

Maedeh P. Shahabi, Adam McHugh, Martin Anda, Goen Ho, A framework for planning sustainable seawater desalination water supply, Science of The Total Environment, Volume 575, 1 January 2017, Pages 826-835

## Cost analysis of small scale SWRO plants

Seongpil Jeong<sup>1,2,†</sup>, Hien Thi Nguyen<sup>1,2</sup>, Jooyoung Park<sup>3</sup>

<sup>1</sup>Center for Water Resource Cycle Research, Korea Institute of Science and Technology, Korea

<sup>2</sup>Division of Energy & Environment Technology, KIST school,

Korea University of Science and Technology, Korea

<sup>3</sup>Graduate School of Energy and Environment (KU-KIST Green School), Korea University, Korea

Remote islands require small scale desalination plants to provide safe water for residents. However, the operational costs of small scale desalination plants are relatively expensive due to low efficiency of the total system and frequent maintenances. In order to evaluate the costs for the small scale SWRO plants (<1,000 m<sup>3</sup>/day), a simple calculation model for the operation cost was suggested based on the references.



---

# Scaling-up New Desalination Technology

(Session D)

---

- Room 2 -





## Design and operation of hollow fiber membrane distillation process

Sangho Lee<sup>a†</sup>, Yongjun Choi<sup>a</sup>, Younghyun Shin<sup>a</sup>, Jihyeok Choi<sup>a</sup>, Juneseok Choi<sup>b</sup>

<sup>a</sup>Civil and Environmental Engineering, Kookmin University, Korea

<sup>b</sup>Korea Institute of Civil Engineering and Building Technology, Korea

### 1. Introduction

In this work, a pilot plant was designed and constructed to demonstrate the technical feasibility of large-scale MD systems.

### 2. Methods

Hollow fiber MD modules with the effective surface area of 10 m<sup>2</sup> were used in a vacuum MD process configuration. The MD process with the capacity of 400 m<sup>3</sup>/day (~ 0.105 MGD) was integrated with a SWRO desalination plant having a capacity of 1,000 m<sup>3</sup>/day.

### 3. Results and Discussion

A systematic approach was carried out to optimize the design of the MD process. The pilot plant was constructed based on the design parameters. Results showed that the MD process was successfully operated to fulfil the design requirements.

### 4. Conclusions

The feasibility of the MD technology for SWRO brine management was confirmed by the techno-economic analysis based on the data from the pilot plant.

### 5. References

Sangho Lee, Juneseok Choi, Yong-Gyun Park, Hokyong Shon, Seung-Hyun Kim, Hybrid desalination processes for beneficial use of reverse osmosis brine: Current status and future prospects, Desalination, In press, 2018

## Novel Modification Method for Membranes Used in Membrane Distillation

Nick Guan Pin Chew<sup>a,b</sup>, Shanshan Zhao<sup>b</sup>, Chandresh Malde<sup>c</sup>, Rong Wang<sup>b,d</sup>

<sup>a</sup> Interdisciplinary Graduate School, Nanyang Technological University, Singapore

<sup>b</sup> Singapore Membrane Technology Centre, Nanyang Environment and Water Research Institute, Nanyang Technological University, Singapore

<sup>c</sup> Johnson Matthey Technology Centre, United Kingdom

<sup>d</sup> School of Civil and Environmental Engineering, Nanyang Technological University, Singapore

Porous hydrophobic polyvinylidene fluoride (PVDF) membranes have been extensively used in direct-contact membrane distillation (DCMD) processes. However, these PVDF membranes are vulnerable to membrane fouling and pore wetting in low surface tension feeds, restricting its application for water recovery from challenging industrial wastewaters. Therefore, it is of paramount importance to engineer fouling- and wetting-resistant MD membranes for robust long-term applications. In this study, a superoleophobic composite hollow fiber membrane with sandwich structure has been developed via accelerated oxidant-induced polydopamine (PDA) deposition on both the outer and inner surfaces of a commercial hydrophobic PVDF membrane under slightly acidic conditions (pH = 5). The modified surface prevents organics adhesion ascribing to its underwater superoleophobicity while the unmodified pores remain hydrophobic for vapour transport. The long-term robustness of the PDA-decorated membrane in highly saline feeds containing low surface tension contaminants has been evaluated via bench-scale DCMD experiments. In contrast to the pristine PVDF membrane, the PDA-decorated membrane exhibits excellent fouling- and wetting-resistant properties in different surfactant solutions as well as oil- in-water emulsion. The PDA-decorated membrane has also been used for seawater desalination, during which it maintains a stable flux and high salt rejection rate. Furthermore, the PDA- decorated membrane presents a flux enhancement of up to 70% over the pristine PVDF membrane in 3.5 wt% NaCl solution at 333 K. This study demonstrates the potential of the PDA-decorated membrane for extended DCMD applications such as water recovery from industrial wastewater containing low surface tension substances.

## Hydrogen Production and Water Purification Using Photoelectrocatalytic Desalination Process

Dong Suk Han<sup>a\*</sup>, Seonghun Kim<sup>b</sup>, Guangxio Piao<sup>b</sup>, Ho Kyong Shon<sup>c</sup>, Hyunwoong Park<sup>b\*</sup>

<sup>a</sup>Chemical Engineering, Texas A&M University at Qatar, Education City, Qatar

<sup>b</sup>School of Energy Engineering, Kyungpook National University, Korea

<sup>c</sup>School of Civil and Environmental Engineering, University of Technology, Sydney (UTS), Australia.

A novel sunlight-water-energy nexus technology is presented that combines the photoelectrocatalytic (PEC) desalination of saline water and desalination-driven wastewater remediation coupled with the production of molecular hydrogen (H<sub>2</sub>) from water [1]. To accomplish this, morphologically tailored TiO<sub>2</sub> nanorod (TNR) and hydrogen-treated TNR (H-TNR) array photoanodes are placed in an anode cell and Pt foils are located in a cathode cell, while a middle cell containing saline water (0.17 M NaCl) faces these cells through anion and cation exchange membranes, respectively. Upon irradiation by simulated sunlight (AM 1.5G, 100 mW cm<sup>-2</sup>), the photogeneration of charge carriers initiates the transport of chloride and sodium in the middle cell to the anode and cathode cells, respectively, leading to the desalination of saline water. The chloride in the anode cell is converted to reactive chlorine species (RCS), which effectively decompose urea to N<sub>2</sub> as a primary product (>80%), while the sodium in the cathode cell accelerates the H<sub>2</sub> production from water with a Faradaic efficiency of ~80%. The PEC performance of the H-TNR photoanodes is superior to that of the TNR in the anodic and cathodic processes because of the reduced charge transfer resistance and sub-nanosecond charge transfer kinetics (~0.19 ns), leading to a specific energy consumption of 4.4 kW h m<sup>-3</sup> for 50% desalination, with an energy recovery of ~0.8 kW h m<sup>-3</sup>. The hybrid system is found to operate for a period of ~60 h with natural seawater, and virtually all the photoanodes are shown to be capable of driving the hybrid process. Although tested as a proof-of-concept, the present technology opens up a novel field involving a sunlight-water-energy nexus, promising high efficiency desalination and the desalination-driven remediation of water with simultaneous H<sub>2</sub> production.

### References

Kim, S.; Piao, G.; Han, D. S.; Shon, H. K.; Park, H., Solar desalination coupled with water remediation and molecular hydrogen production: a novel solar water-energy nexus. *Energy & Environmental Science* 2018, 11, (2), 344-353.

## Development of low energy consumption CDI system and its applications

Namsoo Park<sup>†</sup>, Kyungseok Kang, Hyunwoo Yoo

R&D Center, Siontech, Daejeon, Korea

### 1. Introduction

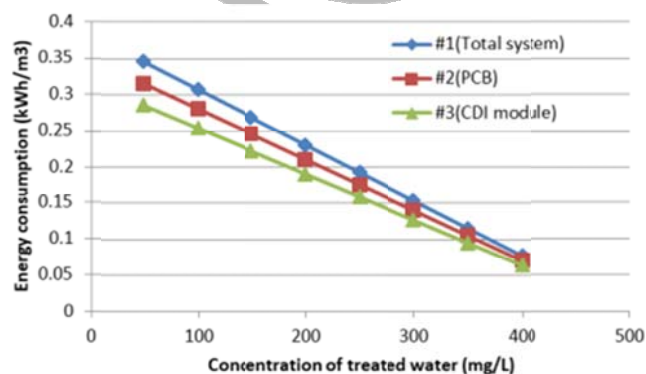
The capacitive deionization (CDI) process is a technology employed to remove ionic materials using an electric double layer created on the electrode surface interface when a potential is applied on the electrode. CDI is operated at a low electric energy to purify brackish water. Therefore, the process is highly advantageous and reduces energy consumption when applying instead of the 2<sup>nd</sup>. Pass RO in desalination plant. Also, because the adsorbed ions are desorbed by either discharging or changing the electrical potential of the electrode, the regeneration of the electrode is simple and recovery rate is very high. So, I did a study to apply CDI to the after SWRO in desalination plant.

### 2. Methods

The CDI system of 50 m<sup>3</sup>/day was prepared to apply to the after SWRO. The concentration of SWRO treated water is about <500 mg/L and it was tried to lower it to <150 mg/L. At this study, the energy consumption of the CDI system was measured.

### 3. Results and Discussion

To reduce energy consumption, we developed high performance CDI electrodes, module and control system. And by applying these, we could get low energy CDI system and the following result.



**Figure 1.** Energy consumption by treated water concentration

### 4. Conclusions

Using this CDI pilot system, we could obtain data of concentration and energy consumption. As a result, it is confirmed that it is applicable to the desalination plant.

### 5. References

- Park B. H., Choi J. H., *Electrochimica Acta* 55, 2888 (2010)  
 Kim T. Y., J.E. Dykstra, S. Porada, A. van der Wal, Yoon J. Y., P.M. Biesheuvel, *Journal of Colloid and Interface Science* 446, 317 (2015)

## Theoretical and experimental approaches of liquid entry pressure determination in membrane distillation processes

Chang-Kyu Lee<sup>a</sup>, Yun-Kyoung Lee<sup>a</sup>, Chansoo Park<sup>b</sup> and Jong-Oh Kim<sup>b†</sup>

<sup>a</sup>Research Engineering Development Inc., Korea

<sup>b</sup>Department of Civil and Environmental Engineering, Hanyang University, Korea

### 1. Introduction

Liquid entry pressure (LEP) of membrane is crucial in the process of membrane distillation (MD) to ensure the quality of distillate since the whole operation will be contaminated as soon as the feed liquid starts to penetrate the hydrophobic membrane. Assuming standard condition, experimental LEP values were inconsistent compare to theoretical LEP, thus rigorous analysis attempt was made to help understanding the wetting phenomena in MD.

### 2. Methods

Deionized water was used as feed solution of all LEP tests. The LEP module was employed in the experiment to embed membranes. Polyvinylidene fluoride (PVDF) flat-sheet membrane having a pore size of 0.45  $\mu\text{m}$  was used.

### 3. Results and Discussion

As a natural result, LEP is temperature dependent; however, other factors which are not reflected in the LEP equation also exists. Experiments show that the wetting at pressure above LEP may not only wet the membrane but also affect membrane properties.

### 4. Conclusions

In the MD process, the importance of preventing wetting exceeds the necessity of recovering after wetting.

### 5. References

M.C. Garcia-Payo, M.A. Izquierdo-Gil, and C. Fernandez-Pineda, "Wetting study of hydrophobic membranes via liquid entry pressure measurements with aqueous alcohol solutions". *J Colloid Interf Sci*, 230 (2000), 420-431.

---

# **Fouling Characterization and Control**

(Session E)

---

- Room 1 -



## Role of fouling control in expanding FO application

Seungkwan Hong<sup>†</sup>, Gimun Gwak, David Inhyuk Kim

School of Civil, Environmental and Architectural Engineering, Korea University, Korea

Membrane fouling occurred during forward osmosis (FO), an osmotically-driven process filtrating water through a membrane, has been a challenging issue for its use sweater desalination and wastewater reuse. This study was aimed to thoroughly understand the fundamental fouling behaviors in FO system, and look into the fouling control strategies for sustainable use of FO process. Lastly, the results shown in this study is expected to provide insights into finding possible applications of FO. A various literatures of membrane fouling in FO, from fundamental fouling mechanism to membrane fouling control in real process have been reviewed through this study. FO was shown to have low fouling potential and be easily control membrane fouling formed on the membrane surface. Therefore, the possible application of FO can be targeted on industries that contains high TDS and high fouling potential. The FO is expected to be sustainably and feasibly operated over the RO reverse osmosis processing by applying in aforementioned fields. Aside from seawater desalination and wastewater reuse fields, the application of FO can be expanded to other industries including flue gas desulfurization wastewater treatment, medical radioactive liquid waste treatment, RO brine treatment, and grapefruit juice concentration, with sustainable operation with proper membrane fouling control.

### References

- B.G. Choi, D.I. Kim, S. Hong, *Journal of Membrane Science* 520, 89-98 (2016).
- D.I. Kim, J. Kim, S. Hong, *Desalination* 389, 197-206 (2016).
- G. Gwak, D.I. Kim, S. Hong, *Journal of Membrane Science* 552, 234-242 (2018).

## Novel biofouling control and detection using Electrical Impedance Spectroscopy (EIS)

Jia Shin Hoa\*, Lee Nuang Sima, Tzyy Haur Chonga, b, H.G.L. Costerc,  
Hideyuki Komorid, Akihiro Fujiid, Kunihiro Hayakawae

<sup>a</sup>Singapore Membrane Technology Centre, Nanyang Environment and Water Research Institute,  
Nanyang Technological University, Singapore.

<sup>b</sup>School of Civil and Environmental Engineering, Nanyang Technological University, Singapore.

<sup>c</sup>School of Chemical and Biomolecular Engineering, University of Sydney, Sydney, Australia.

<sup>d</sup>Kurita R&D Asia Pte. Ltd.

<sup>e</sup>Kurita Water Industries Ltd.

The efficiency of a new slime control method for seawater reverse osmosis (SWRO) biofouling control has been evaluated using an online, *in-situ* monitoring tool, electrical impedance spectroscopy (EIS). The fouling control monitor consists of a crossflow canary cell equipped with an EIS system [1] was installed at the side stream of a RO train (4 × 4" module). The feed water to the pilot RO system was de-chlorinated UF filtrate from an existing seawater desalination plant. Different dosing conditions (i.e., concentration and intermittency) of the slime control agent, Kuriverter® IK-110 (a proprietary product developed by Kurita Water Industries Ltd) have been applied to evaluate the effect on RO membrane fouling and the corresponding EIS signals of the side stream canary cell were recorded. In this study, the normalized conductance of the diffusion polarization ( $G_{DP}$ ) layer was used as the main parameter for fouling monitoring based on the results from previous studies [1-3]. The correlation between  $d\Delta P/dt$  and  $dG_{DP}/dt$  suggests that  $G_{DP}$  is indeed a good indication for fouling events on the membrane surface. This allows various control method to be formulated and optimized based on the  $G_{DP}$  trend [1-4].

This is the first application of EIS fouling monitor in SWRO. The EIS fouling monitor allows the non-destructive monitoring of fouling conditions on the membrane surface. It also provides assistance in the optimization of fouling control agent dosing condition.

### References

- J.S. Ho, L.N. Sim, R.D. Webster, B. Viswanath, H.G.L. Coster, A.G. Fane, Monitoring fouling behavior of reverse osmosis membranes using electrical impedance spectroscopy: A field trial study, *Desalination*, 407 (2017) 75-84.
- J.S. Ho, J.H. Low, L.N. Sim, R.D. Webster, S.A. Rice, A.G. Fane, H.G.L. Coster, In-situ monitoring of biofouling on reverse osmosis membranes: Detection and mechanistic study using electrical impedance spectroscopy, *J. Membr. Sci.*, 518 (2016) 229-242.
- J.S. Ho, L.N. Sim, J. Gu, R.D. Webster, A.G. Fane, H.G.L. Coster, A threshold flux phenomenon for colloidal fouling in reverse osmosis characterized by transmembrane pressure and electrical impedance spectroscopy, *J. Membr. Sci.*, 500 (2016) 55-65.
- L.N. Sim, Z.J. Wang, J. Gu, H.G.L. Coster, A.G. Fane, Detection of reverse osmosis membrane fouling with silica, bovine serum albumin and their mixture using in-situ electrical impedance spectroscopy, *J. Membr. Sci.*, 443 (2013) 45-53.



## Evaluating membrane fouling potentials of dissolved organic matter in brackish water

Jongkwan Park, Sanghun Park, Jeongyeop You, Kyung Hwa Cho<sup>†</sup>

School of Urban and Environmental Engineering, Ulsan National Institute of Science and Technology, Korea

### 1. Introduction

Isolating dissolved organic matter (DOM) is a preliminary step that improves the accuracy of its characterization (Park et al., 2017). In this study, DOM in brackish water was concentrated and desalted by nanofiltration to increase the organic matter detection level to allow for multiple characterization analyses.

### 2. Methods

The pre-treated sample was fractionated into three fractions by preparative high-performance liquid chromatography (preparative HPLC) according to molecular size. The molecular weight homogeneity of each fraction was estimated by analytical size exclusion chromatography (SEC) and fluorescence excitation-emission matrix (FEEM). Pyrolysis gas chromatography-mass spectrometry (Py-GC/MS) and liquid chromatography-organic carbon detection (LC-OCD) were used to characterize the physicochemical properties of the fractions.

### 3. Results and Discussion

Py-GC/MS revealed that Fraction 1 was comprised of evenly distributed organic matter contents as follows: polysaccharides, proteins, polyhydroxy aromatic, lignins, and lipids. However, Fraction 2 was primarily composed of proteins and lipids, and Fraction 3 was composed predominantly of proteins. The LC-OCD results showed that Fractions 1 and 2 were comprised of similar organic carbon (OC) composition: humic substance (ca. 37%), building blocks (ca. 10%), and neutrals (ca. 37%), whereas Fraction 3 contained a high proportion of neutrals (62%). In membrane fouling experiments, the distinct characteristics of DOM in each fraction resulted in different flux decline behaviours in the order of: Fraction 2 > Fraction 1 > Fraction 3. Based on the py-GC/MS and LC-OCD results, this demonstrates that a relatively high proportion of proteins and lipids in Fraction 2 exerted synergistic influence on fouling development. Hydrophobic aggregation between protein and lipids bilayer causing assembly on the membrane surface.

### 4. Conclusions

In this study, we performed a characterization of DOM in brackish water for a better understanding of organic fouling mechanisms. From the various analytical methods, organic matter in brackish water could be characterized in terms of molecular size, structure, and fouling potential.

### 5. References

Park J, Chon K, Lee E, Cho J. Developing a large-volume preparative method using a handmade HPLC column to fractionate dissolved organic matter. *Desalination and Water Treatment* 2017; 67: 97-104.

## **A novel membrane-based spectrophotometric method for quantifying of transparent exopolymer particles (TEP)**

Lee Nuang Sim<sup>a</sup>, Stanislaus Raditya Suwarno<sup>a</sup>, Tzyy Haur Chong<sup>a,b</sup>,  
Emile R. Cornelissen<sup>c</sup> Anthony G. Fane<sup>a</sup>

<sup>a</sup>Singapore Membrane Technology Centre, Nanyang Environment & Water Research Institute,  
Nanyang Technological University, Singapore

<sup>b</sup>School of Civil and Environmental Engineering, Nanyang Technological University, Singapore.

<sup>c</sup>AKWR Watercycle Research Institute, Netherlands

The presence of transparent exopolymer particles (TEP) in water bodies has been related to several adverse impacts in various water treatment processes. In recent years, there have been an increasing number of publications relating to TEP. Unfortunately, this increased interest in TEP measurement has not been accompanied by significant improvement in the analysis method or TEP monitoring. Currently, the most common method to analyse and quantify TEP only allows offline, and often offsite measurement, causing delays and slow response. This study introduces an improved method for TEP monitoring using a membrane-based spectrophotometric technique to quantify TEP in various water bodies. The proposed TEP monitor involves a crossflow filtration unit (30kDa UF membrane), reagent injection and a spectrophotometer system. The TEP retained on the membrane surface is stained by Alcian blue and the amount deposited is quantified directly using an optic fibre reflectance probe coupled with a spectrophotometer. The novel method shows a linear relationship with various concentrations of Xanthan gum (a model representing TEP). When applied to detect the algae growth, it was observed the proposed method shows an obvious TEP release during the growth of algae, whilst the conventional TEP method only shows slight variation throughout the monitoring period. The results indicated the new TEP method is more sensitive than conventional method as it could capture smaller portion of algae-released TEP. Several advantages of this novel method are shorter analysis time, increased accuracy, and the potential to be further developed into an online system.

## Immobilization of antimicrobial chemicals on RO membrane surfaces for in-situ biofouling control

Taek-Seung Kim and Seoktae Kang<sup>†</sup>

Department of Civil and Environmental Engineering, Korea Advanced Institute of Science and Technology (KAIST), Korea

### 1. Introduction

Biofouling was a major cause for deterioration of operation performance in reverse osmosis (RO) membrane process. In previous studies [1], biofouling control has mainly used treatment method of chemical cleaning agents in RO processes. The chemical cleaning agents have to pay careful attention concerning injection concentrations and methods due to membrane surface damage as well as secondary pollution in water system caused from drain water. To overcome these problems, our research group carried out the study for reducing biofouling using surface immobilization of biofilm inhibitors on RO membrane without injection of chemical cleaning agents.

### 2. Methods

Molecular Layer by layer technology was used for surface immobilization on RO membrane. And chlorhexidine (CH) and glutaraldehyde (GA) were used as a biofilm inhibitor and a cross-linker, respectively. Biofilm and biofouling properties were evaluated using confocal laser scanning microscopy (CLSM) and scanning electron microscopy (SEM) after operation of drip flow biofilm reactor and batch scale RO unit, respectively.

### 3. Results and Discussion

Biofilm properties on virgin RO membrane, CH mono-layered RO membrane, and CH bi-layered RO membrane were evaluated after biofilm test using drip flow cell reactor. These properties such as the ratio (%) of live cell, bio-volume ( $\text{m}^3/\text{m}^2$ ), and biofilm thickness ( $\text{m}$ ) of CH bi-layered RO membrane were more decreased than those of virgin RO membrane and CH mono-layered RO membrane. In fact, these properties of CH bi-layered RO membrane showed 16.8 %,  $4.3 \text{ m}^3/\text{m}^2$ , and 17.3 mm, respectively. Especially, bio-volume ( $4.3 \text{ m}^3/\text{m}^2$ ) of CH bi-layered RO membrane was 81.7% lower than that ( $23.5 \text{ m}^3/\text{m}^2$ ) of virgin RO membrane. CH bi-layered RO membrane was observed to be the excellent effect for reducing biofilm. Also, these properties of each membrane identified that they showed similar results with SEM images after biofouling test using batch scale RO unit.

### 4. Conclusions

The surface immobilization of biofilm inhibitors was demonstrated to maintain the operational performance in RO processes due to the delay of biofilm formation induced by the attachment inhibition on membrane surface and the death of microorganisms.

### 5. References

S.A. Creber, J.S. Vrouwenvelder, M.C.M. van Loosdrecht, M.L. Johns, Chemical cleaning of biofouling in reverse osmosis membranes evaluated using magnetic resonance imaging, *Journal of Membrane Science*, 362 (2010) 202-210.

---

# **Desalination Technology Integrating with Water Reuse**

(Session F)

---



## Further Progress of “Mega-ton Water System”

Masaru Kurihara

Toray Industries Inc., Tokyo, Japan

The reverse osmosis (RO) membrane process for seawater desalination is now widely used around the world, but considering the population increase and economic development in the future, a larger plant is necessary for the rest of the 21st century.

For this reason, the "Mega-ton Water System" project was implemented as national research in Japan that aimed at developing sustainable water treatment core technologies necessary for the 21st century.

The vision and missions of the project were established for 1) energy reduction (30%), 2) water production cost reduction (50%), 3) low environmental impact (fewer chemical operations).

Major achievements of “Mega-ton Water System” project;

1. The microstructure analysis of RO membrane functional layer and the development of low pressure SWRO membrane.
2. 30% energy reduction was possible using SWRO-PRO system in the “Mega-ton Water System” at mega-ton scale SWRO plants. The brine disposable problem was also solved by this system.
3. Bio-fouling monitoring technology makes it possible to low environmental impact and the reliable operation.

The pilot verification of “Mega-ton Water System” technology in Saudi Arabia was done successfully.

The next step is the New Energy and Industrial Technology Development Organization (NEDO) verification project, the full plant, 10,000 m<sup>3</sup>/day in Saudi Arabia.

## **Application of novel outer selective thin film composite hollow fiber forward osmosis membrane in osmotic membrane bioreactor treating municipal wastewater**

Van Huy Tran<sup>a</sup>, Sungil Lim<sup>a</sup>, Nirenkumar Pathak<sup>a</sup>, Nawshad Akther<sup>a</sup>, Sherub Phuntsho<sup>a</sup>,  
Dong Suk Han<sup>b</sup> and Hokyong Shon<sup>a\*</sup>

<sup>a</sup>School of Civil and Environmental Engineering, University of Technology, Sydney (UTS), Australia

<sup>b</sup>Chemical Engineering Program, Texas A&M University at Qatar, Qatar

The present study investigated for the first time the performance of a novel in-house made outer selective thin film composite (TFC) hollow fiber (HF) forward osmosis (FO) membrane in osmotic membrane bioreactor (OMBR) treating municipal wastewater. The process performance was investigated in terms of water flux and salinity build up, organic and nutrient removal, fouling propensity and cleaning strategies employing sodium chloride (NaCl) draw solution. In-house made (Centre for Technology in Water and Wastewater (CTWW), University of Technology (UTS), Sydney) outer selective TFC hollowfiber membrane was operated in side stream mode for one-week time. In preliminary study outer selective TFC HF FO membrane has shown 14 LMH (Liters per hour per square meter) initial water flux and very less 0.5 g/L salinity build-up when 30 g/L NaCl was used. More than 97% total organic carbon and ammonia removal efficiency was observed during OMBR operation. Two different membrane cleaning cycles 12 h and 24 h were investigated respectively. More than 90% flux recovery was realized with both physical cleaning and chemical cleaning irrespective of cycle time. This innovative in-house made outer selective TFC HF membrane demonstrated great potential for its application in OMBR process achieving high water flux, low reverse salt flux, high pollutant removal and better flux recovery.

# Performance evaluation and fouling characterization of element-scale forward osmosis process

Sanghyun JEONG, Sung Ju IM, Am JANG<sup>†</sup>

Graduate School of Water Resources, Sungkyunkwan University, Korea

## 1. Introduction

Most of previous FO studies have focused on lab-scale due to installation cost/area, duration and reliability. However, depending on the element type, the optimum operational conditions, performances and fouling behaviours are different. In this study, element-scale FO processes were evaluated to find out the optimal operational conditions and to characterize the fouling on the membrane. Design and operation guideline were suggested from mass balance and modelling based on data base acquired from operation.

## 2. Methods

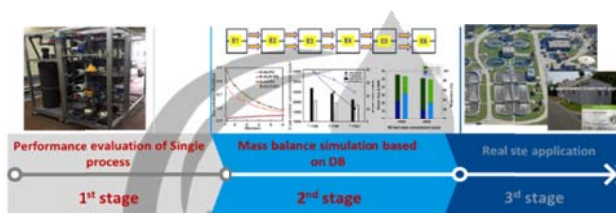


Figure 1. Procedure of element-scale evaluation

## 3. Results and Discussion

Two different types (spiral wound FO; SWFO, and plate-frame FO; PFFO) of FO elements were tested and the performances are shown in Fig. 2.

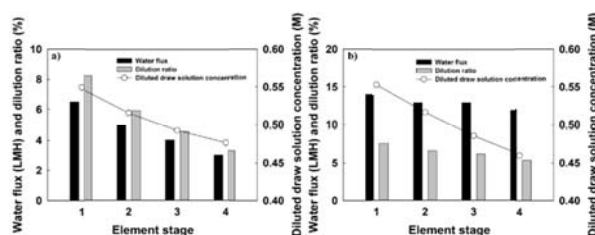


Figure 2. Performance of element scale FO a) SWFO, and b) PFFO

## 4. Conclusions

According to the FO element type and configuration, optimum operation factors were different. Therefore, depending on the FO element type, appropriate application should be considered.

## 5. References

- Sung-Ju Im, Hojung Rho, Sanghyun Jeong and Am Jang, Chemical Engineering Journal, 2018, 336, 141-151.  
 Sung-Ju Im, Sanghyun Jeong and Am Jang, Journal of Membrane Science, 2018, 549, 366-376.

## Nanowires versus Nanosheets – Effect of NiCo<sub>2</sub>O<sub>4</sub> Nanostructures on Ceramic Membrane Filterability and Fouling Potential

Zhiyang LYU<sup>a†</sup>, Tze Chiang Albert NG<sup>b†</sup>, Qilin Gu<sup>a</sup>, Lei ZHANG<sup>a</sup>, Zeming HE<sup>a</sup>,  
Weijie POH<sup>b</sup>, How Yong NG<sup>b\*</sup>, John WANG<sup>a\*</sup>

<sup>a</sup>Department of Material Science and Engineering, National University of Singapore, Singapore

<sup>b</sup>Centre for Water Research, Department of Civil and Environmental Engineering, National University of Singapore, Singapore

Incorporation of metal oxides as functionalized layers on membranes have shown to improve membrane performance (Ng et al., 2013). For example, iron/iron oxide functionalized membranes were shown to enhance toxic metal removal from power plant scrubber water (Gui et al., 2015) and different metal oxides on ceramic membranes improved oil/water separation (Lu et al., 2016). However, metal oxides form different structures because of differences in fabrication, and it is expected that these structures will have a different impact on membrane filterability and fouling potential. Herein, NiCo<sub>2</sub>O<sub>4</sub> nanowires (NW) and nanosheets (NS) were prepared on ceramic membranes via the facile hydrothermal process with structures formed by the growth position in the process. A combination of XRD, TEM and XPS confirmed the formation of the NiCo<sub>2</sub>O<sub>4</sub> layer. Clear morphological differences in NW and NS structures were observed from SEM images, with NW seen as wire-like structures of ~50 nm in diameter and NS as leaf-like structures approximately 200 nm across. The nanoporous NS and NW layers were found to be significantly more hydrophilic than the ceramic membrane substrate but were comparable to each other. However, water flux of NS was 50% lower than that of NW with membrane resistance 40% higher. SEM images after filtration showed that the NS structures had collapsed under filtration and blocked water flow through the membrane. Organic fouling, determined by resistance of alginate or BSA layers on the membranes, was similar on both nanostructures. Resistances caused by carbohydrate fouling were found to be nearly twice that caused by protein fouling due to the reduction of hydrophobic-hydrophobic surface interactions. Biofilm formation, determined by the number of live cells on the membrane surface, was a third lower on the NW membranes. These results demonstrated that the NW structure was found to be more suitable for water filtration due to better structure stability, lower fouling potential and membrane resistance.

### References

- Gui, M., Papp, J.K., Colburn, A.S., Meeks, N.D., Weaver, B., Wilf, I., Bhattacharyya, D., 2015. Engineered iron/iron oxide functionalized membranes for selenium and other toxic metal removal from power plant scrubber water. *J. Memb. Sci.* 488, 79–91. <https://doi.org/10.1016/j.memsci.2015.03.089>
- Lu, D., Zhang, T., Gutierrez, L., Ma, J., Croué, J.P., 2016. Influence of Surface Properties of Filtration-Layer Metal Oxide on Ceramic Membrane Fouling during Ultrafiltration of Oil/Water Emulsion. *Environ. Sci. Technol.* 50, 4668–4674. <https://doi.org/10.1021/acs.est.5b04151>
- Ng, L.Y., Mohammad, A.W., Leo, C.P., Hilal, N., 2013. Polymeric membranes incorporated with metal/metal oxide nanoparticles: A comprehensive review. *Desalination* 308, 15–33. <https://doi.org/10.1016/j.desal.2010.11.033>



## Improving energy efficiency of pretreatment against algal bloom in seawater desalination by novel meshed tube filtration

Jihun Lim<sup>a</sup>, Gyuhyon Cha<sup>a</sup>, Soohoon Choi<sup>b</sup>, Hyunkyung Lee<sup>a</sup>, Kwangse Kim<sup>c</sup>, Sangjun Ahn<sup>c</sup>, and Seungkwan Hong<sup>a†</sup>

<sup>1</sup> School of Civil, Environmental and Architectural Engineering, Korea University, Korea

<sup>2</sup> School of Civil and Environmental Engineering, Sejong University, Korea

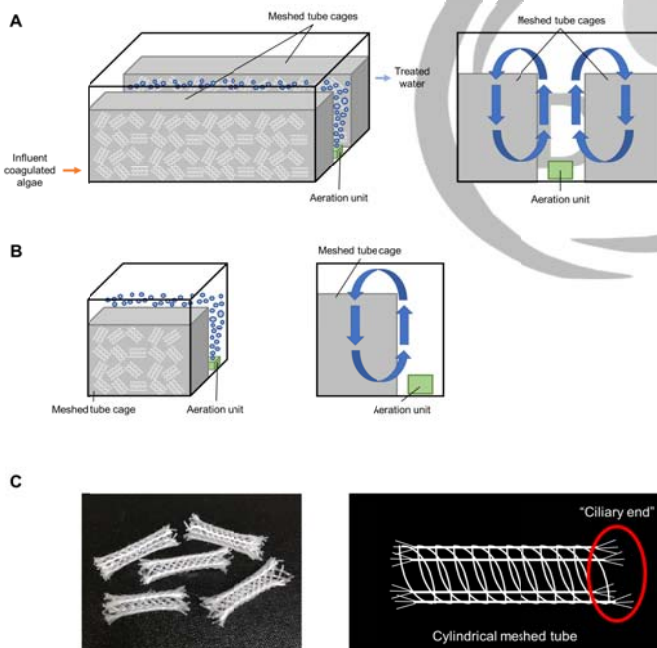
<sup>3</sup> Keosong Construction Co., Ltd., Korea

### 1. Introduction

Seawater reverse osmosis (SWRO) is the preferred technology for desalination [1]. Algal blooms, however, are becoming an emerging threat to SWRO plant operations [2]. In the present study, a novel filtration method using polypropylene meshed tubes was developed as a pre-treatment method for RO membrane processes. The main motivation for this development arose from a low energy-consuming pre-treatment system that would be capable of withstanding algal bloom conditions.

### 2. Methods

#### Lab-scale MTF system



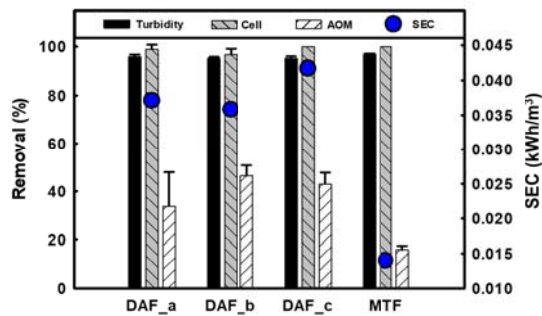
**Figure 1.** Schematic representation of the experimental MTF module with a volume of (A) 6 L (lab-scale) and (B) 1 L (bench-scale). The aeration unit placed on the bottom along the longitudinal direction induced a continuous hydraulic circulation current. The netted meshed tube cages were densely filled with (C) synthetic meshed tubes with ciliary ends.

As seen in Fig. 1 (A), the MTF system is composed of two main components, an aeration chamber and an MTF chamber. Coagulated algae were injected into the bottom of the aeration chamber and circulated into the top section of the MTF chamber. The circular hydraulic stream results in downstream currents in the filtration chambers for MTF. Due to the continuous feed water injected into the system, the water continuously circulates to the end of the system. An additional 1 L bench-

scale unit (Fig 1. (B)) with a single meshed tube cage was also constructed for system optimization experiments.

The meshed tubes were manufactured in two steps. First, long cylindrical meshed tubes with 5 mm diameter were woven with synthetic polypropylene fibres and cut to 25 mm lengths. Next, the tubes were loaded in the meshed tube cages (Fig. 1 (A) and (B)) and, after filling the reactor with feed water, aeration was provided to induce collisions among the tubes. These contacts caused fibres at both ends of the tubes to become untied and become ciliary (Fig. 1 (C)). Ciliary ends of the tubes perform as dense bridges that connects the tubes and enable the meshed tube cage unit to function like a sieve.

### 3. Results and Discussion



**Figure 2.** Comparison of algae removal performance and estimated specific energy consumption between three optimal cases of DAF and optimal MTF.

The performance and energy consumption of DAF and MTF under optimal conditions are depicted in Fig. 2. MTF showed equivalent levels of removal of both algal cells and turbidity compared to the three optimum cases of DAF. However, it showed lower AOM removal, where DAF showed 30-40% removal but MTF showed 16%. Furthermore, MTF energy consumption showed a significant amount of savings, where the MTF consumed 33-39% that of DAF operations.

### 4. Conclusions

We investigated the applicability of MTF technology for SWRO desalination pre-treatment under algal bloom conditions. Based on the results, the MTF system was determined to be competitive with the existing DAF process, particularly for MTF's notable economic feasibility.

### 5. References

- B. Peñate, L. García-Rodríguez, Current trends and future prospects in the design of seawater reverse osmosis desalination technology, *Desalination*. 284 (2012) 1–8. doi:10.1016/j.desal.2011.09.010
- L. Villacorte, S. Tabatabai, N. Dhakal, G. Amy, J. Schippers, M.D. Kennedy, Algal blooms: an emerging threat to seawater reverse osmosis desalination, *Desalin. Water Treat.* (2014) 1–11. doi:10.1080/19443994.2014.940649

---

# **POSTER**

(P-1 ~ P-11)

---



## Application of MFI-UF to manage reverse osmosis (RO) process: a pilot study in ultrapure water (UPW) production system

Hyunkyung Lee<sup>a</sup>, Min Zhan<sup>a</sup>, Yongxun Jin<sup>b</sup>, Seungkwan Hong<sup>a†</sup>

<sup>a</sup>School of Civil, Environmental and Architectural Engineering, Korea University, Korea

### 1. Introduction

This study investigated the applicability of modified fouling index (MFI) to predict performance of reverse osmosis (RO) process at pilot-scale ultrapure water (UPW) production system.

### 2. Methods

Current practical study was performed at a pilot-scale UPW plant (Hwaseong-si, Gyeonggi-do, Korea). The water quality of RO inlet was monitored for a year, in order to evaluate the relation between MFI and RO.

### 3. Results and Discussion

The MFI-UF well predicted RO performance deterioration (i.e., flux decline rate at lab-scale or differential pressure increase in pilot-scale experiment). Moreover, the increment of fouling potential was intimately related with RO performance, the aggravation of permeate quality, as MFI-UF reflects amount of pollutants in feedwater including ionic components. The sensitivity of MFI-UF was also verified with two case studies: 1) foulant injection test and 2) the influence of reclamation loop in UPW production system.

### 4. Conclusions

The applicability of MFI-UF for stable operation of RO process was verified. MFI-UF well informs the fouling characteristics of feedwater which is intimately related with DP increment and permeate quality of RO process.

### 5. References

Jin et al, Desalination Vol 407 (2017), 24-32

# Preparation and characterization of superhydrophobic co-axial electrospun nanofiber membranes

Yun Chul Woo<sup>†</sup>, June-Seok Choi

Department of Land, Water and Environment Research, Korea Institute of Civil Engineering and Building Technology, Republic of Korea

## 1. Introduction

Membrane distillation (MD) is a thermally-driven membrane separation process. Currently, the membranes used for MD studies are usually microfiltration (MF) membranes (Tijing et al., 2016). However, MF membranes are not ideally designed for MD process. Thus, there is a need to design new membranes with structures fit for MD. Electrospinning is one of the alternative techniques to fabricate MD membrane. Electrospun nanofiber membranes (ENMs) have several advantages such as high surface area, high hydrophobicity and porosity, and controllable pore size and membrane thickness. However, despite these advantages, the ENMs still suffer from wetting problems. Co-axial electrospinning technique is one of the electrospinning approaches to fabricate suitable membranes for MD with improved wetting resistance.

## 2. Methods

Co-axial electrospinning utilizes dual tube nozzles, one central tube situated in the centre of the annular tube. Two different polymer solutions, one composes the core, and the other one composes the sheath, are separately injected into the co-axial nozzle, and when voltage is applied, they are ejected simultaneously to produce coaxially-layered ENMs. In the present study, we aim to investigate PVDF-co-HFP (PcH) as core and PcH/silica aerogel (SiA) as sheath for co-axial composite ENMs to obtain superhydrophobic property on the membrane surface.

## 3. Results and Discussion

Results of surface characterization showed that the active layer (i.e., PcH) of all co-axial ENMs exhibited a rough, highly porous (>80%), and superhydrophobic surface ( $CA > 160^\circ$ ). Co-axial ENMs possess small pore sizes ( $< 0.39 \mu\text{m}$ ) and suitable liquid entry pressure ( $> 1.72 \text{ bar}$ ). Upon application in direct contact MD (DCMD) test (feed:  $60.0^\circ\text{C}$ ; permeate:  $20.0^\circ\text{C}$ ) for 72 h operation using 3.5wt% NaCl solution as feed, a high water vapour flux and salt rejection of  $12.1 \text{ L/m}^2\text{h}$  and 100% were achieved, respectively, when optimal SiA loading of 0.4 wt% solution was applied at the sheath (compared to  $10.2 \text{ L/m}^2\text{h}$  and 96.67% for single-nozzle PcH ENM).

## 4. Conclusions

The present ENMs containing SiA by versatile co-axial electrospinning fabrication shows great potential for DCMD desalination application.

## 5. References

Tijing et al., (2016) Fouling and its control in membrane distillation—A review, *Journal of Membrane Science*, 475, 215-244

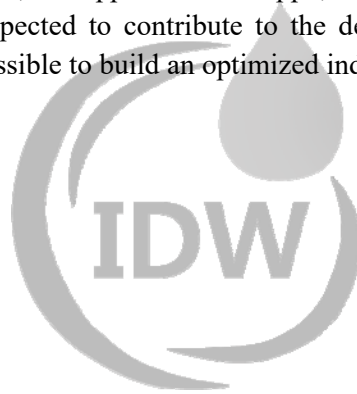
## **Study on prediction of water quality of produced water considering characteristics of individual process design factors for ultrapure water**

Boungsu Kwon<sup>a</sup>, Am Jang<sup>b</sup>, Kyoung Wan Kim<sup>a</sup>, Kyunghyuk Lee<sup>a</sup>, Jaelim Lim<sup>a†</sup>

<sup>a</sup>Water Works Research Center, K-water Institute, Daejeon 34045, Korea

<sup>b</sup>Graduate School of Water Resources, Suwon 16419, Korea

The purpose of this study is to estimate the target water quality through computer simulation for customized high purity industrial water production. The computational simulation for water quality and for ultrapure water demonstration plant (25 m<sup>3</sup> / day) are compared. Some categories such as resistivity and total organic carbon (TOC) showed similar results, however the results for dissolved oxygen (DO), silica, particle and boron had some variations. The results from the computer simulation were 0.5 ppb, 0.5 ppb and 0.05 ppb, for DO, silica and boron, respectively, whereas the results from the demonstration plant were 0 ppb, 0.25 ppb and 0.024 ppb, for DO, silica and boron, respectively. The results from this study is expected to contribute to the development of core technologies for industrial water, and to make it possible to build an optimized industrial water treatment facility.



## Study of the optimization process combination on the ultrapure water treatment system

Bongsu Kwon, Kyoung Wan Kim, Jihye Kim, Kyunghyuk Lee, Jaelim Lim†

Water Works Research Center, K-water Institute, Daejeon 34045, Korea

In this paper, the technique that determines efficient process combinations for the ultrapure water production was studied. The ultrapure water is one of the industrial water used in industrial activity and required in the advanced technology integrated industry. It is produced by combined process including filtration, ion exchange processes, the reverse osmosis (RO) process, degassing (DG) process and UV-oxidation (UVox) process. An ultrapure water production process consists of 15-20 different water treatment unit process. In this study, a pilot plant was built and operated to research the design parameters for the individual process. Through the pilot plant operation, 19 effective combinations were optimized among various processes. And then, 11 of them satisfied the final quality of the ultrapure water. The stability and economic feasibility were evaluated about the final 11 process combinations.



## Effect of Pressure on Feed Solution at hollow Fiber FO Process

Bongchul Kim, Yun-chul Woo, Juneseok Choi<sup>†</sup>

Korea Institute of Civil Engineering and Building Technology (KICT), Korea

### 1. Introduction

Forward osmosis (FO) process has been attracting attention for its potential applications such as industrial wastewater treatment, wastewater reclamation and seawater desalination.<sup>1)</sup> Particularly, in terms of fouling reversibility and operating energy consumption, FO process is assumed to be more preferable to RO process. The objective of this study was to optimize operating condition of pilot scale hollow fibre FO process.

### 2. Methods

The concentration of the solution was measured in place of the electrical conductivity and used to determine the concentration change of the solution in the experiment. At this time, the measurement method was specified using a portable multimeter (ProfiLine Multi 3320, WTW). All pipes were made of polymer material. This experiment was carried out to investigate the effect of the factors on the semi-pilot scale.

### 3. Results and Discussion

The experimental results showed a smaller permeation flux than the Lab-scale test. However, the results showed similar trends as reported. Because the effective membrane area according to the inner diameter of the module is smaller than the increase of the flow rate of the inflow pump, the flow velocity in the actual hollow fibre membrane is increased more greatly. Also, there was little increase in module pressure with increasing flow (<0.1 bar), but salt disspreading was better.

### 4. Conclusions

- 1) Water permeability can be increased due to minor additional pressure in FO process.
- 2) Reverse salt diffusion is increased as water permeation increased
- 3) Applying additional pressure is more effect on reverse salt flux

### 5. References

Bongchul Kim, Sangyoup Lee, Seungkwan Hong, "A Novel Measurement and Analysis of Feed Solute and Reverse Draw Solute Fluxes in Forward Osmosis Membrane", *Desalination* 352 (2014) 128–135



# Long-term evaluation of element-scale plate-frame forward osmosis process

Sehyun Ban, Sung Ju IM, Am JANG †

Graduate School of Water Resources, Sungkyunkwan University, Korea

## 1. Introduction

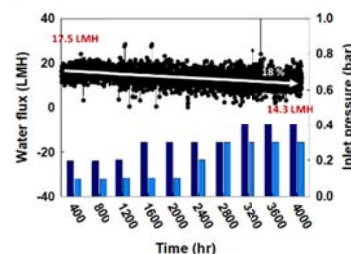
Forward osmosis (FO) has attracted growing attention in many potential applications in water industries. As there are several limitations to directly apply the lab-scale data to a real pilot plant design, reliability test must be conducted through long-term operation in real or application site for practical application of the FO process.

## 2. Methods



**Figure 1.** Element scale plate-frame FO (PFFO) system operated at real site

## 3. Results and Discussion



**Figure 2.** Performance of long term PFFO operation

Secondary wastewater effluents and synthetic seawater are used as FS and DS, respectively. One micron cartridge filter was applied to remove particulates. During six months of operation, the water flux was reduced by only about 18% and the inlet pressure increased by more than 2 times (Fig. 2).

## 4. Conclusions

A long-term operational evaluation of PFFO element is underway at real site. Compared to SWFO element, PFFO element showed relatively stable and high water flux. Therefore, PFFO is more appropriate in the wastewater treatment.

## 5. References

Minjae Song, Sung-Ju Im, Sanghyun Jeong and Am Jang, *Journal of Membrane Science*, 2018, 430, 15-53.

Sung-Ju Im, Sanghyun Jeong and Am Jang, *Chemical Engineering Journal*, 2018, 336, 141-151.

# The effect of TFC-PRO membrane performance parameters and optimization of operating conditions for spiral wound PRO modules

Yeonju Sim\*, Manjae Han, Jonghwa Lee<sup>†</sup>

Toray Chemical Korea Inc., Korea

## 1. Introduction

The RO/PRO hybrid process is considered as the most logical next step for future desalination. The PRO process aims to harness the osmotic energy difference of two aqueous solutions separated by a semipermeable membrane. By using the concentrated water (RO brine) discharged from existing RO plants, the PRO process can effectively exploit a greater salinity gradient to reduce the energy cost of processing concentrated water. However, in order to use RO brine as the draw solution, PRO membrane must have high water flux and enough mechanical strength to withstand the high operational pressure (about 7.0 wt% and 20 bar).

## 2. Methods

### Preparation of a Polysulfone(PSf) backing layer

The PRO support membrane was prepared by the phase inversion precipitation method. The most critical physico-chemical properties influencing the membrane structure in solvent exchange methods are the polymer precipitation rate and the good solvent/non-solvent exchange rate. Polysulfone(Solvay) was used as polymer in preparation of the membrane casting solution. N, N-dimethylformamide(DMF, anhydrous, 99.8%) and N-methyl-2-pyrrolidone(NMP, anhydrous, 99.8%) were used as the polymer solvents without further purification. Deionized water was used as a coagulant. To prepare polyamide PRO membranes, PSf was dissolved in DMF and NMP by stirring at 40°C and then stored in a desiccator for at least 24h prior to casting. The membrane substrate was cast from polymer solutions onto a nonwoven and porous fabric backing layer. The cast membranes were immediately immersed into a deionized water coagulation bath for several minutes to ensure complete precipitation. The membranes were then washed with DI water before interfacial polymerization was carried out.

## 3. Results and Discussion

This study investigates the development of a thin film composite PRO membrane and spiral wound module for high power density. Among the various membrane characteristics, water permeability (A, L/m<sup>2</sup>/hr/bar), salt permeability (B, L/m<sup>2</sup>/hr) and membrane structural parameter (S, mm) were the main focal points of this study. The PRO membrane made with the porous fabric layer showed 17.1 W/m<sup>2</sup> using 7.0 wt% NaCl as the draw solution with the operating pressure at 20 bar.

Finally, the performance test of an 8-inch spiral wound module made with the porous fabric PRO membrane was carried out under various operating conditions (i.e. hydraulic pressure, flow rate, temperature). As the flow rate and temperature increased under the same hydraulic pressure, the PRO performance increased due to the minimization of ICP/ECP on the membrane surface. On the other hand, it was confirmed that the PRO performance decreased along with increasing hydraulic pressure due to the flow pressure on the spiral wound module. For a high performance PRO system, in order to optimize the operating conditions, it is highly recommended that the flow pressure be minimized while the flow rate is maintained at a high level.

#### 4. Conclusions

The PRO membrane was fabricated by interfacial polymerization of polyamide on a hydrophilic support layer that was cast on top of nonwoven and porous fabrics respectively. Based on analysis of PRO membrane characteristics A, B, and S values, PRO membrane performance was affected mainly by the reduction of S value (Structural Parameter). Porous fabric backing was most effective in improving overall power density of the PRO membrane. As the flow rate and temperature increased under the same hydraulic pressure, the PRO performance increased due to the minimization of ICP/ECP on the membrane surface.

#### 5. References

- [1] Yip N.Y., Vermaas D.A., Nijmeijer K. and Elimelech M. (2014), "Thermodynamic energy efficiency and power density analysis of reverse electrodialysis power generation with natural salinity gradients", *Environ. Sci. Technol.*, 48, 4925-4936.
- [2] Loeb S. (2002), "Large-scale power production by pressure-retarded osmosis using river water and sea water passing through spiral modules", *Desalination*, 143, 115-122.
- [3] Yip N.Y. and Elimelech M. (2012), "Thermodynamic and energy efficiency analysis of power generation from natural salinity gradients by pressure retarded osmosis", *Environ. Sci. Technol.*, 46, 5230-5239.
- [4] Lee K.L., Baker R.W. and Lonsdale H.K. (1981), "Membranes for power generation by pressure-retarded osmosis", *J. Membr. Sci.*, 8, 141-171.
- [5] Helfer F., Lemckert C. and Anissimov Y.G. (2014), "Osmotic power with pressure retarded osmosis: Theory, performance and trends review", *J. Membr. Sci.*, 453, 337-358.
- [6] Yip N.Y., Tiraferri A., Phillip W.A., Schiffman J.D., Hoover L.A., Kim Y.C. and Elimelech M. (2011), "Thin-film composite pressure retarded osmosis membranes for sustainable power generation from salinity gradients", *Environ. Sci. Technol.*, 45, 4360-4369.
- [7] Khaled Touati, Christopher Hänel, Fernando Tadeo, Thomas Schiestel (2015), "Effect of the feed and draw solution temperatures on PRO performance: Theoretical and experimental study", *Desalination*, 365, 182-195.

## Investigation of fouling and cleaning behaviour in a pilot-scale forward osmosis process

Duksoo Janga, Seungju Choia, Dongkyu Parka, Yunho Kima, Seoktae Kanga\*

Department of Civil and Environmental Engineering, Korea Advanced Institute of Science and Technology (KAIST), Korea

In this study, we systematically investigated a pilot-scale forward osmosis (FO) membrane fouling and cleaning behaviour using a spiral-wound membrane module under different (1 and 5  $\mu\text{m}$  cartridge filter) pre-treatment. Results showed that the 1  $\mu\text{m}$  pre-treated feed water featured higher water flux than the 5  $\mu\text{m}$  pre-filtered feed water. After the 1  $\mu\text{m}$  pre-treatment, the flux maintained constant even after 30 days operation. This was attributed to the efficient removal of colloidal particles in the feed water by applying 1  $\mu\text{m}$  cartridge filter. In case of 5  $\mu\text{m}$  pre-treatment, 30% of flux decline was observed after 7 days operation but fouling in FO is almost fully reversible with more than 95 % recovery of permeate water flux possible after a physical cleaning procedure without any chemical cleaning reagents. After 30 days operation, however, the flux did not fully recover by physical cleaning then the flux could be recovered to the initial level by using commercial reverse osmosis (RO) cleaning agents. Foulant analysis indicated that major components of the metallic elements were iron and sodium. The dissolved organic matter was mainly composed of aromatic protein (hydrophobic). The most interesting thing is that fouling deposition of spiral wound FO membrane module occurs in the feed inlet channel rather than on the membrane surface. This phenomenon caused by increase of feed inlet pressure in the module. This work demonstrates the optimized pre-treatment and cleaning procedure for FO membrane fouling control and also limitations in spiral wound membrane module that need further improvement in future.

## Direct observation of oil droplets attached on polyamide membrane surface

Pattarasiri Fagkaew, Seoktae Kang†

Department of Civil and Environmental Engineering, Korea Advanced Institute of Science and Technology (KAIST), Korea

### 1. Introduction

Oil/water mixture is inevitable by-products of many industrial processes including oil and gas, food and beverage, textile and metal and machining industries [1 – 3]. Due to their small footprint and high capacity to remove even small oil droplets to meet the discharge limit, membrane-based technologies have been widely used to separate oil compounds. Nevertheless, the deposition and coverage of membrane surface by oil droplets cause severe flux decline and change in solute rejection, resulting in the decrease in membrane performance. Polyamide (PA) membrane is commonly used membrane construction materials because of their lower pressure requirements and more flexible operating conditions. Thus, in this study, the direct observation technique to investigate the attachment of oil droplets on PA membrane surface was proposed.

### 2. Methods

Model oil-in-water (O/W) solution was prepared by mixing 1000 mg/L of hexadecane (99%; Sigma-Aldrich, USA) (fluorescent dyed with Nile red (Sigma-Aldrich, USA) in 0.1 mM of triton X-100 (Sigma-Aldrich, USA), used as surfactant agent, at 1500 rpm for 10 min. The characteristics of oil droplets in prepared solutions (i.e., size and number of oil droplets) were examined by Neubauer improved cell counting chamber (Marienfeld, Germany) and microscope. The attachment behaviour of oil droplets on polyamide membrane (PA) surface (CSM, South Korea) was observed in FO unit cell with crossflow velocity of 2.5 cm/s at different permeation velocity.

### 3. Results and Discussion

The characteristics of oil droplets of prepared O/W solution, including size and number of oil droplets, were firstly measured using Neubauer improved cell counting chamber and microscope. The number of oil droplets was 253,750 droplets/mL with the average oil droplet size of  $9.50 \pm 3.84 \mu\text{m}$ . From the observation of oil droplets, fluorescent dyed with Nile red, attached on PA membrane surface in FO unit cell through microscope, it was found that the increase in permeate velocity provided more attachment of oil droplets on PA membrane surface due to the increase in permeate force, resulting in the stronger net force approach to PA membrane surface. In addition, the higher permeate velocity caused cluster form of oil faster than lower permeate velocity, resulting in more severe flux decline at higher permeate velocity.

### 4. Conclusions

Using the fluorescent dye and microscope to observe the attachment of oil droplets on PA membrane surface was worked. In addition, the permeate velocity was one of significant factors affected to the attachment of oil droplets on membrane surface. The increase in permeate velocity provided more attachment of oil droplets on PA membrane surface, resulting in more severe flux decline.

### 5. References

- [1] Ahmed, A.F., Ahmad, J., Basma, Y., Ramzi, T., 2007. *J. Hazard. Mater.* 141, 557–564.

- [2] Machi'n-Ramírez, C., Okohc, A.I., Morales, D., Mayolo-Deloisa, K., Quintero, R., Trejo-Hernández, M.R., 2008. *Chemosphere* 70, 737–744.
- [3] Chen, G.H., He, G.H., 2003. *Sep. Purif. Technol.* 31, 83–89.



# Prediction of long-term performance in a reverse osmosis desalination plant

Kwanghee Shin<sup>a</sup>, Yongjun Choi<sup>b</sup>, Younggeun Lee<sup>a</sup>, Hyungkeun Roh<sup>a</sup>, Sangho Lee<sup>b†</sup>

<sup>a</sup>Corporate R&D Institute in Doosan Heavy Industries & Construction, Korea

<sup>b</sup>School of Civil and Environmental Engineering, Kookmin University, Korea

## 1. Introduction

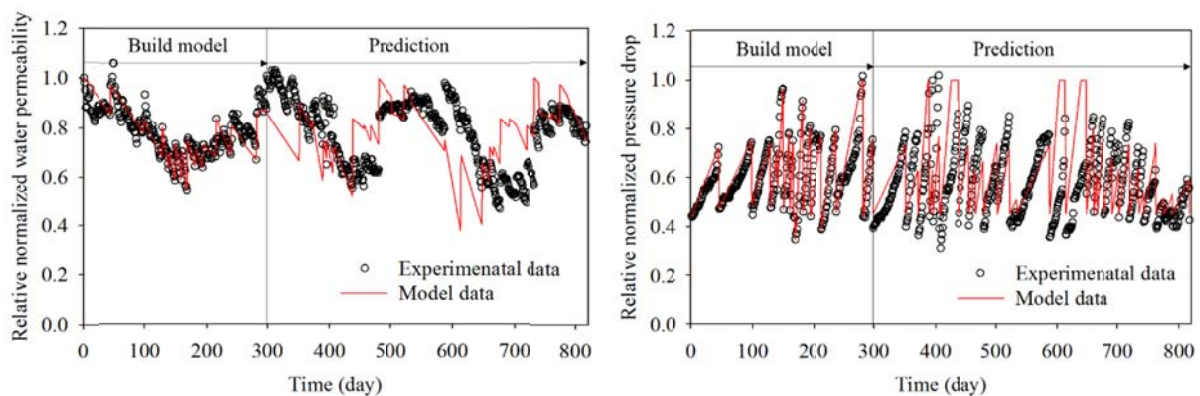
Reverse osmosis (RO) is currently the leading desalination technology. However, an inevitable fouling of the RO system is still the one major hindrance to a reliable operation [1]. The mechanism of membrane fouling is complex, which is not well understood in full-scale plants [2]. Although many researches for developing fouling models have been done, they were mostly carried out using lab/pilot scale systems, which may not reflect fouling behaviours well in full-scale systems. Accordingly, this study focused on the fouling prediction of a full-scale RO plant using an analytical model over long time periods.

## 2. Methods

The targeted RO plant in this study was designed to produce 30 MIGD of product water with 40% recovery, which has been operated since October 2012. The performance of RO plant is largely influenced by feed water conditions such as TDS and temperature, and so on. In order to exclude the effect of seasonal variation from the status of RO membrane for monitoring fouling occurrence itself, the water permeability and pressure drop were normalized with design value in this study. The rate of change and recovery after cleaning in place (CIP) of water permeability and pressure drop were calculated on the basis of CIP intervals using the first 1-year data to build an analytical fouling model, then it was applied to predict fouling at the rest of operating time in the dataset

## 3. Results and Discussion

Fig. 1 shows the variations in the water permeability and pressure drop in the whole operating period. The operating data of the RO plant were collected over a period of 3 years, have been utilized to build the analytical model for predicting fouling in RO plant. The water permeability and pressure drop over long time periods showed seasonal and year-to-year variation. As shown in Fig. 1, although the predicted values from the model has some mismatch points because of irregular recovery rate after CIP, this model are generally well matched with the experimental data.



a) water permeability

b) pressure drop

**Figure 1.** Comparison of the model fit with the experimental data

#### **4. Conclusions**

The analytical fouling model developed in the study are well developed based on the operating data of actual plant. As a result, although long-term operation data (order of years) represented seasonal and year-to-year variability after data normalization, the predicted values are well followed with the actual data. The analytical fouling model developed in the study can be used for a long-term fouling prediction of full-scale RO plant and cost analysis of chemical and membrane replacement.

#### **5. References**

[1] G. Kang, Y. Cao, Development of antifouling reverse osmosis membranes for water treatment: a review, *Water Res.* 46 (2012) 584-600.

[2] E.A. Roehl Jr., D. A. Ladner, R. C. Daamen, J. B. Cook, J. Safarik, D. W. Phipps Jr., P. Xieb, Modeling fouling in a large RO system with artificial neural networks, *J. Membr. Sci.* 552 (2018) 95–106





# Comparison of Vacuum Membrane Distillation and Reverse Osmosis in Water Reuse Application

Younghoon Ko, Yongjun Choi, Hyeonrak Cho, Yongsun Jang, Jihyeok Choi, Sangho Lee†

Civil and Environmental Engineering, Kookmin University, Seoul, Republic of Korea

## 1. Introduction

The main purpose of this study was to investigate the fouling mechanism by treating same wastewater in vacuum membrane distillation (VMD) and reverse osmosis (RO) processes.

## 2. Methods

Experiments were conducted using after primary and secondary treated sewage wastewater as feed water. Bench-scale systems for VMD and RO were used, respectively. The changes in flux with time or volume concentration factor (VCF) were measured and in-depth analysis was carried out.

## 3. Results and Discussion

When both processes were set equal to the initial flux, flux drop was similar in same feed water. But the cake layer of VMD was thicker than the RO. Flux losses due to fouling in the wastewater seemed to be similar reversibility in both processes, and physical cleansing was limited to recovering flux losses. It appears that the fouling mechanisms are also different in two processes.

## 4. Conclusions

VMD and RO have pros and cons in the case of wastewater reclamation and thus further analysis will be needed by considering not only the performance but also the operational cost and energy consumption.

## 5. References

J.H. Kim, M.K. Park, H.K. Shon, J.H. Kim, Performance analysis of reverse osmosis, membrane distillation, and pressure-retarded osmosis hybrid processes, *Desalination* 380 (2016) 85–92.