High-efficiency seawater desalination via NF/RO multi-pass arrays

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ABSTRACT

In recent years, capital and operating costs of seawater desalination plants have decreased remarkably. However, production of potable water from seawater by reverse osmosis membrane desalination remains 2 to 3 times the cost of desalting brackish water, reclaiming wastewater, or importing fresh water even over long distances. In addition, rejection of boron by seawater RO membranes is generally not adequate in one pass systems without pH elevation. Further, environmental issues remain another major limitation of seawater desalination, e.g., impingement/entrainment, energy consumption, and brine discharge. This study will explore various combinations of nanofiltration (NF), brackish water RO (BWRO), low pressure RO (LPRO), and seawater RO (SWRO) membranes to more efficiently and effectively produce potable quality water from seawater.

INTRODUCTION

In recent years, reverse osmosis (RO) seawater desalination technology has undergone a remarkable transformation. The number and capacity of large RO plants have increased significantly. In a parallel shift, the capital and operating costs have decreased such that estimates of total desalted seawater cost in the U.S. ranges from $600 to $1,200 per acre-foot (af). In California, the Metropolitan Water District of Southern California has initiated a program to subsidize member agencies up to $250 /af for potable water produced from seawater. Nonetheless, production of potable water via seawater desalination remains 2 to 3 times the cost of importing water from Northern California or the Colorado River and treating local brackish and reuse waters (~$200 to $400 /af). These costs of treatment include capital cost, energy cost, operation and maintenance (O&M) cost, and material cost. Given the diminishing energy savings from increased membrane permeability and the high efficiency of pumping and energy recovery in seawater RO, further cost reductions to seawater desalination must involve increased product water recovery, decreased operating pressure, and decreased RO membrane fouling.

In the meanwhile, potential environmental impact remains another major limitation of seawater desalination and is likely the principle reason for whether or not a permit to build will be granted. Environmental issues include feed water intake, energy consumption/fossil fuel combustion, and concentrate disposal. Energy consumptions and potential global warming impact is directly related to operating pressure of seawater RO processes. Environmentalists and regulators are also concerned about the potential impact of disposed concentrate (residual) on the local marine environment. Residual from an RO plant is high in salinity as well as chemicals used in pretreatment processes (acid, caustic, polymers, etc.); therefore, it is important to reduce the volume and (potential) environmental burden of RO concentrate disposed directly into the ocean. Additional concerns about impingement and entrainment of sea creatures in seawater intake structures is another environmental concern. Use of beach wells as intake source has been popular due to the difficulty of getting a water intake source permit. Beach wells are also being considered as potential replacement for traditional seawater RO pretreatment (e.g., granular or membrane filtration), but the efficacy of beach well extraction on fouling reduction is not clear. It is critical to remove insoluble microbial, colloidal, organic, and mineral matter before the feed water enters the RO membrane.

The conventional approach to seawater desalination by RO membrane technology is the use of integrated membrane systems consisting of feed water pre-treatment processes (beach wells, media or membrane filtration, pH adjustment), a one-pass RO stage, and product water post-treatment (stabilization, boron removal, disinfection). In such a system, the energy requirements to drive the single stage RO process comprise ~40 percent of the overall cost of produced water. The RO product water recovery cannot be driven beyond about 30 to 40 percent, while disposing retentate, because increasing retentate osmotic pressure at high recovery produces a diminishing economic benefit. In addition, the higher retentate concentration increases salt passage, surface fouling, and residual concentration.

Multi-pass approaches to reduce the energy required in seawater desalination include the use of seawater RO membranes with different permeability (to balance flux and pressure through the system) or the use of multi-stage NF/RO integrated membrane systems. Feed water pre-treatment processes will remain similar to the pretreatments of conventional approach which include beach wells, media or membrane filtration, and/or pH adjustment). However, the pretreatment will be followed by different multi-pass RO approaches, and also different product water post treatment.

We hypothesize that reducing TDS, organic, and mineral concentrations of seawater through NF pre-treatment would allow use of low pressure RO membranes at higher flux (reduced “footprint” and capital cost), lower operating pressure (reduced energy cost), and higher water recovery (more product water), thus, reducing the overall cost of water produced. In addition, with reduced scaling concerns the RO process could be operated at high pH, which would enable high rejection of borate. Selective removal of minerals in the NF pre-treatment stage further allows utilization of efficient brackish water concentrate treatment processes such as chemical precipitation, as well as the option to redirect various concentrate and permeate flows to reduce pressures, enhance recovery, and minimize concentrate.

In this study, we explore the combination of true nanofiltration (NF), brackish water RO (BWRO), low pressure RO (LPRO), and seawater RO (SWRO) membranes to more efficiently and effectively produce potable quality water from seawater. Figure 1 will show the different combinations of approaches we are comparing in this study. The objective is to assess whether or not the efficiency and efficacy of membrane-based seawater desalination processes can be improved through the use of multi-pass/multi-stage arrays. Our goals are to reduce cost of desalted water, improve product water quality, provide multiple-barrier approach, effectively remove boron, and produce a less burdensome concentrate stream. Further, we hope to establish the optimal hypothetical NF/RO membrane properties needed to best utilize multi-pass/multi-stage arrays for seawater desalination.

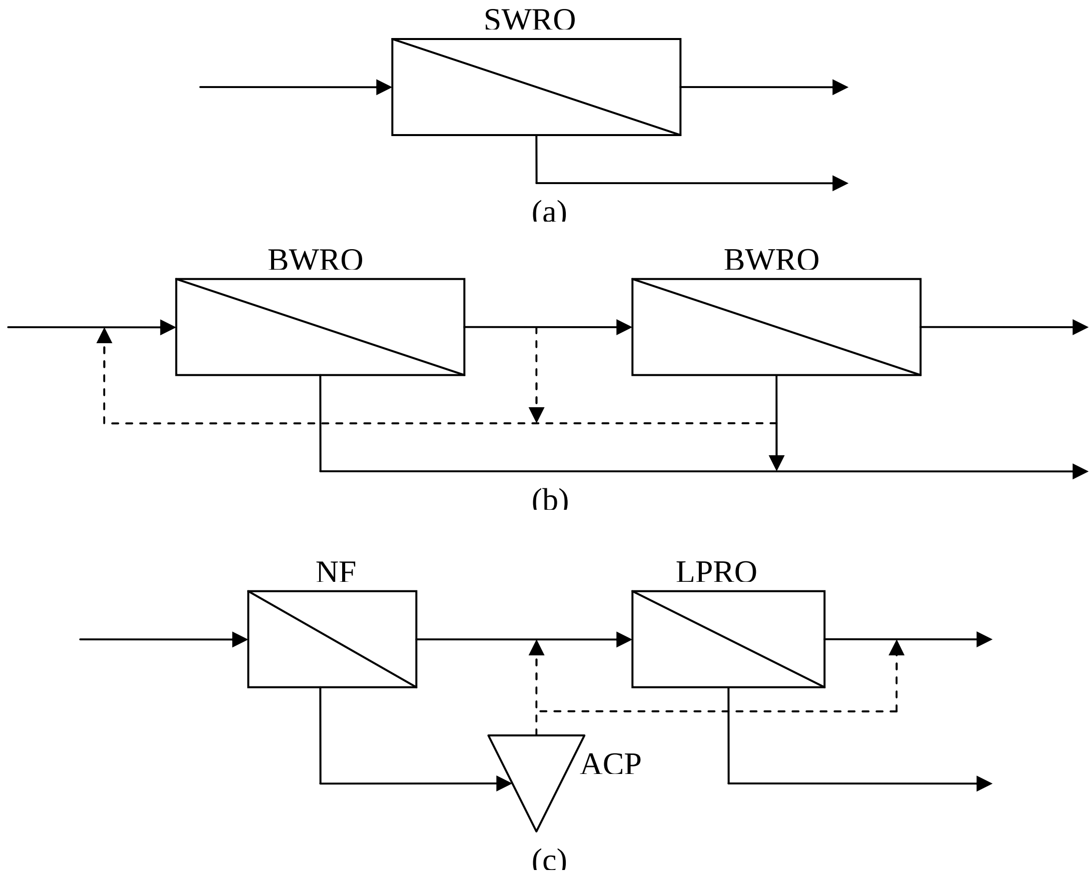

Figure 1: (a). Conventional approach using a single pass SWRO. (b). Multi-pass approach using BWRO followed by another BWRO. (c). Multi-pass approach using NF followed by LPRO while incorporating Accelerated Chemical Precipitation (ACP). Dash line represents other alternatives of redirecting flows.

MODELING

A relatively simple analytical model is used to predict and optimize product water quality, overall water recovery, and specific energy consumption. Our model is based on the following equations to predict permeate concentration, operating flux, and specific energy consumption (SEC) (Mulder, 1992).

$$J = \frac{\Delta p_{avg} - \Delta \pi_{avg}}{\mu R_m} \tag{1}$$

$$R = 1 - \frac{c_p}{c_f} \tag{2}$$

$$Y = \frac{Q_p}{Q_f} \tag{3}$$

$$\bar{c}_p = \frac{c_f}{Y}\left[1 - (1 - Y)^{1-R}\right] \tag{4}$$

$$c_r = c_f \frac{\left[1 - Y(1 - R)\right]}{1 - Y} \tag{5}$$

$$SEC_{tot} = SEC_{pump} - SEC_{rec} \tag{6}$$

$$SEC_{pump} = \frac{Q_{feed} P_{feed}}{Q_{perm} \eta_{pump}} = \frac{P_{feed}}{Y \eta_{pump}} \tag{7}$$

$$SEC_{rec} = \frac{Q_{ret} P_{ret} \eta_{rec}}{Q_{perm}} = \left(\frac{1}{Y} - 1\right) P_{ret} \eta_{rec} \tag{8}$$

$$P_{feed} = \Delta p_m + \Delta \pi_m + \Delta p_x \tag{9}$$

$$\Delta p_m = J \mu R_m \tag{10}$$

$$\Delta \pi_m = f_{os} \Delta c = 0.0106 (psi \cdot L / mg) \Delta c \, (mg / L) \tag{11}$$

$$\Delta p_x = N_{elem} \times \Delta p_{elem} = N_{elem} \times 8 (psi / elem)^* \tag{12}$$

$$P_{ret} = P_{feed} - \Delta p_x \tag{13}$$

Here J is permeate flux, R is rejection, Y is recovery, c_p is permeate concentration, c_f is feed concentration, Q_{feed} is feed flow, Q_{perm} is permeate flow, and Q_r is retentate flow. We will assume pump efficiency, η_{pump} = 80%, and energy recovery efficiency, η_{rec} = 95%. From equation (12), 8 psi of pressure drop per element is assumed, and efficiency of pump and energy recovery system is assumed.

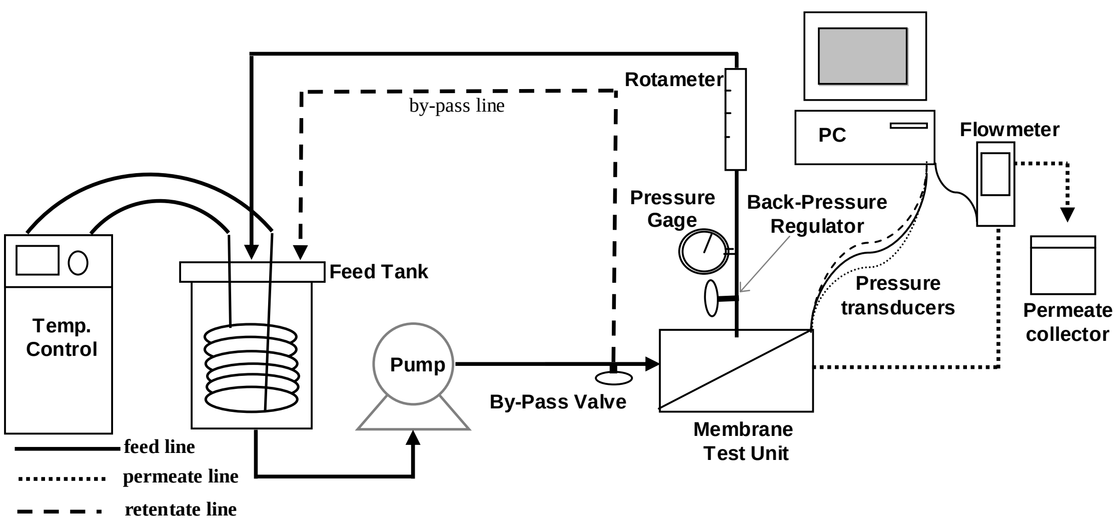

Figure 2: Experimental crossflow RO system.

Table 1: Synthetic seawater recipe

Major Ion	Symbol	Valence	g/mol	g/kg	g/L
Chloride	Cl^-	-1	35.453	19.353	**19.837**
Sodium	Na^+	1	22.990	10.781	**11.051**
Sulfate	SO_4^{2-}	-2	96.062	2.712	**2.780**
Magnesium	Mg^{2+}	2	24.312	1.284	**1.316**
Calcium	Ca^{2+}	2	40.078	0.412	**0.422**
Potassium	K^+	1	39.102	0.399	**0.409**
Bicarbonate	HCO_3^-	-1	61.017	0.126	**0.129**
Bromide	Br^-	-1	79.909	0.067	**0.069**
Boron	$B(OH)_3$	-1	61.830	0.026	**0.026**
Strontium	Sr^{2+}	2	87.620	0.008	**0.008**
Fluoride	F^-	-1	18.998	0.001	**0.001**
			Sum =	**35.169**	**36.048**

Note: Seawater density is assumed to be 1025 kg/m^3

RESULTS AND DISCUSSION

Figures 3, figure 4, and figure 5 are produced by our model simulation. The graph in figure 3 represents the difference of SECs required by different types of membranes. Each membrane behaves as expected, depending on the membrane properties (specific flux and rejections). The membrane with higher specific flux and lower rejection requires less SEC. This graph also shows the importance of energy recovery. An energy recovery system can save us almost half in SEC. The graph in figure 4 represents the difference of SECs required by each scenario without considering energy recovery. According our simple model, without the use of ACP, NF followed by LPRO is very energy intensive. However, combined with ACP, NF-LPRO is more energy efficient than a conventional single pass RO system. This combined with advantages of a multi pass system (effective boron removal, multi barrier approach, less than 600 psi pump equipment, etc.) makes this arrangement to look very attractive. The graph is figure 5 represents the difference of SECs required by each scenario including energy recovery. According to our model, it seems that the 2P-BWRO might have recovery limitation of staying below about 40 percent

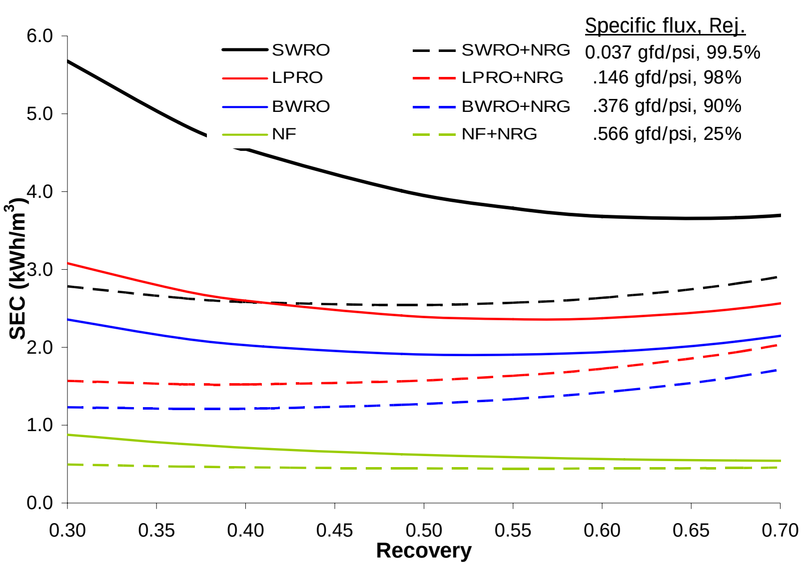

Figure 3: Specific energy consumption (SEC) with and without energy recovery (ER) for each type of membrane treating raw seawater.

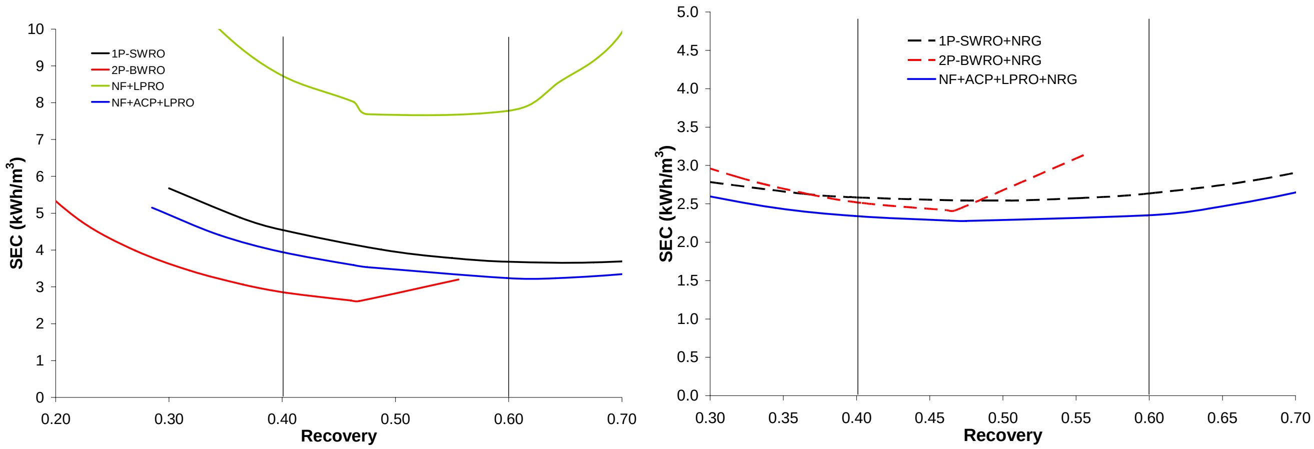

Figure 4: Specific energy consumption for all three system configurations (a) without energy recovery and (b) with energy recovery. Note the use of an inter-stage chemical precipitation process to demineralize stage 1 nanofiltration concentrate and re-blend with permeate substantially reduces the overall energy demand.

Summary and Conclusion

In conclusion, we now know that the multi pass systems are potentially better than the conventional single pass RO approach. It reduces TDS, foulant, and mineral concentration, removes organic matters and divalent ions effectively; which allows us to operate the reverse osmosis module (2nd pass) at higher flux which then reduces capital cost. We also think that the NF pretreatment will be a beneficial approach to a multi pass approach. It provides selective ion removal, and combined with ACP, it can yield higher product water recovery, reduced energy consumption, less brine, and stable permeate water quality. Future work is to continue with bench scale experiments using brackish water reverse osmosis membrane, nanofiltration membrane, conventional seawater reverse osmosis membrane, and ultra low pressure reverse osmosis membrane. And continue with model work, and eventually develop a model that can predict the behavior of each individual ions for any given membrane properties.

Acknowledgments

The authors are grateful for financial support received from the UCLA Henry Samueli Fund.

Reference:

Mulder, M., *Basic Principles of Membrane Technology*, Second Edition, Kluwer Academic Publishers: Dordrecht/Boston/London, 1996, Chapter 8.