DESALTECH 2015

Friday, August 28, 2015 (Day One)

Emerging Processes and Municipal Applications

ORAL PRESENTATION ABSTRACTS

9:30 AM – 10:00 AM	**Plenary Presentation: Overview and Roadmap for Membrane Process Development in Desalination.** Anthony Fane, Ph.D., Singapore Membrane Technology Center (Singapore)	
10:00 AM – 10:30 AM	**Plenary Presentation: Energetics of Desalination**. Menachem Elimelech, Ph.D., Yale University (USA)	
	Track A *Forward Osmosis (FO)*	Track B *Membrane Distillation (MD)*
11:00 AM – 11:30 AM	**A101. Keynote Presentation: Forward Osmosis Principles, Trends, and Applications.** Tzahi Cath, Ph.D., Colorado School of Mines (USA)	**B101. Keynote Presentation: Opportunities for Membrane Distillation.** Stephen Gray, Ph.D., Victoria University (Australia)
11:30 AM – 11:50 AM	**A102. FO Membrane Design: Innovative Approaches to Rethinking Thin Film Composite Membranes.** Jeffrey McCutcheon, Ph.D., University of Connecticut (USA)	**B102. Mass and Heat Transfer Model for Vacuum Membrane Distillation in a Hollow Fiber Module.** Andrea Corral, Ph.D., University of Arizona (USA)
11:50 AM – 12:10 PM	**A103. Polymer-Based Draw Solutions for Osmotically Driven Membrane Processes: Opportunities and Challenges.** Mamadou Diallo, Ph.D., Korean Advanced Institute of Science and Technology (Korea) and California Institute of Technology (USA)	**B103. MVC MD Hybrids for Reduced Specific Energy Consumption.** Jaichander Swaminathan, Massachusetts Institute of Technology (USA)
12:10 PM – 12:30 PM	**A104. Pressure Assisted Fertiliser Drawn Forward Osmosis Desalination for Fertigation.** Ho Kyong (HK) Shon, Ph.D., University of Technology, Sydney (Australia)	**B104. Sustainable Operation of Vacuum Membrane Distillation for Mineral Recovery from Hypersaline RO Concentration.** Saravanamuthu Vigneswaran, Ph.D., University of Technology, Sydney (Australia)
	Track A *Salinity Gradient Energy: Pressure Retarded Osmosis (PRO)*	Track B *Membrane Distillation (MD)*
1:30 PM – 2:00 PM	**A201. Keynote Presentation: PRO: Should It Stay or Should It Go?** Amy Childress, Ph.D., University of Southern California (USA)	**B201. Keynote Presentation: Comparative Assessment of Membrane Distillation Configurations and Modules.** Noreddine Ghaffour, Ph.D., King Abdullah University of Science and Technology (Saudi Arabia)
2:00 PM – 2:20 PM	**A202. Gross vs. Net Energy Output: A Rational Framework for Assessing the Viability of Pressure Retarded Osmosis.** Zhangxin Wang, Vanderbilt University (USA)	**B202. Simplified Thermodynamic Analysis on Direct Contact Membrane Distillation.** Shihong Lin, Ph.D., Vanderbilt University (USA)
	A203. Analysis of Pressure Retarded Osmosis Under Varying Draw Pressure by a Novel	**B203. Solar Membrane Distillation for Off-Grid, Decentralized Water**

2:20 PM – 2:40 PM	**Method.** Seungkwan (SK) Hong, Ph.D., Korea University (Korea)	**Purification.** Wendell Ela, Ph.D., National Centre of Excellence in Desalination Australia (Australia)
2:40 PM – 3:00 PM	**A204. Fouling Characterization of Forward Osmosis Biomimetic Aquaporin Membranes Used for Water Recovery from Municipal Wastewater.** Agata Zarebska, Ph.D., Technical University of Denmark (Denmark)	**B204. Solar Membrane Distillation Desalination Research.** Mitchell Haws, U.S. Bureau of Reclamation (USA)
	Track A *Salinity Gradient Energy:* *Reverse Electrodialysis (RED)*	Track B *Other Emerging Technologies*
3:30 PM – 4:00 PM	**A301. Keynote Presentation: Overview of European and International Projects for upscaling of Reversed Electrodialysis and Pressure Retarded Osmosis Applications in Relation to Desalination and Waste Water Treatment.** Frank Neumann, Ph.D., Institute for Infrastructure, Environment and Innovation (Belgium)	**B301. Keynote Presentation: Biomimetic Forward Osmosis and Pressure Retarded Osmosis Membranes.** Rong Wang, Ph.D., Singapore Membrane Technology Centre (Singapore)
4:00 PM – 4:20 PM	**A302. Techno-Economic Assessment of a Novel Osmotic Heat Engine for Energy Recovery from Low-Grade Heat.** Tzahi Cath, Ph.D., Colorado School of Mines (USA)	**B302. Forward Osmosis Under Pressure: Performances and Challenges of Pressure Assisted Osmosis (PAO).** Pierre Le-Clech, Ph.D., University of New South Wales (Australia)
4:20 PM – 4:40 PM	**A303. Masdar's Renewable Energy Water Desalination Program.** Mohammad El Ramahi, Abu Dhabi Future Energy Company (UAE)	**B303. Performance Enhancement of Capacitive Deionization System by Modified 3D SWCNT/RVC Electrodes Using Microwave Irradiated Graphene Oxide.** Mohammed Almoiqli, Ph.D., King Abdulaziz City of Science and Technology (Saudi Arabia)
4:40 PM – 5:00 PM	**A304. Harvesting Renewable Energy from Waste of Reverse Osmosis Seawater Desalination Using Salinity Gradient Based Design of Capacitive System.** Haizhou Liu, Ph.D., University of California, Riverside (USA)	**B304. Energy Efficiency Modelling for Capacitive Deionization and Membrane Capacitive Deionization** Xia Shang, University of Illinois at Urbana-Champaign (USA)

9:30 AM – 10:30 AM

PLENARY SESSION

Moderated by **Jeff Mosher**, Executive Director, National Water Research Institue (NWRI)

Overview and Roadmap for Membrane Process Development in Desalination

Presented by Anthony Fane, Ph.D., Director Mentor, Singapore Membrane Technology Center (Singapore)

The 21st Century imperatives of water scarcity and energy restraint have brought an added urgency to developments in membrane desalination. This presentation provides an overview of the current scenario and then discusses a possible road map for future technology development. The current scenario has a steady increase of 10 to 15% per annum for membranes in the water domain, dominated by RO for seawater desalination and water reclamation. The trends include larger plants and larger modules, pretreatment by low pressure membranes, some revival in desalting by ED, and intense global R&D in novel membranes and potentially useful processes such as FO, PRO, RED and MD. These processes promise to complement RO, for example as feed pretreatment hybrids and brine concentrate handling. Developments in MBRs are also relevant in the context of water reclamation. Technology "road mapping" requires a vision. Based on an earlier road map we could consider the 2015 vision to be that, by 2030 membrane desalination and water purification will contribute significantly to safe, sustainable, affordable and adequate water supply globally. With state-of-the-art membrane technology we can be assured that water can be safe. However sustainability and affordability are more challenging and require membrane technologies that minimize energy and operating costs and also strive to lower capital costs. These tend to be competing criteria, leading to trade-offs. Important future objectives will involve improved membranes, optimized modules and systems, ancillary process advancement, and minimization of inefficiencies such as fouling. Examples will be provided based on a recent assessment of the status and future of membranes in the water domain.

Energetics of Desalination

Presented by Menachem Elimelech, Ph.D., Roberto Goizueta Professor at the Department of Chemical and Environmental Engineering, Yale University (USA)

Seawater and brackish water desalination has become an important pathway for augmenting fresh water supply to alleviate the global problem of fresh water scarcity. Among available technologies, reverse osmosis (RO) has become the gold-standard for desalination due to its process maturity and reliability. Other emerging technologies such as forward osmosis (FO) and membrane distillation (MD) can find niche applications in treating high salinity feed waters that cannot be desalinated by RO. In this presentation we will discuss the energy efficiency of desalination and the possible reductions in energy demand by state-of-the art seawater desalination technologies and advanced membranes. The energy efficiency of reverse osmosis desalination will be discussed first, focusing on single-stage operation as well as various approaches of multi-staged operations. It will be shown that multi-staged operations, such as closed-circuit desalination, can significantly reduce the specific energy of desalination, approaching the theoretical thermodynamic minimum energy of desalination. The relationship between the specific energy of desalination and RO membrane permeability and selectivity will also discussed and guidelines for membrane design will be proposed. Finally, an analysis of the energy efficiency of FO and MD desalination will be presented and the implications for process selection and design will be provided.

11:00 AM – 12:30 PM

TRACK A – FORWARD OSMOSIS

Abstract #A-101 - Tzahi Cath, Ph.D., Associate Professor, Colorado School of Mines (USA)

Forward Osmosis Principles, Trends, and Applications

Processes and systems must be simple in order to successfully make it to the market. Forward osmosis (FO) has the promise of being that simple process that can treat almost any impaired stream (being both the pretreatment process and the desalination process) in one step and at low energy and maintenance expenditure. To make FO successful one needs a good FO membrane, a good draw solution, a good draw solution re-concentration process, and good system integration. These are more than the simple requirements for successful reverse osmosis (a good membrane and good pretreatment). Commercial FO membranes are offered by a small number of companies, some of which cannot provide robust FO membranes that can treat highly impaired waste streams, and some limit the availability of the membranes to the research community. Universities are developing new FO membranes, but these membranes are also not available to the research community. Novel draw solutions are being developed by universities and National Labs, but recent research shows that the simple salts and their mixture are still the best draw solutions for most applications. And reconcentration processes are specific for the different draw solutions and are specifically developed for the novel draw solutions or are just RO in various configurations for the simple salts draw solutions. System engineering and integration is the beacon for the development of future, successful FO applications. We see signs that FO has the potential to be successful in the upstream sector of the oil and gas industry, in direct potable reuse (osmotic MBRs), and in the desalination industry.

Abstract #A-102 - Jeffrey McCutcheon, Ph.D., Associate Professor, University of Connecticut (USA)

Forward Osmosis Membrane Design: Innovative Approaches to Rethinking Thin Film Composite Composite Membranes

The sub-discipline of forward osmosis (FO) has been an active area of research for the academic and industrial community for the past decade. Literally hundreds of papers have been authored on the subject from groups around the world. This explosion of work has largely stemmed from our 2005 paper in Desalination that marked what could be considered the beginning of the modern era in FO. Many of the subsequent papers published have focused on membrane designs that are finely tuned for excellent osmotic performance with high selectivity. In this work, we highlight a number of membrane platforms developed at the University of Connecticut including modified reverse osmosis membranes, membranes made from commercial microfiltration membranes, nanofiber supported osmotic membranes, and hollow fiber membranes. We quantify critical performance metrics of these membranes and connect them to the key structure-property relationships that are tunable with choosing or adjusting key material properties. We also describe this work in the context of new scientific questions in the area, including the challenge of accurately characterizing structural resistances in these new membranes and quantifying largely ignored ion-exchange effects that impact selectivity of polyamide based membranes that have been widely adopted across the field. With these new insights, we describe a path forward that enables better transfer of the most important ideas from the academic community to the industrial entities that are key to ensuring commercial success of the technology.

Abstract #A-103 - Mamadou Diallo, Ph.D., Professor, KAIST and CalTech (Korea/USA)

Polymer-Based Draw Solutions for Osmotically Driven Membrane Processes: Opportunities and Challenges

Forward osmosis (FO) is a promising low-pressure membrane separation technology for various environmental applications including (i) water reuse, (ii) desalination and (iii) resource recovery (e.g. microalgae harvesting for biofuel generation). However, a major and unresolved challenge in FO remains the availability of efficient draw solutions that can be separated and reconstituted using low-energy separation processes. Because of this, potential large-scale applications of FO have been for the most part limited to cases where a “low grade” heat source or steam is available to regenerate (by thermal distillation) a “thermolytic salt” draw solute with lower boiling point such as ammonium bicarbonate. Polymeric draw solutions could provide novel opportunities to develop efficient and regenerable FO draw solutions. In this presentation, I will discuss the opportunities and challenges associated with the utilization of polymer-based FO draw solutions using four examples including recent data from my research group: 1) polyethylene glycol (PEG), 2) thermally responsive hydrogels, 3) linear polyelectrolytes and 4) branched macromolecules (dendrimers and hyperbranched macromolecules). In each case, I will discuss both physical chemistry (e.g. osmotic pressure measurements and calculations) and engineering issues (e.g. water flux measurements, solute leakage and draw solution regeneration). I will conclude my presentation by providing an outlook of the field and highlight key remaining challenges that need to be addressed including the development of tailored membrane materials/systems and regeneration/reconstitution systems for polymer-based FO draw solutions.

Abstract #A-104 - Ho Kyong (HK) Shon, Ph.D., Associate Professor, University of Technology, Sydney (Australia)

Pressure Assisted Fertiliser Drawn Forward Osmosis Desalination for Fertigation

The forward osmosis (FO) process is a promising and emerging low energy desalination technology that works on the principles of natural osmotic process. 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 (DS) that can be easily separated from the pure water and recover for regeneration and reuse. It irrefutably requires an additional process, which could consume energy. However, FO has been found to be ideal for those applications where the separation of draw solute and the water is not essential and where in fact the presence of the draw solutes adds value to the product water from the FDFO process. Fertiliser drawn forward osmosis (FDFO) process is one such applications where fertilisers are used as the DS and the diluted fertiliser solution can be directly applied for fertigation, therefore avoiding the need for separation and recovery of the DS. This paper presents the concept of the pressurised FDFO desalination process and the effectiveness of the fertilisers as DS. The paper also identifies some of the major limitations of the FDFO process and options available to overcome these limitations.

11:00 AM – 12:30 PM

TRACK B – MEMBRANE DISTILLATION

Abstract #B-101 - Stephen Gray, Ph.D., Professor and Director, Institute for Sustainability and Innovation, Victoria University, Melbourne (Australia)

Opportunities for Membrane Distillation

Applications for membrane distillation are few despite the large research effort devoted to the development of the process. One potential area of opportunity for membrane distillation is in the treatment of industrial wastewater streams, where available heats sources exist. A review of pilot plants operating on wastewater streams from a textile mill, power station, and other process industries will be presented, with a focus on operating performance. A range of products of varying patterns and colours are produced by the textile mill, which operates in batch mode. This leads to varying wastewater quality, particularly with regard to the dyes. However, the wastewater is always high in salt and surfactants. Wetting of membrane distillation membranes is a major challenge for wastewaters containing surfactants, and recovering the membranes to a state ready for further processing of wastewater is problematic. Several approaches to managing wetting were identified in laboratory trails, these being the use of a low wetting or non-wetting membrane, and four approaches to removal of surfactant from the wastewater: (I) physical removal, (II) physico-chemical removal, (III) chemical removal and (IV) biological removal. The physical pre-treatment method and the bio-physical pre-treatment approaches were trialled on the plot plant and performance data of these pre-treatments will be outlined. A power plant ion exchange regeneration waste stream contained high salt and ammonia concentrations, and treatment of this process stream by membrane distillation was piloted over three months. Low rates of fouling were observed and high water recoveries were possible. There was sufficient waste heat available to treat all the ion exchange regenerant wastewater.

Abstract #B-102 - Andrea Corral, Ph.D., Research Assistant, Univeristy of Arizona (USA)

Mass and Heat Transfer Model for Vacuum Membrane Distillation in a Hollow Fiber Module

Coupled mass and energy balances were used to simulate the performance of a hollow fiber membrane module for Vacuum Membrane Distillation (VMD). Membrane tortuosity was the sole adjustable parameter in fitting the model to experimental observations. Experiments were conducted using a hollow fiber module with heated brine fed to the lumen side, varying the feed temperature, vacuum pressure in the permeate channel, and brine velocity. The calibrated model was used to explore the limits of module

performance (permeate flux) in response to module design and operational variables. Permeate flux predictions increased by ~0.05 kg/m2h for every additional oC in the influent brine temperature, and by ~0.4 kg/m2hr for each 10 kPa increase in the bulk (shell side) gas-phase vacuum level. Improvements in water production rate that can be obtained by increasing the effective membrane pore size were determined theoretically.

Abstract #B-103 - Jaichander Swaminathan, Doctoral Student, Massachusetts Institute of Technology (USA)

Mechanical Vapor Compression/Membrane Distillation Hybrids for Reduced Specific Energy Consumption

Mechanical Vapor Compression (MVC) is a relatively well developed and mature desalination technology with a lower than average specific energy consumption. A novel membrane distillation (MD) configuration referred to as Conductive Gap MD (CGMD) has been suggested for improved energy recovery and energy efficiency. CGMD also requires a lower membrane area for the same energy efficiency as other MD configurations. This study investigates a hybrid MVC-MD system for reduced overall specific energy consumption. Preliminary results indicate that energy consumption of the proposed hybrid system is about 10% lower than that of a stand-alone MVC. Economic analysis is carried out to further evaluate the suggested hybrid configuration.

Abstract #B-104 - Saravanamuthu Vigneswaran, Ph.D., Professor, University of Technology, Sydney (Australia)

Sustainable Operation of Vacuum Membrane Distillation for Mineral Recovery from Hypersaline Reverse Osmosis Concentration

Reverse osmosis (RO) desalination process is being used to convert seawater into fresh drinking water. One of the problems of this process is the need to dispose of the concentrated brine. Seawater RO concentrate (ROC) contains high concentration of rubidium (Rb), which is very valuable ($10,000/kg). The performance of vacuum membrane distillation (VMD) was investigated for the treatment of seawater ROC and Rb recovery. The VMD system was able to concentrate the ROC further by three times its original concentration. During the experiments, the permeate flux decline (50% of its initial value) followed by membrane wetting was observed. Membrane autopsy revealed that the deposition of salts on the membrane surface was the main contributor to these phenomena. Two sustainable scale-mitigation approaches were tested in this study. In the first approach, the VMD was integrated with a continuous crystallizer. This prevented the formation of crystals on the membrane surface. The VMD crystallizer operation enabled to achieve a stable permeate flux with proper hydrodynamic control to reduce the supersaturation polarization effect. In the second approach, a net filter was placed at the brine channel of the VMD to trap the crystals. The increased transmembrane pressure in the net filter was used as an indicator for water flushing on the membrane in the VMD. This approach enabled to maintain the permeate flux while mitigating membrane wetting.

1:30 PM – 3:00 PM

TRACK A – SALINITY GRADIENT ENERGY: PRESSURE RETARDED OSMOSIS

Abstract #A-201 - Amy Childress, Ph.D., Professor and Director, Environmental Engineering Program, University of Southern California (USA)

Pressure Retarded Osmosis (PRO): Should It Stay or Should It Go?

Investigators around the world are considering pressure-retarded osmosis (PRO) as one component of an alternative energy portfolio that will reduce dependence on fossil fuel combustion. In laboratory and desktop analyses, PRO is being considered for large-scale seawater desalination applications as well as other targeted applications. This presentation will describe our recent work on the RO-PRO system, a system designed to synergistically reduce the energy demand of reverse osmosis (RO) desalination and mitigate issues associated with discharge of RO brine to sensitive receiving environments. The RO-PRO Gen-1 system demonstrated that pressure could be exchanged between PRO and RO subsystems and provided the first experimental power density data for PRO membranes in a RO-PRO system. The Gen-2 system will be scaled for flow rates appropriate for newer PRO membranes and modules that have been significantly improved over those that were available for the Gen-1 system. It is expected that PRO performance will increase due to substantial technology improvements in recent years. This presentation will also describe the state-of-the-art of PRO membrane and module development as well as the progress of other PRO applications that are focusing on higher salinity gradients to improve the viability of this technology.

Abstract #A-202 - Zhangxin Wang, Doctoral Student, Vanderbilt University (USA)

Gross vs. Net Energy Output: A Rational Framework for Assessing the Viability of Pressure Retarded Osmosis

Pressure retarded osmosis (PRO) is an engineered osmosis process capable of harvesting energy from salinity gradient to do useful work. As a clean energy source that is claimed to have the potential of providing 13% of global electricity demand, PRO has aroused extensive research interests in both academia and industry. While PRO has been demonstrated to be technologically feasible, there remain many unanswered questions about the practical viability of the technology. In this study, we focus on assessing the net energy output of a PRO system considering several major energy losses in a practical PRO system, including those related to pretreatment, cross flow pressure drop, and pressure exchange. We formulate a general equation with three primary variables (applied pressure, normalized membrane area, and relative flow ratio) to evaluate the net energy output of the system taking into account the aforementioned energetic losses, which allows us to conduct optimization to obtain the net energy output in the best-case scenario. We believe that the framework we develop in this study can serve as a paradigm for rational cost-performance analysis for PRO.

Abstract #A-203 - Seungkwan (SK) Hong, Ph.D., Professor, Korea University (Korea)

Analysis of Pressure Retarded Osmosis Under Varying Draw Pressure by a Novel Method

Osmosis membrane characteristics in terms of intrinsic transport parameter (A and B) and structure parameter (S) can provide a useful approach to estimate membrane performance, including power density, water and reverse solute flux (RSF). In this study, single pressure retarded osmosis (PRO) method to determine A, B, and S value of PRO membrane was proposed to analyze PRO performance more accurately. This method is composed of four consecutive experiments with different concentration of draw solution at certain pressure. The experimental water and reverse solute fluxes calculated from each experiment are used for determination of A, B, and S by performing a nonlinear least squares fitting. Compared to conventional reverse osmosis (RO)/forward osmosis (FO) method, the single PRO method gave good prediction during PRO process whereby pressure was applied on draw sides. A and B values were generally high in conventional RO mode where water and solute move in same direction by hydraulic pressure. In PRO method, solute permeability, B, was found to be increased by applied draw pressure, while water permeability, A, was slightly decreased. Especially, solute permeability showed a strong pressure dependent behavior. Modelded results was best correlated with experimental data when A, B, and S value determined at the corresponding pressure applied. Thus, the results indicated that membrane characteristics should be determined from the PRO method identically simulating its operating condition for predicting the power density accurately in PRO.

Abstract #A-204 - Agata Zarebska, Ph.D., Technical University of Denmark (Denmark)

Fouling Characterization of Forward Osmosis Biomimetic Aquaporin Membranes Used for Water Recovery from Municipal Wastewater

Generally more than 99.93% of municipal wastewater is composed of water, therefore water recovery can alleviate global water stress which currently exists. Traditional ways to extract water from wastewater by the use of membrane bioreactors combined with reverse osmosis (RO), or micro/ultrafiltration coupled with RO and sand filtration, or advanced oxidation process require high energy. Contrary to pressure driven membrane processes, forward osmosis (FO) offers advantages such as no need of high hydraulic pressure, reduced fouling and simple cleaning. Even though fouling of FO membranes is less severe compared to other pressure driven membrane processes, some fouling can occur. This entails that by reducing fouling, increased FO membrane performance can be expected, thus increasing the economic viability of FO processes. Since various types of fouling might occur in membrane systems such as inorganic, organic, and biological fouling, membrane characterization is not a trivial task. The aim of this work is to characterize fouling of FO biomimetic aquaporin membranes during water recovery from municipal wastewater. Membrane fouling was characterized using Scanning Electron Microscopy, X-ray Dispersive Spectrometry, Fourier Transform Infrared Spectrometry, Inductively Coupled Plasma Optical Emission Spectrometry, Ion chromatography, zeta potential, and contact angle measurements. Our preliminary experimental results indicate that FO membrane fouling is dominated by organic fouling caused by adsorption and deposition of organic matter (mainly proteins and carbohydrates) in combination with biofouling and inorganic scaling. This can provide understanding of how fouling can be mitigated by considering various feed pretreatment and cleaning methods.

1:30 PM – 3:00 PM

TRACK B – MEMBRANE DISTILLATION

Abstract #B-201 - Noreddine Ghaffour, Ph.D., Research Professor, King Abdullah University of Science and Technology (Saudi Arabia)

Comparative Assessment of Membrane Distillation Configurations and Modules

Membrane distillation (MD) is considered as an attractive new desalination technology combining the advantages of conventional thermal and membrane-based processes. However, despite the MD process has been under investigation for several decades, it has still not been commercialized, even at small scale applications. On the other hand, although MD is still under lab and small pilot studies, it has a great potential for scale-up, especially in niche applications where the conventional technologies face extreme operational challenges or are very costly. However, MD still runs at low flux especially at large scale modules where the driving force across the membrane becomes relatively small regardless of the operating parameters and feed water quality. This talk addresses the main challenges of scaling-up the MD process, mainly development/manufacturing of proper membranes and modules with efficient heat recovery systems. Simulation and experimental studies of different conventional and innovative process configurations are presented and compared with and without heat recovery schemes aiming to optimize the system's performance. High fluxes obtained with lab scale modules are quite optimistic when compared to larger modules due to several factors mainly the significant variation of the driving force due to conductive losses and low thermal efficiency. Reasons behind the differences in performance of the different module configurations as well as the effects of concentration polarization and temperature polarization (TP) on MD flux will be discussed. Parameters used in evaluating the extent of TP effect on flux, mainly flux sensitivity factors and TP coefficient will be highlighted. Highly efficient hybrid systems will also be presented.

Abstract #B-202 - Shihong Lin, Ph.D., Assistant Professor, Vanderbilt University (USA)

A Simplified Thermodynamic Analysis on Direct Contact Membrane Distillation

Membrane distillation (MD) is a thermally driven desalination process that is inherently energy intensive. Therefore, understanding the energy efficiency of MD and its influencing factors is critical to assess the competiveness of MD compared with other desalination technologies and to optimize MD system design and operation. Here, we will present simplified results from a relatively thorough thermodynamic analysis on a module-scale direct contact MD system coupled with heat exchanger for latent heat recovery. By employing novel concepts such as mass transfer parameter and operation regimes, our analysis answers important questions regarding the thermodynamic limits of energy efficiency and single-pass mass recovery, as well as the impacts of membrane area, membrane thermal efficiency and feed-to-distillate flow rate ratio. We will also present simple equations, with highly intuitive interpretations, for estimating several key MD performance parameters such as maximum mass recovery and optimal feed-to-distillate ratio. Finally, the technical and economical implications of findings from our thermodynamic analysis will also be discussed.

Abstract #B-203 - Wendell Ela, Ph.D., Professor, Murdoch University, National Centre of Excellence in Desalination Australia (Australia)

Solar Membrane Distillation for Off-Grid, Decentralized Water Purification

The constraints on growth, health and economic well-being imposed by water scarcity, which the rural population of the Navajo Nation in northeastern Arizona experiences, are not atypical of those experienced by rural populations in arid and semi-arid regions globally. Also not atypical, the difficulty of overcoming this challenge is exacerbated by the lack of access to an electrical grid by much of this population. In response and in concert with Bureau of Reclamation and the Navajo Nation, an autonomous, solar-driven membrane distillation desalination demonstration site has been developed. It recently began operation providing livestock and human use water from the underlying brackish aquifer. Key operational challenges which system development faced were frequent on-off cycles, distance from and cost of technical and materials support, lack of established integrated control systems between solar and desalination technologies, an overriding requirement for simplicity of components and operation, frequent and large fluctuations in quantity and ratio of thermal and electrical energy demand, rattle snakes, and adaptation to inhospitable and variable weather conditions. The system's underlying hybrid, vacuum/sweeping gas membrane distillation process and its integrated solar thermal and electrical cogeneration technology will be detailed. However, primarily the talk will focus on the functionality of the system with particular emphasis on its relative strengths and weakness against those of other alternative technologies. It will conclude with observations on still outstanding research and development needs as well as barriers to wider deployment of decentralized, autonomous desalination technologies.

Abstract #B-204 - Mitchell Haws, Water Resources Planner, US Department of the Interior, Bureau of Reclamation (USA)

Solar Membrane Distillation Desalination Research

Many Native Americans living on reservations in the southwest lack access to running water, sanitary facilities and line-connected electricity. The Navajo Nation (NN) has faced these challenges for generations. The water is often impaired and no other water is economically accessible. They are forced to haul water from distant wells. As a result these water users pay a larger share of their income to obtain water compared to others in the region. Researchers from the Bureau of Reclamation (BOR) and University of Arizona (UA) are developing an applied research site to test off-grid, advanced water treatment technologies using renewable energy. The researchers are focusing on sustainability factors in designing the solar energy/membrane distillation system to supply livestock water and with the knowledge gained from this non-potable application, develop a renewable energy/advanced water treatment package to supply the rural/remote dispersed population with potable water. This applied research project (now operational near Leupp, Arizona) combines a Concentrating Photovoltaic Thermal Hybrid System (CPVTHS) as the heat and electrical energy source, with a Membrane Distillation (MD) treatment train for the advanced water treatment system. One objective of the project is to develop a system using "off-the-shelf" products designed to minimize the operation, maintenance and replacement costs. The researchers envision a stand-alone system producing distilled water to be blended with the existing well water to reduce the TDS. This project currently serves livestock water and is the prerequisite in developing a potable water system for human consumption.

3:30 PM – 5:00 PM

TRACK A – SALINITY GRADIENT ENERGY: REVERSE ELECTODIALYSIS

Abstract #A-301 - Frank Neumann, Ph.D., Director, Institute for Infrastructure, Environment and Innovation (Belgium)

Overview of European and International Projects for Upscaling of Reversed Electrodialysis and Pressure Retarded Osmosis Applications in Relation to Desalination and Waste Water Treatment

Innovation trajectories for PRO suffered from a slow down after Statkraft, a key developer, halted its development of a PRO stand alone application for salinity gradient power production in 2013, just before upscaling to a bigger plant. However, since that time the financing for PRO application developments focused on improving the energy and environmental efficiencies of desalination processes has increased. Since 2013, the number of known R & D initiatives for that application has doubled. RED, from a position of modest development in 2004-2010 has caught on with the first larger stand alone process in a natural environment, out of the laboratory, operating now for a full year since 2014; while an increasing number of new European and international projects focused on RED and desalination/ waste water treatment are underway. In this article a limited number of upscaling efforts including RED and PRO will be reviewed and their main challenges described, as well as the structure of the industrial R & D programmes they fit in. This information will be complemented with collated outcomes of INES workshops. Tentative recommendations will be formulated with respect to enhancing the upscaling of salinity gradient power applications and their infrastructure based on that description.

Abstract #A-302 - Tzahi Cath, Ph.D., Associate Professor, Colorado School of Mines (USA)

Techno-Economic Assessment of a Novel Osmotic Heat Engine for Energy Recovery from Low-Grade Heat

Osmotic power harnesses the energy of mixing between a high salinity and low salinity stream to produce useful energy. The osmotic heat engine (OHE) is a closed-loop, membrane-based cycle that utilizes osmotic pressure gradients and thermal energy (i.e., low-grade heat) to produce electrical energy. This system couples pressure retarded osmosis (PRO), an osmotically driven membrane process, with membrane distillation (MD), a thermally driven membrane process. In PRO, water permeates through a semi-permeable membrane from a low-concentration stream into a high-concentration stream, subsequently generating a mixed stream and a hydraulic pressure build-up. The mixed stream is then expanded through a hydroturbine and converted into electric energy. MD utilizes low-grade heat to regenerate the mixed stream into a high-concentration and low-concentration stream, which are resupplied to the PRO process. PRO and MD were experimentally evaluated at the bench-scale and results were used to validate PRO and MD models and to construct an Excel-based techno-economical cost model. The economic potential of a full-scale OHE was investigated to evaluate, among others, the economy of scale, low-grade heat temperatures, and the impact of PRO power densities on system costs and net power output. Results indicate that increased PRO membrane power densities have the greatest impact on increasing process efficiencies and decreasing process costs (0.25 to 0.07 $/kWh). Although OHE electricity costs are not yet competitive with conventional grid energy costs (~0.04 $/kWh), the system does offer additional benefits such as increased utilization of low-grade heat and the potential for energy storage.

Abstract #A-303 - Mohammad El Ramahi, Associate Director, Abu Dhabi Future Energy Company (Masdar) (UAE)

Masdar's Renewable Energy Water Desalination Program

In order to sustainably tackle the challenge of increased water requirement, advanced and innovative water solutions need to be implemented. To commercialize such technologies, capital, time and technology validation is required. Masdar's renewable energy water desalination program, an initiative of the Abu Dhabi government, demonstrates different energy-efficient desalination technologies on a pilot scale. In Abu Dhabi, Masdar and four global water technology providers will develop novel technologies and process configurations which have not yet been commercially applied. The demonstrated technologies are: (1) Innovative combination of reverse osmosis and membrane distillation by Abengoa; (2) Hybrid of reverse osmosis and liquid ion exchange (for brine management) by Degremont; (3) Advanced reverse osmosis configuration by Veolia; and (4) Novel forward osmosis desalination technology by Trevi Systems. Expected to produce a total of up to 1,450 cubic meters per day of potable water, the pilot plants will be operated for 18 months in Abu Dhabi. The process protocols and the quality of the produced water will be analyzed to prove the performance, reliability, and cost-effectiveness of the selected technologies and their ability to be powered by renewable energy sources. The pilot projects will be supported with R&D projects in collaboration with Masdar Institute, a graduate research university in Abu Dhabi. The R&D projects focus on membrane scaling and fouling, techno-economic evaluation of PV and solar thermal energy technologies for desalination, capacitive deionization, and membrane manufacturing.

Abstract #A-304 - Haizhou Liu, Ph.D., Assistant Professor, University of California, Riverside (USA)

Harvesting Renewable Energy from Waste of Reverse Osmosis Seawater Desalination Using Salinity Gradient Based Design of Capacitive System

Climate change and the unprecedented multi-year droughts that are taking place in Australia, China and a large part of the United States limit the access to reliable and clean drinking water. These processes have necessitated the development of alternative water sources and treatment methods, notably brackish water and seawater desalination using reverse osmosis (RO) membrane technology. Although desalination is attractive as a water treatment process, it has high capital and energy costs and generates highly saline waste. The disposal of the saline waste (also known as brine) back to the ocean can also threaten the health of marine ecological system. However, a remarkable amount of energy is available from the salinity difference between brine waste and the seawater. Approximately 3000 kJ of free energy per cubic meter of brine waste could be extracted, equivalent to the energy generated from water falling from 420 meters high. A typical medium-size desalination plant therefore has more than 6 million watts of energy to harvest from brine every day. In this study, we sought to develop a porous carbon electrode-based capacitive system and harvested the salinity gradient-based energy from brine. Experimental apparatus was developed by using desalination brine waste and seawater alternatively to charge and discharge the capacitor and consequently extract the energy. Theoretical work is also being conducted to model the capacitor surfaces and to predict the most efficient surface morphology to attract the saline gradient. Results from this study will bring a complete diagram shift to the application of desalination technology, by recovering energy from brine waste and produce renewable clean energy.

3:30 PM – 5:00 PM

TRACK B – OTHER EMERGING TECHNOLOGIES

Abstract #B-301 - Rong Wang, Ph.D., Professor and Director, Singapore Membrane Technology Centre (Singapore)

Biomimetic Forward Osmosis and Pressure Retarded Osmosis Membranes

Aquaporins (AQP)-based biomimetic membranes have attracted considerable interest over the last years. The AQPs or water-channel proteins, inserted in cellular membranes, are highly permeable to water but highly retentive to solutes. It has been suggested that the properties of this natural 'water channel' are extremely attractive for water treatment, if they could be incorporated into synthetic membranes. Over the past five years, much effort has been devoted to developing AQP-based biomimetic membranes. Excitingly, this concept has been proven in the laboratory recently. AQPs have been demonstrated to be able to increase the water flux of RO flat sheet membranes when incorporated into the selective layer of the membrane. The commercialization of the AQP-based biomimetic membranes has also been initiated. However, the practical application of AQP-based biomimetic membranes still faces many challenges, further R&D efforts are needed to develop high performance AQP-based biomimetic membranes for various applications, including forward osmosis (FO) and pressure retarded osmosis (PRO) processes. In this presentation, the development of AQP-based biomimetic membranes in hollow fiber configuration for FO and PRO applications at Singapore Membrane Technology Centre will be reported.

Abstract #B-302 – Pierre Le-Clech, Ph.D., Associate Professor, University of New South Wales (Australia)

Forward Osmosis Under Pressure: Performances and Challenges of Pressure Assisted Osmosis

With the use of additional hydraulic pressure on the feed side, the concept of pressure assisted osmosis (PAO) process has been recently considered as a new strategy to enhance water flux and to limit reverse salt diffusion (RSD), overcoming two critical limitations of forward osmosis (FO) operation. When pressure (up to 6 bar) was applied on the feed side of the process, the membrane water permeability (A) was observed to double, mainly due to the membrane deformation against the spacers. Under those conditions, the additional driving force provided resulted in 70% increase in permeation flux, despite the more severe concentration polarisation. Once considered within seawater dilution application, the economic sustainability of the osmotic processes hybridised with conventional reverse osmosis was assessed. It was demonstrated that improvement in water permeation flux, typically above 30 Lm−2h−1 for classical water recoveries, is an absolute prerequisite to lower investment costs down to an economically acceptable level. With the aim to obtain more sustainable fluxes, the use of commercially available nanofiltration (NF) membranes under PAO operating conditions has also be considered. With flux up to 36 Lm-2h-1 and RSD lower than 0.05 gL-1, PAO-NF process demonstrated potential interest in a number of applications. However, diffusion of salts from feed to draw solutions (or forward salt diffusion) was observed for all NF membranes in PAO mode (ranging from 0.26 to 0.96 g.L-1). Finally, a new generation of NF membrane was tested with highly promising results.

Abstract #B-303 - Mohammed Almoiqli, Ph.D., Assistant Professor, King Abdulaziz City for Science & Technology (Saudi Arabia)

Performance Enhancement of Capacitive Deionization System by Modified 3D SWCNT/RVC Electrodes Using Microwave Irradiated Graphene Oxide

In order to obtain excellent desalination behaviour during the capacitive deionization (CDI) process, electrodes should provide efficient pathways for ion and electron transport. Here we open up a new material and substrate to prepare high performance CDI electrodes based on a three-dimensional (3D) structure. Graphene oxide (GO) nanosheets were successfully synthesised through a modified Hummer's method and were reduced and exfoliated using microwave irradiation. The XRD confirms the exfoliation of the GO and the distance between graphene nanosheets layers and EDX spectra confirms the reduction of the GO. The microwave irradiated graphene oxide (mwGO) solution was combined with SWCNT solution at various ratios to form the SWCNT/mwGO composite solutions. In this work, new route for the formation of 3D novel CDI electrodes using dip coating technique for depositing layers of SWCNT/mwGO composite materials onto reticulated vitreous carbon (RVC) substrates. SEM was used to access information about materials formation and its morphology; while Raman and XPS reveal the formation of structure. Moreover, the highest electrosorption capacity value for SWCNT/mwGO/RVC electrode reached 3.82 mg/g when tested with 75 mg/L NaCl solution and the overall improvement in one desalination cycle per day compared with the SWCNT/RVC electrode under the same conditions, reached 76.8 %. In addition, the time saving of one electrosorption–desorption cycle with the SWCNT/mwGO/RVC electrode was 27.78 percent, compared with the CNT/RVC electrode which required 18 min.

Abstract #B-304 - Xia Shang, Doctoral Student, University of Illinois at Urbana-Champaign (USA)

Energy Efficiency Modelling for Capacitive Deionization and Membrane Capacitive Deionization

A typical capacitive deionization (CDI) cell consists of two conductive supercapacitor electrodes and two current collectors sandwiched together in a symmetrical arrangement across a porous spacer, which insulates the electrodes and creates a water channel. Cation- and anion-exchange membranes are commonly placed between the spacer channel and the corresponding electrodes to enhance the ion storage efficient of the electrodes by preventing the co-ions repelled in the charging stage from entering the flow channel. This modified system is referred to as membrane capacitive deionization (MCDI). In the desalination market, the reported energy consumption of a typical capacitor-based deionization technique is only lower than that of reverse osmosis (RO) at feed water salinity below around 2 g/L. However, the energy efficiency and the ion removal performance of a CDI/MCDI system are highly variable depending on factors such as system design and operation parameters such as dimension of electrode and flow channel, cycling frequency, flow rate, and inlet/outlet concentration. In this presentation, the existing models of CDI and MCDI will be briefly reviewed, followed by a demonstration of a numeric model to predict the energy input and recovery in a galvanic charging/discharging cycle. The energy associated with charge storage/release, diffusion resistance, solution resistance, Donnan potential, electrode electrical resistance, and contact resistance is modeled in real-time. The model is intended to provide insight into the tradeoffs between ion-removal performance and energy efficiency and to optimize the system design and operation scheme.