NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE

Singapore Membrane Technology Centre
Nanyang Environment and Water Research Institute

SMTC

"Our membrane technology provides purer water and cleaner environments"

Singapore Membrane Technology Centre (SMTC)

About Us

The Singapore Membrane Technology Centre (SMTC) under the Nanyang Environment & Water Research Institute (NEWRI), at Nanyang Technological University (NTU) of Singapore, was established in January 2008 to do fundamental and applied research in membrane technology. In particular, it has a mission to be a world-class research centre in membranes for the environment, water, energy and cleaner production. This is achieved through combining multidisciplinary talents at NTU as well as working closely with government institutions, other universities and industry partners to bring the outcomes of the research activities to larger scale through collaborative projects.

Mission

The SMTC's objectives are:

- Research & Development: research with links to industry and international community;
- Education & Training: to produce PhDs and Researchers in membranes technology;
- Industry & Application: to act as incubator for novel membrane technology.

People

The SMTC family members comprise of:

- Director: Prof Wang Rong
- Deputy Director: Asst Prof Chong Tzyy Haur
- Visiting Professor: Prof AG Fane
- 40 Research Fellows, Research Associates, Research Assistants
- 40 PhD Students
- Visiting Professors/Researchers
- 30 NTU Faculty members from 7 Schools of NTU

Academics, Research Fellows and PhD Students of SMTC

Research Facilities

SMTC has a dedicated laboratory of 1000 m^2, equipped with state-of-the-art research facilities and supported by advanced analytical instruments to enable high quality membrane research, including: field emission scanning electron microscopy (FESEM), atomic force microscopy (AFM), Fourier transform infrared (FTIR) microscopy, surface potential analyzer, porometer, liquid chromatography-organic carbon detector (LC-OCD), electrical impedance spectroscopy (EIS), ultrasonic time-domain reflectometry (UTDR), optical coherence tomography (OCT), etc.

Analytical room

Industrial project area

Membrane fabrication facilities for both hollow fiber and flat sheet membranes.

Pressure Retarded Osmosis (PRO) system for osmotic power harvesting from seawater/RO brine and NEWater brine.

Pilot facilities located at Tuas R&D site with access to seawater.

Research

The SMTC's research activities are mainly focused on applied membrane technology for environment, water, energy and cleaner production within the following thematic areas:

- Water Production
- Water Reclamation
- Wastewater Membrane Bioreactors (MBR)
- Energy Issues
- Special Needs
- Sensors and Monitors

The fundamental and applied research topics including:

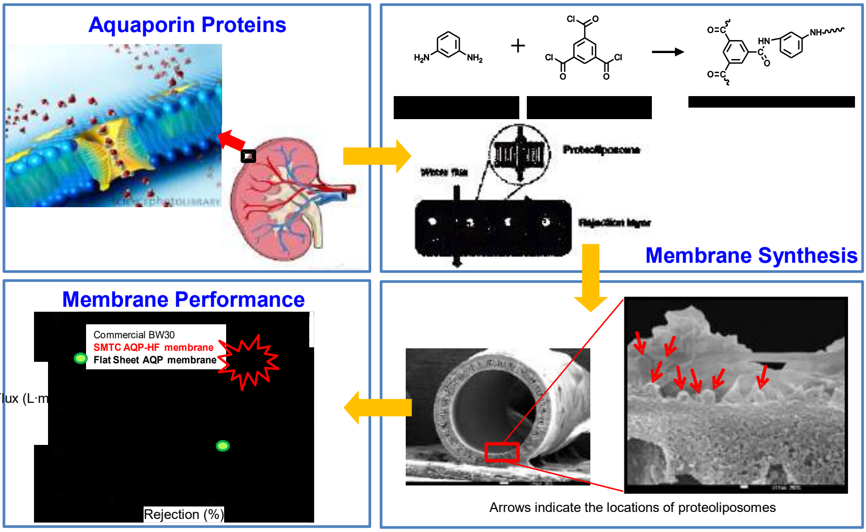
- ***Novel Membranes*** – based on advanced material science and nanomaterials including biomimetic, forward osmosis, pressure retarded osmosis, low pressure nanofiltration, membrane distillation membranes;
- ***Enhanced Module & System Design*** – improved performance through hydrodynamic modeling, module design optimization via 3D printing technology, multi-stage approach;
- ***Fouling Control*** – novel control and cleaning strategies towards lower chemical usage, antifouling surfaces;
- ***Characterization*** – non-invasive and online biofilm and scale sensors for smart membrane system;
- ***Energy from Brines*** – harvesting of chemical potential energy using pressure retarded osmosis (PRO) technology;
- ***Novel Membrane Bioreactor (MBR) and Energy*** – forward osmosis MBR, membrane distillation MBR, anaerobic MBR, extractive MBR, fluidized bed MBR;
- ***CO_2 Separation*** – biogas upgrade and GHG capture with membrane contactor;
- ***Cleaner Production*** – membranes for bio-pharmaceutical, food, petrochemical, electronic industries.

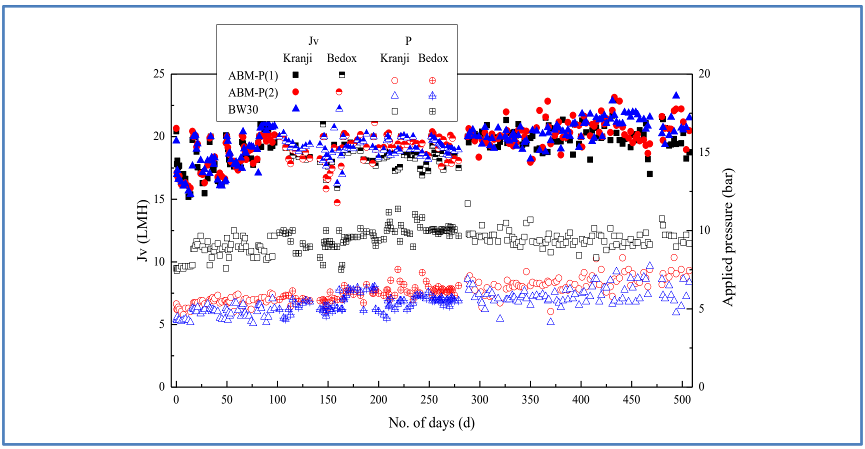
The funding support from National Research Foundation (NRF) and Economic Development Board (EDB) of Singapore are greatly acknowledged.

Project Highlights

(1) Aquaporin Based Biomimetic Membrane

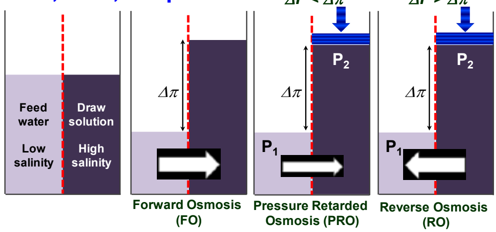
Nature has developed a most efficient way for water transport across an osmotic pressure gradient via aquaporin (AQP) proteins. The aquaporins or water channel proteins, typically bound in phospholipid cellular membranes, are highly permeable to water but highly retentive to solutes. This makes water delivery possible across a cell wall at sufficiently low energy. An artificial membrane can be developed to mimic the natural cellular membranes by incorporating the aquaporins into the thin film composite structure. The aquaporin biomimetic membrane can be applied for water reuse and seawater desalination at low cost due to reduction in energy requirement.

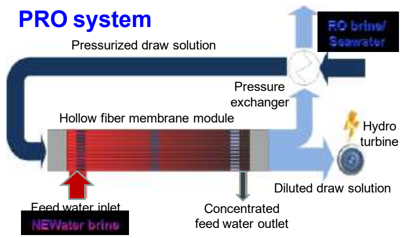


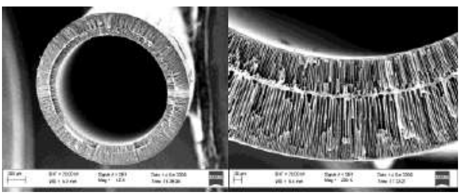


(2) Forward Osmosis (FO) and Pressure Retarded Osmosis (PRO) Membranes

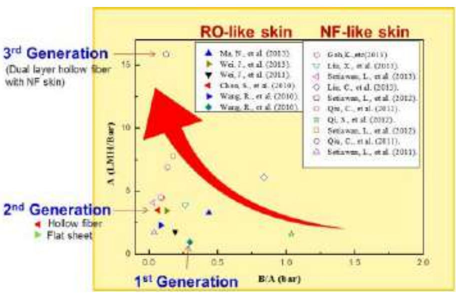
Forward osmosis (FO) is a natural phenomenon where the water molecules move across a semipermeable membrane from a less concentrated solution to a more concentrated solution. In a PRO process, water flows across the membrane from a feed solution to a pressurized draw solution, where the volume expansion of pressurized solution can be utilized to drive a hydroturbine for power generation. The PRO technology can be used to harvest osmotic power of seawater or RO desalination brine using NEWater (i.e. wastewater reclamation) brine. Both FO and PRO membranes require selective layer with high flux (i.e. high A value) and high solute rejection (i.e. low B value) and the support layer with low thickness, high porosity and low tortuosity (i.e. low S parameter) to minimize the internal concentration polarization. In PRO case, the membrane needs to withstand the high operating pressure.





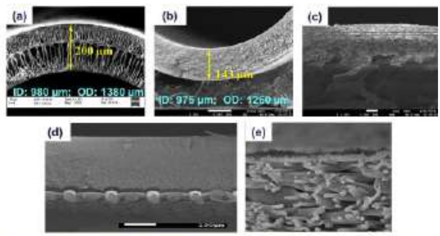


First Thin Film Composite HF-FO



FO Membrane Evolution at SMTC

Novel PRO Membranes Fabrication



Cross-section morphology of PRO composite membranes: (a) PES hollow fiber; (b) PEI hollow fiber; (c) PEI flat sheet; (d) PSF flat sheet; (e) PEI nanofiber

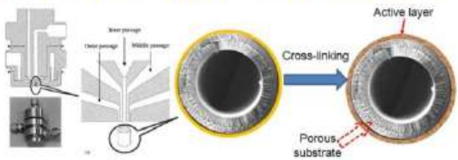
Overall comparison of PRO composite hollow fiber and flat sheet membranes

Salty water	Fresh water	Operation pressure ΔP (bar)	Water flux J_v (LMH)	Power density W (W/m²)	Specific salt flux J_s/J_w (g/L)	Membrane	Reference
1.0M NaCl	DI water	15.1	16.4	6.9	-	TFC-PEI HF small od/id	Current work
1.0M NaCl	DI water	12.7	12.0	4.25	-	Nanoparticles incorporated PEI HF	Current work
1.0M NaCl	DI water	12.7	10.7	3.79	-		
1.0M NaCl[b]	1 mM NaCl	15.1	49.9	**20.9**	1.7	TFC-PEI HF	JMS 448-44
	10 mM NaCl	15.1	44.7	18.7	1.7		
1.0M NaCl[b]	10 mM NaCl	8.4	47.2	11.0	-	TFC-PES HF	JMS 389-25
1.0 M NaCl	DI water	20.0	-	24.3	-	TFC-PES HF	Zhang, Chung 2013
1.0 M NaCl	DI water	21.0	-	12.0	-	TFC-P84 HF	Li and Chung 2014
1.0 M NaCl	DI water	15.0	-	16.5	-	TFC-Matrimid HF	Han and Chung 2014
1.0M NaCl[b]	10 mM NaCl	17.2	28.11	**13.5**	0.05	TFC-PEI FS	Current work
1.0M NaCl[b]	10 mM NaCl	18.5	13.4	6.9	0.152	TFC-PSF FS	Current work
1.0M NaCl[b]	DI water	15	-	12	-	TFC flat sheet	JMS 440-108
3.5% NaCl	DI water	6	-	2.84	-	TFC-PAI FS	JMS 434-204
1.0M NaCl[b]	10mM NaCl	15.0[a]	8.9[a]	3.7[a]	0.1[a]	HTI CTA-W	JMS 401-262
1.06M NaCl[b]	0.9 mM NaCl	15.2	36	15.2	>0.1[a]	TFC nanofiber flat sheet	EES 6-1199
	80 mM NaCl	15.2	27	11.4			

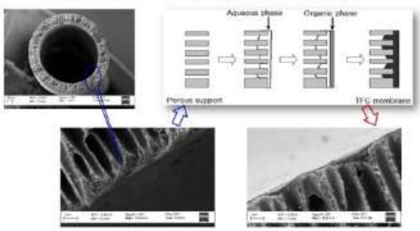
(3) Low Pressure Nanofiltration (NF) Membrane

Nanofiltration (NF) membrane technology, based on both separation mechanisms of steric-hindrance and electrostatic (Donnan exclusion) effects, is an attractive option for water softening to remove divalent cations (in particular, Ca^{2+} and Mg^{2+}), groundwater treatment, cooling tower water recycling and seawater pretreatment. SMTC has developed novel low pressure hollow fiber NF membranes with 3 different approaches that can be easily scaled-up. The membranes have high flux and high rejection properties that only requires operating pressure of 2 bars, compared to commercial membranes that typically require 5 – 10 bars, thus reducing the energy consumption.

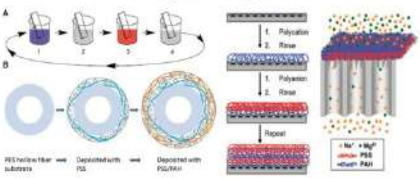
Approach 1: Dual-Layer Hollow Fiber Membranes



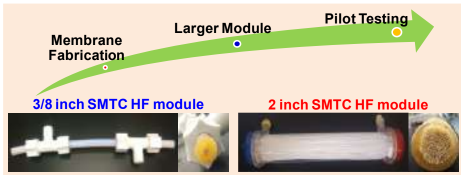
Approach 2: Thin Film Composite membrane by in-situ interfacial polymerization (IP)



Approach 3: Layer-by-Layer (LBL) Deposition of Polyelectrolytes



SMTC HF-NF Membrane Development



Comparison of 3 Approaches

Approach	Dual-Layer	IP	LBL
Water permeability (L/m² h bar)	15.7	11.4	10
Mg^{2+} rejection (%)	95.4	95.6	91.1
Ca^{2+} rejection (%)	93.8	91	88.8
Na^{+} rejection (%)	12.5	13.4	15.2

Feed: Hard water with 3000 ppm TDS;
Operating pressure: 2 bar

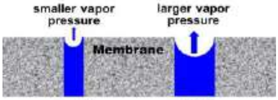
Membranes	Permeability (l/m² h bar)	Ionic rejection (%)			Pressure (bar)	Brackish water TDS (ppm)
		Mg^{2+}	Ca^{2+}	Na^{+}		
SMTC hollow fiber NF	**10**	**91**	**89**	**15**	**2**	**3000**
Commercial membrane A	4.1	84	97	85	10	2300
Commercial membrane B	9.2	45	40	14	10	2300

Comparison with Commercial NF Membranes

(4) Sensors and Instruments

Evapoporometer – for determination of pore size, pore size distribution and porosity of clean and fouled membrane

Based on Kelvin equation by evaporating a wetting volatile liquid from a membrane under conditions for which the gas at the membrane, but surface is saturated with respect to the liquid in the pore size that is draining supersaturated with respect to the liquid in all the smaller pores; hence, evaporation will progress from the largest to the smallest pores



$$\frac{p'_A}{p^0_A} = \frac{x_A}{x^0_A} = e^{\frac{4\gamma_A V_A}{dRT}}$$

Measured quantities: W^0_A, W_A

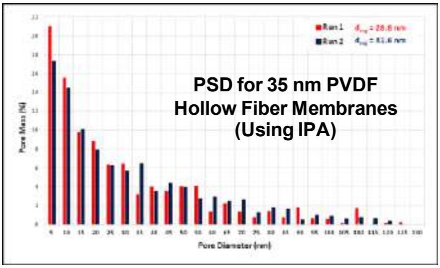
Parameters & properties: γ_A, c, V_A, x^0_{A0}, d_c

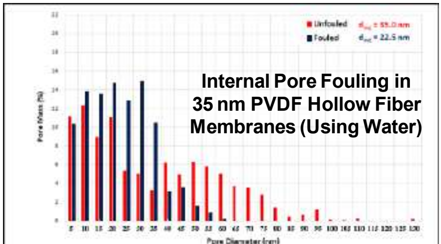
Derived quantities: k_x, x_{A0}, d

$$x^0_{A0} = 1 - e^{-\frac{4W^0_A}{\pi d_c^2 k_x}}$$ Mass transfer coefficient from evaporation rate of free-standing liquid

$$x_{A0} = 1 - e^{-\frac{4W_A}{\pi d_c^2 k_x}}$$ Mole fraction at membrane surface from evaporation rate during pore draining

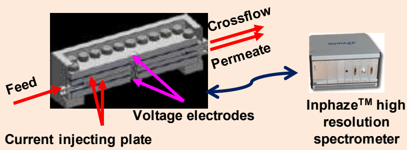
$$d = -\frac{4\gamma_A V_A}{RT \ln \frac{x_{A0}}{x^0_{A0}}}$$ Pore diameter from mole fraction at membrane surface using the Kelvin equation



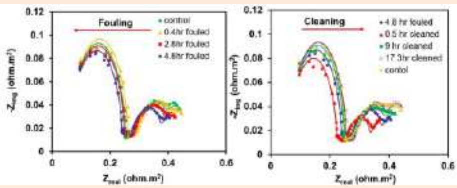


1 g/l of bentonite and 20 mg/l of humic acid at a flux of 70 l/m²h

Electrical Impedance Spectroscopy (EIS)



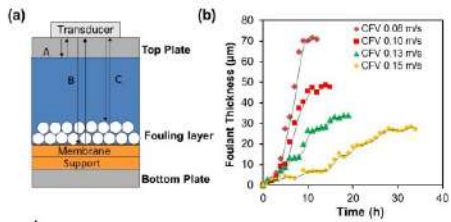
Canary cell fitted with electrodes and EIS

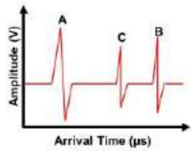


Fouling and cleaning process monitored through EIS

- ❑ Canary cell equipped with electrodes allows electrical properties of membrane and fouling layer to be monitored continuously via EIS
- ❑ Detects occurrence of fouling as soon as a thin foulant layer deposited or adsorbed on membrane surface
- ❑ Signal preempts TMP rises
- ❑ Able to monitor cleaning/cake removal

Ultrasonic Time Domain Reflectometry (UTDR)





(a) UTDR measurements in a flat sheet module and corresponding time domain response

(b) Foulant layer thickness determined via UTDR as a function of time at various crossflow velocities

- ❑ Uses ultrasonic wave to give information on distance (i.e. thickness) and acoustic impedance (i.e. density and velocity) of the media through which it travels
- ❑ Detects cake growth and its signal amplitude detects cake densification over time
- ❑ Detects biofilm growth using an acoustic enhancer (Patent: WO2013066268)

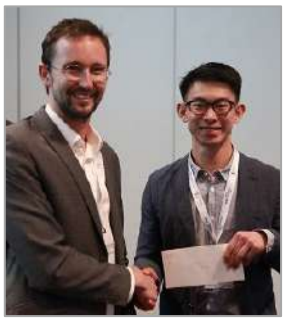
AWARDS

Prof. Wang Rong and Prof. Tony Fane
awarded the Alternative Water Resources Prize
7th Award of the Prince Sultan Bin Abdulaziz International Prize for Water (PSIPW), 2016

SMTC Project Team
awarded the Minister for National Development (MND) R&D Award, 2013

Ms. Zan Ong
awarded the Efficiency Medal, National Day Award Investiture for Education Service, 2016

Dr. Shi Lei
awarded the Prosper.Net-Scopus Young Scientist Award in Sustainable Development, 2013



Mr. Zhao Jie
awarded the International Membrane Science & Technology Conference (IMSTEC) Travel Award, 2016

AWARDS

Mr. Victor Sim (left) and
Dr. She Qianhong (right)
awarded the
Green Talent Award by
German Federal Ministry of
Education and Research (BMBF),
2013 & 2016

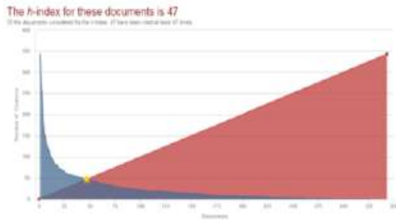
PUBLICATIONS

Scopus June 2016:

Total Publications: 327

Total Citations: 7508

***h*-index: 47**



Date range: 2010 to 2016

Exclude self citations of all authors

Exclude Citations from books

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Update

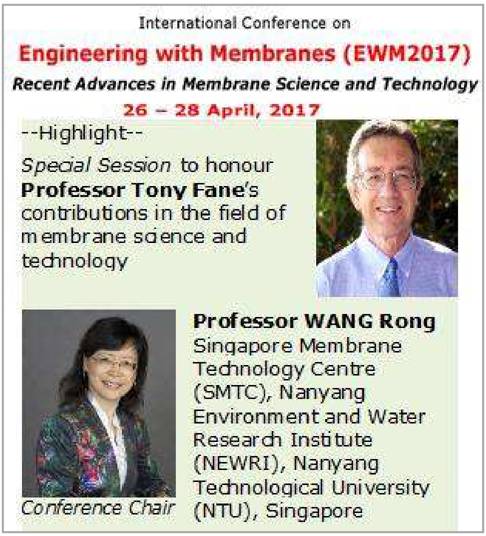
Documents

Citations

Sort on: Date (newest) Citation count (descending) ...

Document	Year	<2010	2010	2011	2012	2013	2014	2015	2016	Subtotal	>2016	Total
	Total	4	45	264	845	1169	1618	2114	1649	7504	0	7508
1 Recent developments in forward osmosis: Opportunities and ch...	2012				13	72	91	102	65	343		343
2 Coupled effects of internal concentration polarization and f...	2010		2	31	42	45	43	60	37	260		260
3 Characterization of novel forward osmosis hollow fiber membr...	2010		5	30	44	51	39	50	32	251		251
4 Synthesis and characterization of flat-sheet thin film compo...	2011			6	27	31	38	53	35	190		190
5 Colloidal interactions and fouling of NF and RO membranes: A...	2011			6	20	26	44	37	22	155		155
6 Thin-film composite hollow fiber membranes for pressure reta...	2012				14	34	33	36	32	149		149
7 Effect of draw solution concentration and operating conditio...	2010		5	18	18	14	28	28	24	135		135
8 Characteristics and potential applications of a novel forwar...	2010		1	17	25	25	22	21	15	126		126
9 The role of physical and chemical parameters on forward osmo...	2011			9	23	27	22	23	14	118		118
10 Osmotic power production from salinity gradient resource by ...	2012				1	26	27	30	31	115		115
11 C-N-S tridoped TiO<inf>2</inf> for photocatalytic degradatio...	2011				15	31	26	16	14	102		102
12 Fabrication of novel poly(amide-imide) forward osmosis hollo...	2011			6	19	26	12	22	15	100		100
13 Synthesis and characterization of novel forward osmosis memb...	2011			3	15	30	13	20	13	94		94
14 Direct microscopic observation of forward osmosis membrane f...	2010			13	13	17	15	17	16	91		91
15 Performance improvement of PVDF hollow fiber-based membrane ...	2011			4	13	16	27	18	6	84		84
16 Modeling salt accumulation in osmotic membrane bioreactors: ...	2011			11	22	12	14	15	8	82		82
17 Current status and development of membranes for CO2/CH4 sepa...	2013					4	26	38	14	82		82
18 Impacts of salinity on the performance of high retention mem...	2010		2	10	14	14	14	14	13	81		81
19 Synthesis of high flux forward osmosis membranes by chemical...	2011				14	23	11	22	5	75		75

KEY CONFERENCES ORGANISED / INVITED TO HOST



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Professor WANG Rong, Centre Director

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SMTC welcomes collaboration with other research institutions and industry on projects related to membrane technology for environment, water, energy and cleaner production. For more information on collaborating with the SMTC, please contact: **SMTC Director: Prof WANG Rong, rwang@ntu.edu.sg**