Membrane Processes to Address the Global Challenge of Desalination

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Increasing salinity: A major environmental concern of the 21st century

Salinity refers to the presence of soluble salts in soils and water, including surface waters and groundwater. The main chemical species contributing to salinity include: sodium, calcium, magnesium, chloride, carbonate, bicarbonate, and sulfate. In the oceans, which contain 97% of the Earth's water, salinity ranges from 35,000-41,000 mg/L of salts (usually referred to as total dissolved solids or TDS). Inland waters have salinities ranging from less than 1,500 mg/L for fresh water to 1,500-20,000 mg/L for brackish water. The salinity in inland regions may be due to the existence of soils formed from marine sediments left behind by retreating seas, the weathering of rock minerals, or the deposition of oceanic salt onto the land by wind or rain. Some inland regions have naturally elevated salinity levels due to environmental features such as mineral springs, carbonate deposits, salt deposits, and seawater intrusion. Other inland regions have anthropogenically elevated salinity levels. Like many environmental degradation processes, increasing salinity is exacerbated by human activities. Urban run-off, land use practices (clearing, irrigation, industrial farming, over-extraction), septic systems, chemicals used in water treatment processes, and road de-icing can substantially increase the extent of the problem. However, unlike many other environmental contaminants, salts do not naturally degrade over time. Salts that are deposited (naturally or anthropogenically) into a body of water accumulate until they are intentionally removed.

Increasing salinity is one of the most important environmental issues of the 21st century. Rising salinity levels have both environmental and economic costs. These include reduction in agricultural productivity, loss of biodiversity in both terrestrial and aquatic ecosystems, and decline in water quality for drinking, irrigation, industrial reuse, and recreation purposes (Tsiourtis, 2001; Ettouney et al., 2002; USBOR and SNL, 2003).

In terms of drinking water treatment, the need for additional potable water supplies has led to increased numbers of seawater and brackish water desalination facilities being constructed worldwide. To be fit for human consumption, drinking water should contain less than 1,500 mg/L of salts. In the U.S., the EPA has set a secondary standard for TDS in drinking water at 500 mg/L. In terms of wastewater treatment, TDS discharge standards vary for different facilities but are consistently becoming more stringent for all facilities. This has substantial implications for conventional wastewater treatment facilities which were not designed for salinity removal. Many facilities must retrofit with additional processes specifically for TDS removal. Thus, desalination has developed from a concept related to seawater applications in coastal regions to a concept applying to a range of applications across all regions. Furthermore, as concerns about water scarcity and quality continue to grow, the research and engineering of economic and environmentally-friendly desalination systems will continue to grow at a tremendous rate.

Desalination: From its ancient roots to its current prominence

The roots of desalination can be traced back to the 4th century B.C., when Aristotle and Hippocrates described the process of evaporating salt water to produce fresh water (Service, 2006). The first actual practice of desalination is attributed to sailors in 200 A.D. who distilled seawater by collecting freshwater steam from the boilers on their ships (Schirber, 2007). Modern seawater desalination began in the early 20th century; the first distillation facility was put into operation on the island of Curacao in the Netherlands Antilles in 1928. Modern reverse osmosis (RO) began in the 1950s when Reid and Breton (Reid and Breton, 1959) found that a cellulose acetate film rejected sodium chloride from aqueous solution and Loeb and Sourirajan (Loeb and Sourirajan, 1962) developed a high flux modified cellulose acetate membrane. The first commercial RO facility began operation in 1965 in Coalinga, CA.

Today, some form of desalination is used in approximately 130 countries; as of 2005, more than 10,000 desalting units larger than 0.3 MGD (nominal) had been installed or contracted worldwide (Cooley et al., 2006). The two processes at the core of conventional desalination facilities continue to be distillation and RO. RO generally has lower capital costs and requires less energy than distillation; a typical seawater RO plant requires 1.5-2.5 kilowatt-hours (kWh) of electricity to produce 1 m^3 of water (Service, 2006) and a typical distillation plant requires 10 times that amount (Ettouney et al., 2002; Cooley et al., 2006). On the other hand, distillation typically produces water with much lower salt content than RO systems; distillation systems typically produce water with less than 25 mg/L and RO systems typically produce water with less than 500 mg/L (Cooley et al., 2006; Service, 2006).

Although substantial improvements have been made to RO and distillation processes in the past decades, there is a strong need for improved desalination systems, especially systems that will achieve a greater rate of production of treated water at lower energy expenditure and cost. Several systems being investigated include dewvaporation, capacitive deionization, chemical precipitation, membrane distillation (MD), and forward osmosis (FO). This paper focuses on the viability, efficiency, and practical application of MD and FO for brackish water, seawater, and brine desalination at low energy expenditure and with minimal impact on the environment.

Membrane Distillation and Forward Osmosis: Promising technologies for desalination applications

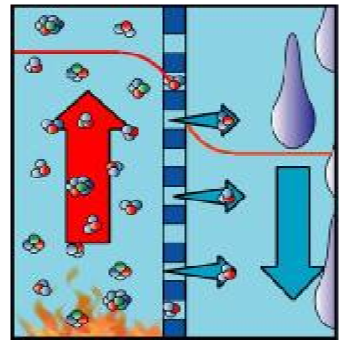

Figure 1. Direct contact membrane distillation. Adapted from: http://www.water-technology.net/

MD is a non-pressure-driven separation process involving the transport of mass and heat through a hydrophobic, microporous membrane. The driving force for mass transfer in direct contact MD (DCMD) is the vapor pressure gradient across the membrane. In a configuration referred to as vacuum-enhanced DCMD, warmer feed water is in contact with the feed side of the membrane and a cooler water stream, under vacuum, is in direct contact with the opposite side of the membrane (Figure 1). The temperature difference between the streams and the vacuum applied on the permeate side of the membrane induce the vapor pressure gradient for mass transfer. Compared to conventional distillation methods, MD requires only small temperature differences – temperature differences achievable through the use of low-grade or waste heat sources. Compared to RO, the driving force in MD is not reduced by osmotic pressure (Figure 2) and thus, MD can provide enhanced recovery through brine desalination (Cath et al., 2004). For these reasons, MD may have substantial energy and recovery advantages. MD has shown to be an effective process for desalination of brackish water and seawater (Lawson and Lloyd, 1997; El-Bourawi et al., 2006), removal of urea and endocrine disrupting chemicals (Cartinella et al., 2006), and concentration of brines (Martinez-Diez and Florido-Diez, 2001; Childress and Cath, 2006).

FO is a non-pressure-driven separation process involving the diffusion of water through a semipermeable membrane. Water diffuses from a stream of low solute concentration to a draw solution (DS) stream of high osmotic pressure (Figure 3). The driving force for mass transport is the difference in osmotic pressure between the DS and the feed solution. The main advantages of using FO are that it operates at low or no hydraulic pressures, it has high rejection of a wide range of contaminants, and it may have a lower membrane fouling propensity than pressure-driven membrane processes (Cath et al., 2006). Because the only pressure involved in the FO process is due to flow resistance in the membrane module (a few bars), the equipment used is very simple and membrane support is less of a problem (Cath et al., 2006). FO has been shown to be an effective pretreatment process for RO (Figure 4) and has been used to desalinate feed streams ranging from brackish water to brine (McCutcheon et al., 2005; Martinetti et al., 2007).

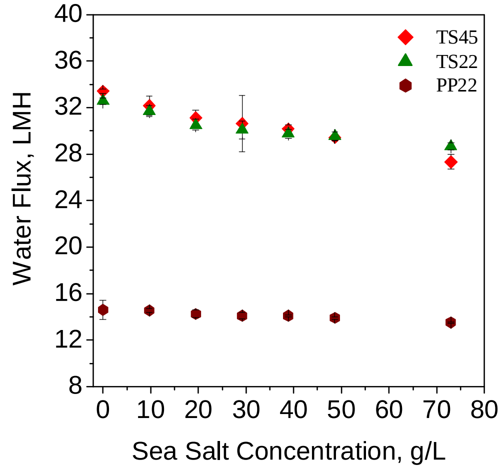

Figure 2. Flux as a function of seawater concentration in DCMD.

Direct Potable Reuse: A future frontier

MD and FO have been investigated together in a hybrid system designed for direct potable reuse in long-term space missions. Long-term human missions in space require a continuous and self-sufficient supply of fresh water for consumption,

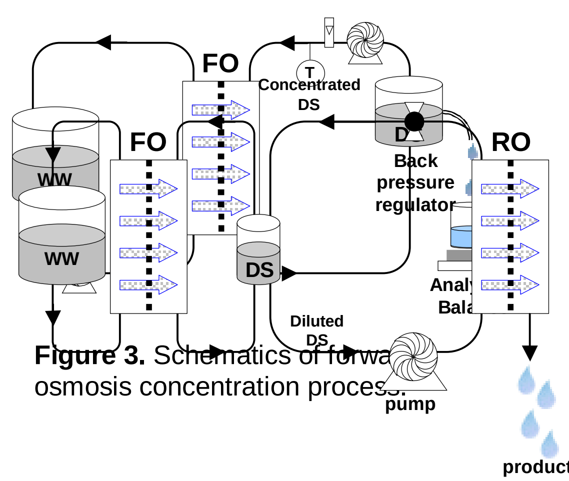

Figure 3. Schematics of forwa
osmosis concentration process.

Figure 4. Combined RO-FO system for

hygiene, and maintenance. Long-range/long-duration missions, like lunar missions or a human Mars exploration mission, depend on a water treatment system that recovers potable water from wastewater generated on board a spacecraft or in the planetary habitat. The three main sources of wastewater that can be reclaimed and reused in long-term space missions are hygiene wastewater, urine, and humidity condensate. The system to treat these wastewaters must be reliable, durable, capable of recovering a high percentage of the wastewater, and lightweight. Additionally, the system should operate autonomously with low maintenance, minimum power consumption, and minimal consumables (Wieland, 1994).

A pilot-scale system, referred to as the direct osmotic concentration (DOC) is one of several technologies that are being evaluated by the U.S. National Aeronautics and Space Administration (NASA) (Beaudry and Herron, 1997; Beaudry et al., 1999) to reclaim wastewater. In the original DOC concept, three different membrane processes (RO, FO, and osmotic distillation (OD)) were integrated into one system. Due to poor performance of the OD process the system design was revised. In the new design (Figure 5), DCMD is used to treat urine and to pretreat humidity condensate; FO is being used as pretreatment for RO for the hygiene wastewater. Separation of the feed streams in this hybrid system prevents the surfactants from hydrophilizing the hydrophobic MD membrane; this is critical because the MD membrane is required to remove the urea which would pass through an RO membrane. One important aspect of this investigation is the removal of trace contaminants. During long space missions, crewmembers will consume water that is continuously recycled. Thus, it is important to ensure that trace contaminants, and particularly endocrine-disrupting chemicals (EDCs), be removed from the treated water. EDCs (e.g., estrone and estradiol) are excreted in urine by both males and females and conventional wastewater treatment is often insufficient for removing them (Belfroid et al., 1999; Johnson et al., 2000; Johnson and Sumpter, 2001).

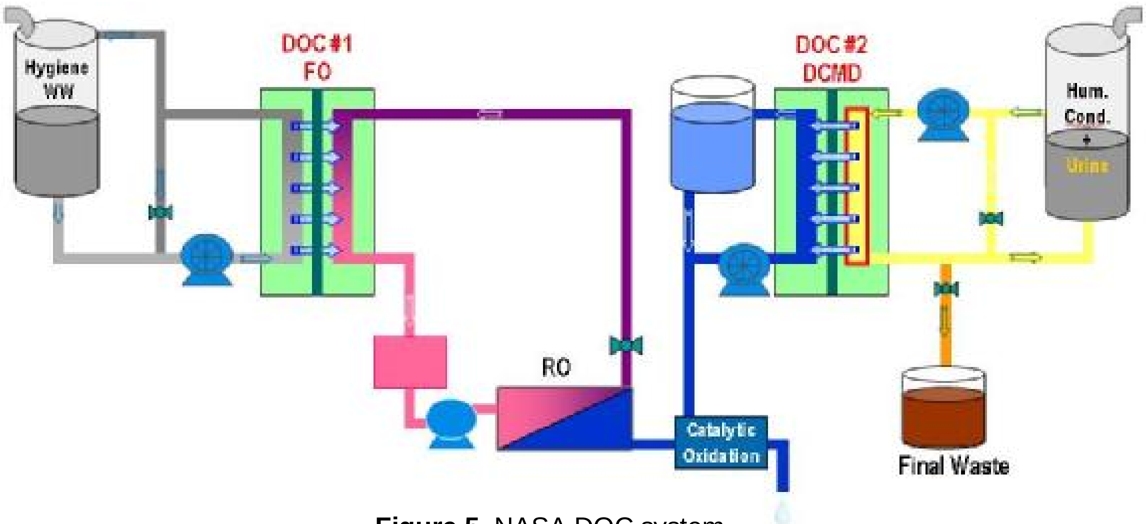

Figure 5. NASA DOC system

Preliminary testing of the new DOC concept revealed that DCMD achieves greater than 99% estrone and estradiol removal and greater than 99.9% urea removal. Furthermore, the FO membrane provides an economical means to pretreat the hygiene wastewater and prevents the RO membrane from having high fouling rates. These results confirm that MD and FO processes can be combined with RO in a hybrid membrane configuration to treat complex liquid streams that cannot be treated with the individual processes. These results are not only pertinent to NASA's DOC system but they also have implications for terrestrial wastewater treatment applications.

Terrestrially, much less emphasis is currently being placed on wastewater reclamation than on seawater desalination for direct potable water treatment. However, wastewater reclamation costs are only a fraction of seawater desalination costs. Furthermore, wastewater (sewage) is the only guaranteed abundant source of water wherever there are people. Thus, for environmental sustainability, the major barriers to direct potable reuse must be overcome. Ironically, most of these barriers relate to public acceptability rather than technical capability. Further studies on systems such as the DOC will bring the concept of direct potable reuse closer to a reality.

Sustainability: A goal for developed and developing countries

According to an Association of Environmental Engineering and Science Professors (AEESP) Research Frontier Conference summary (Dentel and Cannon, 1999), there are five research directions that must be pursued in order to meet the demands of a sustainable environment. One of these directions, “Targeted or Tailored Separation and Destruction Systems”, includes membrane processes. More specifically, the summary refers to the development of membrane applications that employ new advances in membrane chemistry, membrane physical properties, and flow configurations. Furthermore, the Desalination and Water Purification Technology Roadmap has identified membrane technologies as an area of research necessary to develop cost-effective technological tools that can be used to help solve the nation’s water supply challenges. The research areas identified in the Roadmap were selected to both speed the evolution of existing (current-generation) desalination and water purification technologies and to lay the scientific and technical foundation for the development of advanced, next-generation technologies (USBOR and SNL, 2003).

Water reuse and low energy consumption are key objectives to achieving sustainability in water and wastewater treatment. Furthermore, because energy and water are inextricably bound, energy usage and production must be considered when evaluating water and wastewater treatment processes. Thus, a major objective of all desalination investigations should be to reduce energy costs and to explore opportunities for energy production. Consideration of these objectives has led to the development of desalination systems powered by renewable energy. One of the more well-studied of these systems is solar-powered MD (Hogan et al., 1991; Banat et al., 2002). In a similar type of application, the combination of MD with a solar pond has also been considered (Walton et al., 1999). A major goal is to make these systems economically viable for remote regions.

Conclusion

MD and FO offer the potential for substantial energy and resource savings over conventional desalination processes. Use of these technologies may substantially mitigate the environmental impacts associated with current desalination practices. For developing countries, combination of these technologies with renewable energy may enable potable water production in remote, arid locations. For developed countries, combination of these technologies with existing desalination practices may help the goal of direct potable reuse come closer to a reality and the goal of zero liquid discharge be more cost efficient.

References

Banat, F.A., Jumah, R. and Garaibeh, M. (2002) Exploitation of solar energy collected by solar stills for desalination by membrane distillation. Renewable Energy 25 (2), 293-305.

Beaudry, E.G. and Herron, J.R., Direct osmosis for concentrating wastewater, Proceedings of the 27th International Conference on Environmental Systems (ICES), July 14-17, Lake Tahoe, Nevada.

Beaudry, E.G., Herron, J.R. and Peterson, S.W. (1999) Direct osmosis concentration of waste water: Final report, Osmotek Inc., Corvallis, OR.

Belfroid, A.C., Horst, A.V.d., Vethaak, A.D., Schäfer, A.J., Rijs, G.B.J., Wegener, J. and Cofino, W.P. (1999) Analysis and occurrence of estrogenic hormones and their glucuronides in surface water and waste water in the Netherlands. Science of The Total Environment 225 (1-2), 101-108.

Cartinella, J.L., Cath, T.Y., Flynn, M.T., Miller, G.C., Hunter, K.W. and Childress, A.E. (2006) Removal of Natural Steroid Hormones from Wastewater Using Membrane Contactor Processes. Environmental Science and Technology 40 (23), 7381-7386.

Cath, T.Y., Adams, V.D. and Childress, A.E. (2004) Experimental study of desalination using direct contact membrane distillation: A new approach to flux enhancement. Journal of Membrane Science 228 (1), 5-16.

Cath, T.Y., Childress, A.E. and Elimelech, M. (2006) Forward osmosis: principles, applications, and recent developments. Journal of Membrane Science 281 (1-2), 70-87.

Childress, A.E. and Cath, T.Y. (2006) Direct contact membrane distillation and forward osmosis for the concentration of primary and secondary RO brine - Final Report, University of Nevada, Reno, Reno, NV.

Cooley, H., Gleick, P.H. and Wolff, G. (2006) Desalination, with a grain of salt, Pacific Institute for Studies in Development, Environment, and Security, Oakland, CA.

Dentel, S. and Cannon, F., Proceedings of the Association of Environmental Engineering and Science Professors Research Frontiers Conference, July 31-August 3, 1999,

El-Bourawi, M.S., Ding, Z., Ma, R. and Khayet, M. (2006) A framework for better understanding membrane distillation separation process. Journal of Membrane Science 285 (1-2), 4-29.

Ettouney, H.M., El-Dessouky, H.T., Faibish, R.S. and Gowin, P.J. (2002) Evaluating the economics of desalination. Chemical Engineering Progress 98 (12), 32-39.

Hogan, P.A., Sudjito, Fane, A.G. and Morrison, G.L. (1991) Desalination by solar heated membrane distillation. Desalination 81, 81-90.

Johnson, A.C., Belfroid, A. and Corcia, A.D. (2000) Estimating steroid estrogen inputs into activated sludge treatment works and observations on their removal from the effluent. Science of The Total Environment 256 (2-3), 163-173.

Johnson, A.C. and Sumpter, J.P. (2001) Removal of Endocrine-Disrupting Chemicals in Activated Sluge Treatment Works. Environmental Science & Technology 35 (24), 4697-4703.

Lawson, K.W. and Lloyd, D.R. (1997) Review: membrane distillation. Journal of Membrane Science 124 (1), 1-25.

Loeb, S. and Sourirajan, S. (1962) Sea water demineralization by means of an osmotic membrane. Advances in Chemistry Series 38, 117-132.

Martinetti, C.R., Cath, T.Y. and Childress, A.E., Novel application of membrane distillation and forward osmosis for brackish water desalination, Proceedings of the 2007 AWWA Membrane Technology Conference and Exposition, March 18-21, 2007, Tampa, FL.

Martinez-Diez, L. and Florido-Diez, F.J. (2001) Desalination of brines by membrane distillation. Desalination 137, 267-273.

McCutcheon, J.R., McGinnis, R.L. and Elimelech, M. (2005) Desalination by a novel ammonia-carbon dioxide forward osmosis process: Influence of draw and feed solution concentrations on process performance. Journal of Membrane Science 278 (1-2), 114-123.

Reid, C.E. and Breton, E.J. (1959) Water and ion flow across cellulosic membranes. Journal of Applied Polymer Science 1 (2), 133-143.

Schirber, M. (2007) Why desalination doesn't work (yet), www.livescience.com/environment/070625_deesalination_membranes.html.

Service, R.F. (2006) Desalination Freshens Up. Science 313, 1088-1090.

Tsiourtis, N.X. (2001) Desalination and the environment. Desalination 138 (1-3), 1.

USBOR and SNL (2003) Desalination and Water Purification Technology Roadmap - A Report of the Executive Committee, Bureau of Reclamation, Denver Federal Center, Denver, CO, http://www.sandia.gov/water/docs/RoadmapV21.pdf.

Walton, J., Solis, S., Lu, H., Turner, C. and Hein, H. (1999) Membrane distillation desalination with a salinity gradient solar pond, http://rorykate.ce.utep.edu/Projects/1999MembraneTechConf/1999-17thAnnualMembrneTechConf.htm.

Wieland, P.O. (1994) Design for human presence in space: an introduction to environmental control and life support systems, NASA George C. Marshall Space Flight Center, Alabama, http://flightprojects.msfc.nasa.gov/book/rp1324.pdf.