Considerable progress has been made since the early days of Reverse Osmosis (RO) water treatment/desalination in reducing energy consumption through the development of more efficient membranes, effective process configurations and energy recovery devices. There have also been effective developments of low fouling membranes, high performance water treatment chemicals (e.g., antiscalants and coagulants) and feed pretreatment processes to mitigate membrane mineral scaling and fouling. Major challenges to reducing the cost of membrane-based water treatment and desalination technologies and their widespread deployment (particularly for inland water desalination) remain such as: reducing membrane fouling and mineral scaling (especially when water feed quality is temporally variable), reducing energy consumption, decreasing plant footprint, and reducing operational costs. Through fundamental analysis that considers the thermodynamic limit of RO operation and the present availability of high performance membranes, it is apparent that optimal process configuration and plant operability (including feed pretreatment) are now the most critical elements to reducing the overall cost of water desalination. In order to address the above, a multi-pronged approach was undertaken that considers the following elements and their development from fundamental research to field deployment: (a) new class of membrane monitoring approaches for early detection of fouling/mineral scaling and integration with plant control, (b) self-adaptive operation of directly integrated MF-UF-RO systems that integrates model-based process control (e.g. of both UF backwash coagulant feed dosing), (c) machine-learning tools for plant fault detection and isolation, and (d) energy optimal operation that considers both plant configuration, operational strategy and realistic physical and thermodynamic constrains. Given the quest for reducing energy consumption in membrane-based desalination brief account will first be provided of the fundamental thermodynamic and mass transport and hydrodynamics barriers that are often overlooked, and have thus led to overoptimistic expectations of various promoted technological solutions. Subsequently, various possible options of improving the efficiency of RO desalination will be discussed with a focus on flexible and robust operation that considers the path to high recovery (toward zero liquid discharge) and handling the variability of feed water quality. Examples of recent developments in the above areas will be presented and discussed with respect to successful field demonstrations of seawater, brackish water, as well as industrial water treatment and reuse.

This presentation will describe our recent work on two systems. The first is an osmotic membrane bioreactor (OMBR) system that has been developed for potable reuse of wastewater at military forward operating bases. The three major processes of this system (biological reactor, forward osmosis, and membrane distillation (MD)) have been systematically investigated at the bench-scale and larger scale versions have been integrated into a single system that will operate using low-grade ("waste") heat existing at forward operating bases. The abundance of low-grade heat produced by power generators at forward operating bases make the OMBR-MD system the ideal system for such locations. To the author’s knowledge, this is the first OMBR-MD system to be tested at pilot scale. At this time, the complete system has been connected and programmed. This presentation will include assessment of performance data, tasks towards system automation, and plans for enhanced system efficiency. It will also include brief excerpts from a video showing the research progress from bench-scale, to subsystems, to complete water reuse prototype. The second system that will be discussed is the RO-PRO Gen 2 system. This system is being designed to use pressure-retarded osmosis (PRO) to synergistically reduce the energy demand of reverse osmosis (RO) desalination and mitigate issues associated with discharge of RO brine to sensitive receiving environments. This system is unique in that the hydraulic pressure generated is not converted to electrical energy as it is in other PRO systems. This presentation will describe the state-of-the-art of the system. The RO-PRO system is being considered as one of four options to synergistically utilize RO concentrate and treated wastewater streams to achieve the highest beneficial use of both streams while minimizing energy consumption and environmental concerns. By analyzing each option in terms of energy consumption, potable water generation, energy recovery, and waste stream management (i.e., management of the RO concentrate and wastewater concentrate streams), a system-scale perspective on the viability of RO-PRO will be gained.
The growth in desalination capacity is about 10% per year, and membrane based desalination comprises more than 60% of the total installed capacity (55Mm$^3$/day). However, membrane fouling in seawater reverse osmosis (SWRO) desalination plants is an ongoing concern. This increases the head loss across the feed spacer of spiral wound elements as well as decreasing membrane permeability. The consequences are higher energy and chemical costs and frequent membrane replacement, which increases the overall operation and maintenance cost of the desalination process. The situation is even worse during an algal bloom, a serious threat to SWRO plants. One example is the “red tide” algal blooms in the Middle East Gulf region in 2008-2009. Most of the seawater RO desalination plants were shut down due to clogging of media filters (pre-treatment) and unacceptably high SDI (>5) of the effluent from media filters. During algal blooms, sticky biopolymers/polysaccharides are released by algae and if not effectively removed by pre-treatment, organic/biological fouling can occur in SWRO systems. Therefore, there is a need for sustainable robust pre-treatment systems which can remove these algal biopolymers as well as limit essential nutrients and prevent biofouling in downstream SWRO membranes. The focus of this research is on investigating innovative pre-treatment options that can improve the sustainable operation of seawater reverse osmosis systems.

Algal bloom enhanced biofouling experiments were performed using membrane fouling simulators (MFS). The feed solution used was algal organic matter (AOM) produced from marine bloom-forming algae (Chaetoceros affinis). The biopolymer and phosphate concentration of AOM was 0.5 mgC/L and 68 µgPO$_4$/L, respectively. Chlorophyll a and algal cell count of feed was 83 µg/L and 15000 cells/mL, respectively. The effectiveness of pre-treatment options a) low molecular weight cut off (LMWCO) ultra filtration (10 kDa) and b) conventional UF (150 kDa) were assessed in terms of the efficiency of each technology in delaying biofouling. Feed channel pressure drop ($\Delta P$) in MFS cells were monitored. Other test such as biopolymer concentration (LC-OCD), phosphate concentration, MFI-UF and bacterial growth potential were also performed. The results suggest that the application of both UF 150kDa and 10kDa reduced substantially; a) biopolymers produced by Chaetoceros affinis i.e., >95% (10kDa) and 75 % (150kDa) b) bacterial growth potential of UF permeate i.e, bacterial growth potential reduction factors for UF permeate were 1.85 and 5, respectively for the 150 kDa and 10 kDa membranes and c) head loss development in MFS cells ie., $\Delta P$ in MFS cells fed with 10 kDa permeate increased only after 17 days of operation. The effect of the UF membranes can be attributed to the removal of biodegradable organic carbon in terms of algal-derived biopolymers (90-95%) and the effect of the phosphate adsorbent was due to phosphate removal (>95%).

In conclusion, the application of innovative pre-treatment i.e., low molecular weight cut off (LMWCO) ultra filtration (10 kDa) may be considered as a sustainable solution to prevent or significantly delay biofouling during the operation of SWRO systems.

This lecture will focus on recent results regarding UF and RO membrane fouling due to dilute aqueous solutions of organic matter, commonly encountered in desalination and other water treatment processes; such organic compounds include polysaccharides, humic acids and proteins. The presentation will emphasize the output of fouling R&D studies required for optimizing the design and operation of water treatment plants; i.e, adequate understanding of fouling phenomena (in terms of key parameters) and a methodological approach leading to the development of tools capable of a) predicting the fouling propensity of feed-fluid and b) monitoring/assessing the performance of an entire membrane plant in the presence of common organic foulants. The selection of specific fouling resistance $\alpha$ will be stressed, as the most representative parameter of membrane fouling, which should be correlated in a sound manner with key membrane filtration process parameters (mainly permeate flux).
UF membrane fouling will be dealt with first, under constant flux and constant pressure mode of operation. Recently obtained data from filtration tests, combined with fouling layer rheological properties, help improve our understanding of fouling phenomena and lead to the development of constitutive expression(s) for the representative fouling parameter $\alpha$. In parallel, fouling data obtained during RO filtration/desalination experiments, combined with measurements of rheological characteristics of fouling layers, can also lead to sound correlations (i.e. constitutive expressions) of the specific fouling resistance $\alpha$ for practical use. The conditions under which facile UF-fouling laboratory tests could yield constitutive expressions applicable to RO filtration, for predictive purposes, will be briefly assessed.

The usefulness and applicability of experimental fouling results and correlations, from the aforementioned small-scale tests, will be evaluated next, for the development of a comprehensive membrane-process dynamic simulator; the latter should be capable of predicting overall performance, including spatio-temporal fouling evolution, of an entire RO (or UF) plant. Progress made in this direction will be outlined, including typical simulation results. Finally, R&D priorities will be suggested, viewed from the above-mentioned standpoint.

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[KYN05]
Nalan Kabay
Ege University, Turkey
Boron removal from seawater

The World Health Organization (WHO) revised the permissible level of boron for potable water as 2.4 mg/L in 2011 although the limit was 0.5 mg/L before. It was reported that boron is toxic for reproduction and development in experimental animals at high doses. However, there were not any negative effects of boron which are observed in animal experiments for humans. Thus, the reason of limiting boron concentration in potable water is due to the possibility of the plant damage rather than human-related concerns.

There is no simple technology for boron removal from water. Among the various separation technologies tested such as adsorption, ion exchange, solvent extraction, co-precipitation and membrane processes, ion exchange using boron selective chelating resins having N-methyl-D-glucamine functional groups is the most effective method for removal of boron from water. Recently, sorption-membrane hybrid process was also considered as an alternative process to the fixed-bed ion exchange operations. Due to the higher efficiency and lower cost, the hybrid process was an attractive process for separation of boron from water.

In this presentation, recent studies on boron separation processes will be discussed. Some data obtained on boron removal from seawater and geothermal water using various methods will be presented.

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[KYN06]
Marty Peery
Dow Water and Process Solutions, USA
Reverse osmosis and nano-filtration membranes for water re-use

Industrial plants located in regions of water scarcity are seeing increasing challenges due to limited water supply and access to only low quality water. There are often additional complications due to stringent discharge standards to avoid further polluting of the existing water supply. In many cases, this is driving the need to achieve Zero Liquid Discharge (ZLD) in order to continue to operate. For many, the expense of current ZLD technologies is cost prohibitive and leaves plant owners desperate to find alternative solutions. The concept of Minimal Liquid Discharge (MLD) has been developed to provide options to cost effectively treat industrial waste water for reuse. MLD can enable water recovery of up to 95%, at a fraction of the cost of ZLD, while greatly reducing the burden of water extraction on the environment. Furthermore, it provides a source of high quality water for reuse in industrial applications. Case studies showing the performance of DOW FILMTEC™ FORTILIFE™ and DOW™ Ultra-high Pressure membranes products in MLD applications such as for Flue Gas Desulfurization wastewater in power industry, Coal to Chemical wastewater, and Textile wastewater treatment will be presented.
**[KYN07]**

Raphael Semiat  
Technion, Israel  

Environment and energy issues in water treatment processes

The challenges in water management are among the most important problems facing the world today. The shortage of clean water is at the heart of critical health issues in developing countries and is the focus of ecological and safety concerns even for the highly developed nations. To adequately provide water for drinking and agriculture, we must desalinate and clean natural water sources, reclaim polluted water, purify water with different degrees of contaminants and improve the effectiveness of water handling (storage and delivery) systems ranging from desalination plants to waste water treatment facilities and to home water purification systems. We must remove contaminants that include inorganics (metals and ions), organics (e.g., toxic waste, pharmaceuticals) and microorganisms (bacteria, viruses, etc.). At the heart of these diverse problems stands the need for new ways to clean water, to safely dispose of the extracted waste, to properly reuse the cleaning systems and to keep the environment clean.

Israel made significant steps to provide affordable solutions, based on wide distribution system, desalination (close to 80% of the urban water consumption), Tertiary treatment of wastewater for irrigation, drip irrigation for reduction of water consumption and improved agriculture techniques. However, there is always place for improvements. The directions may include improved membranes, improved desalination steps in order to reduce the cost, improve pretreatment processes, increased recoveries (near zero liquid discharge in brackish water desalination), increase product quality, improved wastewater treatment by better techniques like MBR and MBBR, better treatment for removal of tracers of organic and inorganic contaminants, treatment of polluted aquifers, develop small water treatment and recovery for remote locations, reduce water losses on the piping systems and more. The aspects related to techniques, energy and environmental issues investigated in our water research program will be briefly presented.

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**[KYN09]**

Raed Hashaikeh  
Masdar Institute of Science and Technology, UAE  

Electrically conductive nanofibers for membranes fabrication and fouling prevention

Membranes are widely employed in desalination processes, but their performance can be severely deterred by fouling due to organic, inorganic and biological foulants. Periodic electrolysis is a fast and simple technique for membrane cleaning. An electrically conductive membrane can work as an electrode in an electrochemical system where the saline water is used as an electrolyte. However, such a system requires membranes with high electric conductivities and with controlled properties. The fabrication of electrically conductive membranes based on nanostructured fibrous materials will be presented and their performance for in-situ membrane cleaning will be discussed. The efficiency of the cleaning procedure in the flux recovery has been proved with typical bio- and inorganic membrane foulants such as CaCO3 and yeast suspensions. The applicability of such a system in different membrane technologies will be explored.

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**[KYN10]**

Domingo Zarzo  
AEDyR, Spain  

Desalination and energy consumption. What can we expect in the near future?

Desalination technologies have become necessary tools for hydrological planning along with conventional water resources; more than 94 million m3/day and around 18,000 installations all over the world demonstrates that fact. Besides, food demand will grow nearly double over the next 50 years, making the link clearer between WATER, FOOD and ENERGY.

One of the main barriers for the extension of Desalination (more severely in developing countries) is the higher water costs, which is seriously influenced by energy consumption (representing more than 50-60% of the total costs).

In this presentation, relevant aspects regarding energy and desalination will be showed, while taking the different technologies available into account. The presentation will be mainly focused on Reverse Osmosis, which is the most used technology, and will consider aspects such as the major consumers and their contribution to overall consumption. Configuration of high pressure pumps, membranes and energy recovery devices will be explored and what we can expect in the future, while keeping in mind that we are currently very close to the thermodynamic limits for energy consumption.

Special dedication will be taken to renewable energies and how they can be combined with desalination to produce more efficient systems, though not necessarily directly coupled to desalination plants.
How to choose the most adequate energy rates and the combination of production and smart storage is another important consideration for energy cost optimization. An adequate strategy in the management of water production can significantly reduce the cost of water.

To conclude, emerging technologies will be analyzed (forward osmosis, pervaporation, graphene, etc.), looking at all the possible improvements and potential uses generated.

All the considerations and solutions will be illustrated with real case studies from all over the world.

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Seawater desalination using membrane technology has come a long way since the invention of the asymmetric cellulose acetate reverse osmosis (RO) membrane by Sidney Loeb and Srinivasa Sourirajan from University of California, Los Angeles (UCLA), United States in 1950s. Presently, the seawater desalination using RO technology has become an essential tool to enable effective management of water strategies in many countries. This technology in general has the capability of addressing large-scale demand for fresh water, offering humans a viable and sustainable means to effectively address increasing water scarcity issues.

Despite the advantages, the issue related to membrane surface fouling is still the most common problem reported in desalination treatment plants. As membrane fouling occurs, basic membrane functions deteriorate, including salt passage through the membrane, permeate flow and pressure drop across the membrane. Typically, sources of fouling can be divided into four major categories, i.e. scale, colloids, bacteria and organics; and their occurrences are dependent on the characteristics of seawater source. In all practical cases of treatment plants, fouling material deposited on an RO membrane is reported to be a combination of all these four types of foulants. However, one type of foulant might be the major one, i.e. one of the above listed phenomena might be dominant over the others. To tackle the membrane fouling issue, chemical cleaning using acid or base-based solution is widely practiced, but the cleaning process would lead to operational downtime. In order to improve membrane operational efficiency, several appropriate ways of fouling control are recommended. These include the use of highly antifouling resistant thin film composite RO membrane, incorporation of non-conventional pretreatment units and optimization in operational conditions. The main focus of this paper is to review the recent developments of these mitigation strategies in reducing/minimizing membrane fouling during seawater desalination process. The efficiencies of the respective control strategy in overcoming the fouling factors without compromising the excellent removal rate of dissolved salts are evaluated.

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I have experiences to have had identified unknown non-ionizable organic matters which fouled the membrane surfaces, using surface characterizing tools, including zeta potential measurement. We used the streaming potential theory to measure the zeta potential, among other available theories and corresponding methods. The methods worked well with the foulant identification. However, we found an unexpected problem regarding the streaming potential measurement method to give the fact that the zeta potential, indicative of the surface potential, increases as ionic strength increases, which is nonsense, according to the double and triple layers (i.e., DLVO) theory. I have also to remind myself of that the zeta potential is only indicative of the surface charge in which we are interested.

One of my students named RHO Hojung have tried to measure the surface potential directly using the acidic or basal titration, with both clean and organically fouled membranes. We hypothesized that ionizable functional groups existed on the membrane surface provide variation patterns, such as reflection point, against pH, both quantitatively and more importantly qualitatively (i.e., an implication of a phenomenological signature). We believe the method is trustable, straightforward, and easy to perform with varying conditions.

Another student named NAM Taewoo are trying to demonstrate to couple our findings of the surface potential works to the surface energy theory through the contact angle measurements. The hypothesis is that hysteresis as measured using organic matters containing solution can give intrinsic and extrinsic aspects of inter-relationships between the targeted organic matters and the membrane surface. Both the attempts target minimization of organic fouling in, and maximization of removal of various organic contaminants by, the membranes for desalination.
The largest consumer of water is food and agriculture, where up to 70% of water drawn from rivers and groundwater is used for irrigation. Given the global priority of food security and the stresses on fresh water supplies, approaches such as desalination will become part of more sustainable water supply for global food production. Several desalination technology approaches including reverse osmosis, solar thermal, forward osmosis and membrane distillation have been considered. As shown in Figure 1, a unique application of membrane distillation is to capture not only fresh water from saline waste, but also nitrogen nutrients for agricultural application. Meanwhile the industry motivation for the research is to reduce waste water treatment costs and carbon emissions, and improve sewer safety. Two membrane distillation pilot trials demonstrated not only fresh water recoveries exceeding 90%, but also a unique effect where a pH ~8 feed increased to pH >9 in the concentrate, causing nearly all feed ammonium to evolve into the desalinated permeate. This clean ammonium nutrient permeate would be suitable for irrigation. A new vacuum membrane distillation process is also being developed which strips ammonia from the waste water, producing a concentrated ammonium product which could be used as a fertilizer. Similar ammonia stripping processes specify operation above pH 9, but the research has found effective ammonia removal from industry waste and anaerobic digester effluents closer to pH 7, making the concept more practically viable. These promising research outcomes show that current and emerging desalination technologies will likely play a key role in more sustainable water supplies for agriculture.

Figure 1: Concept for membrane distillation as a technology for providing desalinated water and nutrients for agriculture

Many large-capacity sea water desalination plants have been built recently or are being planned for the near future for those coastal areas which are experiencing water-stress. Currently, reverse osmosis remains one of the most energy efficient of established technologies and is the standard benchmark for comparison. In spite of this, seawater desalination is, in general, more energy intensive than the treatment of fresh water. Recent decreases in energy consumption are attributed to continual technological improvements. These include the installation of energy recovery devices, more efficient pumps and the use of higher-permeability membranes. The theoretical minimum energy of desalination for seawater with a salinity of 3.5 wt% is just 1.1 kWh/m³ for a recovery of 50%. An energy consumption rate of just 1.8 kWh/m³ has now been achieved on a pilot-scale system using novel SWRO membrane elements with higher permeability.
The actual energy consumption is larger than the theoretical minimum because a desalination plant does not operate as a reversible thermodynamic process. But when operating at the thermodynamic limit, flux considerations no longer influence the energy consumption of the process. This means that novel, highly permeable membranes may help to reduce membrane area and cost, but energy consumption per unit throughput will not be reduced any further. Fortunately, a multi-stage process may allow further savings for SWRO systems, using two or more high pressure pumps and membrane modules in series. This is because the first stage can operate at a lower pressure and recovery. The concentrate is then brought to the second stage at a higher pressure. Since smaller volumes are brought to higher pressures, less energy is consumed, though this might not offset the additional capital costs.

Although the RO stage in SWRO can now approach within a factor of two of the theoretical minimum energy, the overall energy consumption of new SWRO plants is 3 to 4 times higher than the theoretical minimum energy. This is because a considerable amount of additional energy (> 1 kWh/m³) is consumed by the desalination plant outside of the reverse osmosis unit; this includes energy penalties for the intake, the pre-treatment, the post-treatment and the brine discharge stages; of these, pre-treatment of the raw seawater accounts for a majority of this energy use. It is therefore very clear that future energy efficiency improvements should focus on pre-treatment processes of SWRO plants.

For the pre-treatment, robust membrane-based methods such as MF or UF pre-treatment can reduce energy consumption when compared with conventional coagulation and sand filtration. An additional pre-coagulation stage would also reduce membrane fouling and transmembrane pressures. Although ultra-high permeability membranes can only offer small energy savings, the effects of fouling and biofouling – the growth of microbes on the membrane surface – are important factors for energy consumption and could potentially be reduced or prevented using oxidants for pre-treatment. As well as decreasing the energy usage, the reliability and environmental impact of SWRO would also improve. For membranes that have a low surface energy, foulants can be washed away more easily, but water flux and salt rejection should not be compromised. Energy savings would then be possible through a reduced fouling rate and associated frequency of chemical cleaning – which itself is a form of pre-treatment. Forward Osmosis may be viewed as a new desalination technology in its own right; a novel way to view it is as a low energy pre-treatment technology for RO. In the latter case, the RO then acts on the draw solution and does not need further pre-treatment.

Finally, during intake, the entrainment of small planktonic organisms can be substantially eliminated by locating intakes away from areas of production, such as in deep waters or using sub-surface sea wells. This would also improve feed water quality and hence pre-treatment demands, although the rate of water uptake from the aquifer is limited by the permeability.

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[KYN15]

Takeshi Matsuura

University of Ottawa, Canada

Thin film composite membrane for water desalination- recent developments and future potential

This paper is a review on the recent development of thin film composite (TFC) and particularly thin film nanocomposite (TFN) membranes for desalination and water treatment.

There are a large number of reports in the open literature on the fabrication, characterization and performance evaluation of TFN membranes, in which nanoparticles such as metal oxides, carbon nanotubes and graphene are incorporated in the in-situ polymerized polyamide thin layer of the TFC membrane. The main purpose of the TFN membrane development is to increase the flux and selectivity of the reverse osmosis (RO) membrane for desalination. Increase of fouling and biofouling resistance is another purpose of nanoparticle incorporation. Attempts have also been made to enhance the performance of forward osmosis (FO) and pressure retarded osmosis (PRO) membranes as FO and PRO are gaining popularity for a component of the RO-FO or RO-PRO hybrid systems. The paper is a state of the art review, showing the future direction of the R & D on TFN membrane development.