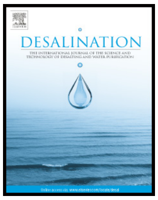
Desalination xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal



Membrane-based seawater desalination: Present and future prospects

Gary Amy [a,b,c,*], Noreddine Ghaffour [c], Zhenyu Li [c], Lijo Francis [c], Rodrigo Valladares Linares [c],
Thomas Missimer [d], Sabine Lattemann [c]

[a] *College of Engineering and Science, Clemson University, Clemson, SC 29634, USA*
[b] *Chemical and Biomolecular Engineering, National University of Singapore, 119077, Singapore*
[c] *Water Desalination and Reuse Center, King Abdullah University of Science and Technology, Thuwal 23955, Saudi Arabia*
[d] *Florida Gulf Coast University, Fort Myers, FL 33965, USA*

HIGHLIGHTS

- Membrane-based seawater desalination is presently limited by significant specific energy consumption, high unit costs, and environmental impacts including GHG emissions.
- Seawater reverse osmosis (SWRO), the conventional technology, is undergoing a significant transformation as we witness the *greening* of SWRO.
- Future of membranes in desalination and salinity gradient energy includes ultrahigh permeability RO membranes, renewable-energy driven desalination, and emerging processes.
- Emerging processes include membrane distillation, forward osmosis, pressure retarded osmosis, and reverse electrodialysis according various niches and/or hybrids.

ARTICLE INFO

Article history:
Received 16 April 2016
Received in revised form 1 October 2016
Accepted 4 October 2016
Available online xxxx

Keywords:
Membranes
Seawater desalination
Specific energy consumption
Greening of SWRO

ABSTRACT

Given increasing regional water scarcity and that almost half of the world's population lives within 100 km of an ocean, seawater represents a virtually infinite water resource. However, its exploitation is presently limited by the significant specific energy consumption (kWh/m^3) required by conventional desalination technologies, further exasperated by high unit costs ($/m^3) and environmental impacts including GHG emissions (g CO_2-eq/m^3), organism impingement/entrainment through intakes, and brine disposal through outfalls. This paper explores the state-of-the-art in present seawater desalination practice, emphasizing membrane-based technologies, while identifying future opportunities in step improvements to conventional technologies and development of emerging, potentially disruptive, technologies through advances in material science, process engineering, and system integration. In this paper, seawater reverse osmosis (RO) serves as the baseline conventional technology. The discussion extends beyond desalting processes into membrane-based salinity gradient energy production processes, which can provide an energy offset to desalination process energy requirements. The future membrane landscape in membrane-based desalination and salinity gradient energy is projected to include ultrahigh permeability RO membranes, renewable-energy driven desalination, and emerging processes including closed-circuit RO, membrane distillation, forward osmosis, pressure retarded osmosis, and reverse electrodialysis according various niche applications and/or hybrids, operating separately or in conjunction with RO.

1. Introduction

Given an increase in regional freshwater scarcity, interest in, and the practice of, seawater desalination are rapidly increasing. While mature thermal desalination technologies exist (e.g., multi-stage flash (MSF) and multi-effect distillation (MED)), interest has turned to membrane-based technologies because of more favorable energetics (i.e., lower specific energy consumption (kWh/m^3)), with seawater reverse osmosis (SWRO) presently considered as the *conventional* technology. However, SWRO is still an energy-intensive technology with associated greenhouse gas (GHG) emissions and other environmental impacts (e.g., organism impingement/entrainment at intakes and brine disposal at outfalls). Thus, there is an interest in both the *greening* of SWRO and *emerging* technologies beyond SWRO.

---

* Corresponding author at: College of Engineering and Science, Clemson University, Clemson, SC 29634, USA.
E-mail addresses: gamy@clemson.edu (G. Amy), noreddine.ghaffour@kaust.edu.sa (N. Ghaffour), zhenyu.li@kaust.edu.sa (Z. Li), lijo.francis@kaust.edu.sa (L. Francis), rodrigo.valladares@kaust.edu.sa (R.V. Linares), tmissimer@fgcu.edu (T. Missimer), sabine.lattemann@uni-oldenburg.de (S. Lattemann).

http://dx.doi.org/10.1016/j.desal.2016.10.002
0011-9164/© 2016 Elsevier B.V. All rights reserved.

Please cite this article as: G. Amy, et al., Membrane-based seawater desalination: Present and future prospects, Desalination (2016), http://dx.doi.org/10.1016/j.desal.2016.10.002

2. Present status of SWRO

Presently, seawater reverse osmosis (SWRO) dominates the global desalination market [20] based on installed capacity, having surpassed thermal technologies (MSF and MED) that are common in the Gulf Cooperation Council (GCC) and Middle East-North Africa (MENA) regions; of the 2015 installed desalination capacity of 86.5 Mm^3/day, the shares of RO (versus other processes) and seawater applications (versus other sources) are 65% and 59%, respectively. While SWRO annual installed capacity is now globally dominating over thermal technologies, its emergence into GCC-MENA region, particular in the Gulf of Arabia, has been slow because of higher-salinity feed waters that are impacted by hydrocarbons and Red Tide events.

With the integration of energy recovery devices (ERD) in SWRO during the early 1990s, considered a disruptive technology at the time, specific energy consumption has been significantly reduced from 5 to 10 kWh/m^3 to its present 3–4 kWh/m^3 with the most efficient ERD systems [18]; most of this energy (about 85%) is associated with the SWRO process itself with lesser energy requirements (about 15%) are for other SWRO system components (i.e., intake, pre-treatment, and post-treatment). While there are opportunities for reducing the energy consumption of pre-treatment, our discussion will of energetics will focus on the most energy-intensive system component, the RO process itself.

Dual media filtration (DMF) remains the conventional pretreatment process, however, integrated membrane systems (IMS) with ultrafiltration (UF) pretreatment, UF-SWRO, are becoming more common [45], especially for difficult-to-treat waters. Both UF and dissolved air flotation (DAF) are receiving increasing attention for their potential resilience during Red Tide events (harmful algal blooms (HABs)) (e.g., experienced at the Gulf of Arabia) [44]. Subsurface intakes have recently been shown to provide a significant degree of pre-treatment in acting as a biological filter to remove biodegradable organic carbon and reduce associated RO membrane biofouling [29]. Effective pretreatment can affect the energetics oft the RO step by reducing fouling.

Given a virtually infinite supply of seawater, SWRO facilities are typically run as one-pass systems with recoveries of 35–60%; some facilities incorporate a second (split stream) pass for boron removal [31]. Acid addition and/or anti-scalant addition continue to be practiced for scaling control and chlorine-sodium bisulfite for biofouling control although interest in alternative pre-disinfectants is increasing: chloramines (carried through the RO membrane as a residual) or chlorine dioxide (followed by sodium bisulfate before the membrane) as practiced at the Tampa Bay SWRO facility. SWRO trends include larger capacity facilities (e.g., the Sorek facility in Israel, 624 MLD (2013)), larger elements (16-in.), vertical orientation for RO membrane modules and pressure vessels (to permit air scouring), and improved operations (fouling control and sensors). While present SWRO practice serves the desalination industry well, it remains an energy-intensive technology with significant environmental impacts.

3. The *greening* of SWRO

The major environmental impacts of SWRO facilities include: greenhouse gas (GHG) emissions associated with (fossil fuel) energy use, entrainment/impingement of organisms by (open) intakes, brine disposal impacts on coastal marine ecosystem, marine pollution, chemical use, land use, and material use. However, sustainable solutions are available to mitigate these impacts [24,25].

GHGs can be offset by minimizing (fossil fuel) energy use, using renewable energy, or practicing energy compensation (i.e., taking energy from the grid and compensating with renewable energy) [19]; moreover, energy consumption is directly correlated with GHG emissions. Moreover, the source of fossil fuel energy (e.g., natural gas or coal) can affect the magnitude of GHG emissions [25]. Entrainment/impingement of organisms can be mitigated by subsurface intakes or submerged intakes with low-velocity intakes. Concentrate discharge can be managed by dispersion through a multiport diffuser system in a suitable marine site, controlling the extent and concentration of the salinity plume. Treatment of all backwashing and cleaning wastes can reduce marine pollution. Chemical use can be minimized by low chemical technologies (e.g., pretreatment by subsurface intakes or ultrafiltration without coagulant addition), which can eliminate the need for chemical pretreatment or cleaning entirely. Furthermore, harmful chemicals can be substituted by less toxic, more degradable substances. Land use and landscape impacts can be minimized through site selection. Material use can be offset by improved recyclability and reuse of materials, including replaced SWRO modules.

4. Step improvements in SWRO performance

Several RO membrane manufacturers have released new SWRO membrane products that include: (i) low fouling membranes, (ii) enhanced boron-rejection membranes, and (iii) inorganic-organic nanocomposite membranes with purported higher permeability. The main step improvement for SWRO would be reduced specific energy consumption (kWh/m^3) and associated GHG emissions (g CO_2-eq/m^3) through higher permeability/lower pressure RO membranes. Fouling-resistant membrane can also significantly reduce energy consumption, given the increase in transmembrane pressure (TMP) needed to maintain constant RO flux during an operational/cleaning cycle. Further advances in material science offer the promise of ultrahigh permeability (UHP) RO membranes through a new generation of nanocomposite, biomimetic (aquaporins and synthetic water channels), and possibly graphene membranes [30]. However, there is a limit to lowering energy by increasing permeability because one cannot escape the inherent osmotic pressure penalty (about 28 bar for seawater, increasing to double along the element/pressure vessel assuming a 50% recovery); operating pressure to overcome RO membrane resistance and provide flux is typically about 10–20% above the highest osmotic pressure condition in the element/pressure vessel. Any improvements in specific energy consumption through higher permeability membranes should not compromise product water quality in terms of salinity and specific problematic salt constituents such as boron. Thus far, only inorganic-organic nanocomposite RO membranes have been commercialized for seawater desalting while other UHP RO membranes are still under development [36].

Biomimetic membranes, based on aquaporins (a water-channeling protein), are being developed as UHP RO membranes; with impregnation of aquaporins (or vesicles) into polymeric matrix, aquaporins can provide water channeling/gating, leading controlled water permeability and ion selectivity. One company has commercialized an aquaporin tap-water RO membrane but it is not applicable to SWRO. There are also protein ion channels that transport ions rather than water. A constraint to aquaporin membranes is the cost of the industrial production of aquaporins, e.g., Aquaporin Z from *E. coli* cultures. Given concerns about aquaporin stability under long-term operation, there is recent interest in the use of synthetic water and ion channels [34] as an attempt to mimic aquaporins while being more stable and easier to manufacture.

Other energy trends are renewable energy-driven SWRO [17], especially using solar energy (the largest solar-SWRO plant (30,000 m^3/day) in the world is under construction in Saudi Arabia), and energy compensation by wind energy in Australia. While use of renewable energy does not necessarily reduce specific energy consumption, it provides a reduction in GHG emissions. This interest in renewable energy is now evolving toward *integrated* systems beyond just electricity provided solar PV panels or wind turbines.

The Energy Task Force of the International Desalination Association has targeted a 20% reduction in energy requirements for SWRO in the near term, which suggests a target of below 3.0 kWh/m^3. Given that the thermodynamically minimum energy requirement for seawater desalination is about 1.2 kWh/m^3 for a typical 50% recovery system (0.78 kWh/m^3 for 0% recovery) [12], we can assume a practical thermodynamic limit of 1.0 kWh/m^3. Based on present SWRO (process only)

Please cite this article as: G. Amy, et al., Membrane-based seawater desalination: Present and future prospects, Desalination (2016), http://dx.doi.org/10.1016/j.desal.2016.10.002