Energy Cost Optimization In Membrane Desalination and the Thermodynamic Restriction[*,†,‡,§,¶,‖,**,††]

Aihua Zhu, Panagiotis D. Christofides and Yoram Cohen
Department of Chemical and Biomolecular Engineering
Water Technology Research Center
University of California, Los Angeles, CA 90095-1592, U.S.A.

September 21, 2008

Reverse osmosis (RO) membrane water desalination is now well established as a mature water desalination technology. However, there are intensive efforts to reduce the cost of RO water desalination in order to broaden the appeal and deployment of this technology. The water production cost in a typical RO desalination plant generally consists of the cost of energy consumption, equipment, membranes, labor and maintenance and financial charges. Energy consumption is a major portion of the total cost of water desalination[1–3] and can reach as high as about 58% of the total permeate production cost as shown in Fig. 1. The energy cost per volume of produced permeate (i.e., the Specific Energy Consumption or SEC) is significant in RO operation due to the high pressure requirement (up to about 1000 psi for seawater and in the range of 100-600 psi for brackish water desalting). Considerable effort has been devoted to find means for reducing the transmembrane pressure required for a given water permeate productivity level dating back to the initial days of RO development in the early 1960's.

[*] American Institute of Chemical Engineers (AIChE),
[†] Annual Meeting,
[‡] November 16-21, 2008,
[§] Loews Philadelphia Hotel,
[¶] Philadelphia Marriott Downtown,
[‖] Pennsylvania Convention Center,
[**] Philadelphia, Pennsylvania, USA,
[††] Paper 624b

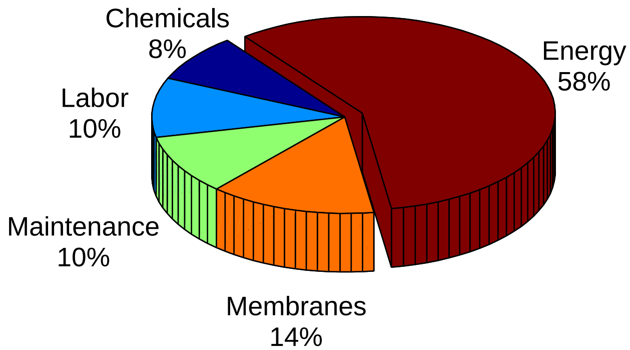

Figure 1: Annual operating cost distribution of a seawater reverse osmosis facility[4].

Early research in the 1960's[5–8] focused on unit cost optimization with respect to water recovery, energy recovery system efficiency, feed flow rate and the applied transmembrane pressure. Efforts to reduce the SEC also considered increasing the permeate flow rate, at a given applied pressure and feed flow rate, by either optimizing the membrane module with respect to its permeate flux[9–16] and/or by using more permeable membranes[17–20]. For example, studies have shown that specific permeate productivity of spiral wound RO and nanofiltration modules could be improved by optimizing module configuration (e.g., feed channel height, permeate channel height, and porosity)[13].

The introduction of highly permeable membranes in the mid 1990's with low salt passage[17] has generated considerable interest given their potential for reducing the pumping energy required to attain a given permeate[17–20]. Wilf[17] and later Spiegler[21] reported that operation close to the minimum level of applied pressure (i.e., pressure approaching the concentrate osmotic pressure plus frictional pressure losses), would result in the lowest energy cost. Clearly, in the absence of pressure drop in the membrane module, the minimum required applied pressure when a highly permeable membrane is used would be very close to the osmotic pressure of the RO concentrate that would be reached at the membrane outlet[17,22–24]. As illustrated in Fig. , in order to achieve a given water recovery and utilize the entire membrane area, there is a minimum pressure that must be applied and this pressure must be greater than the osmotic pressure of the concentrate exiting the process, but this applied pressure can approach the osmotic pressure of the brine stream when highly permeable membranes are used. It is noted, that the requirement of a minimum pressure, for the lowest energy cost, will apply even when one considers concentration polarization, albeit the required pressure will be based on the osmotic pressure at the membrane surface at module exit[22].

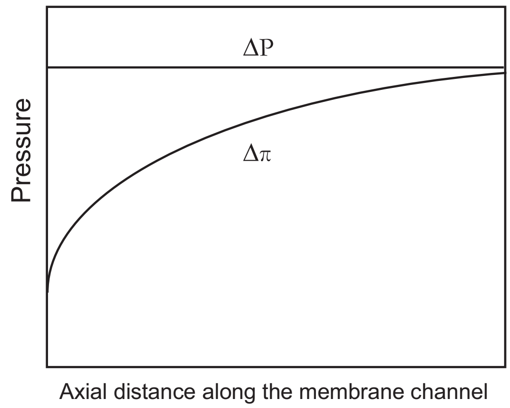

Figure 2: Schematic illustration of the thermodynamic restriction for cross-flow RO desalting[22].

In order to reduce energy consumption, energy recovery from the concentrate stream has been implemented using a variety of energy recovery devices (ERDs), in addition to optimization of the configurations of the RO membrane arrays. The effect of an energy recovery device (ERD) on the SEC was first studied in the early 1960's[6,7]. Avlonitis et al.[25] discussed four kinds of ERDs (i.e., Pelton wheel, Grundfos Pelton wheel, Turbo charger, Pressure exchanger) and reported that the pressure exchanger was the most efficient energy recovery device. More recently, Manth et al.[1] proposed an energy recovery approach, in which a booster pump is coupled with a Pelton turbine (instead of a single-component high-pressure feed pump), or is used as an interstage booster for dual-stage brine conversion systems.

Simplified process models to optimize the structure of RO membrane desalination plants have been proposed in the literature[26–33]. Early studies have shown that the "Christmas tree" configuration developed in the early 1970's was suitable for the early generation of RO spiral-wound membranes. However, with the emergence of higher permeability membranes, it is unclear if the above configuration of membrane modules is also optimal for ultra low pressure RO modules[26]. It has been argued that the SEC can be lowered by utilizing a large number of RO membrane units in parallel so as to keep the flow and operating pressure low[29]. It has also been claimed that the SEC decreases upon increasing the number of membrane elements in a vessel[3]. In the mid 1990's researchers have suggested that a single-stage RO process would be more energy efficient[34]. However, it has also been claimed that two-stage RO is more energy efficient than single-stage RO[29]. The above conflicting views suggest that there is a need to carefully compare the energy efficiency of RO desalination by appropriately comparing single and multiple-stage RO on the basis of appropriately normalized feed flow rate and SEC taking into consideration the feed osmotic pressure, membrane permeability and membrane area.

Optimization of RO water production cost with respect to capital cost has also been addressed in order to explore means of reducing the total specific cost of water production[29,34]. Such optimization studies have considered the costs associated with feed intake (primarily for seawater) and pretreatment, high pressure pumps, energy recovery system, and membrane replacement[34]. The problem of maximizing RO plant profit, considering energy cost, amortized membrane plant cost, cleaning and maintenance cost, and amortized cost of process pumps in the absence of energy recovery devices has also been addressed[29]. The majority of the existing studies have accepted the standard operating procedure whereby the applied pressures is set to be significantly higher than the minimum required pressure limit that would correspond to the lowest SEC. Moreover, a formal mathematical approach has not been presented to enable an unambiguous evaluation of the optimization of the RO water production cost with respect to the applied pressure, water recovery, pump efficiency, membrane cost and the use of energy devices.

It is important to recognize that previous studies that focused on optimization of the SEC have only evaluated the SEC dependence on water recovery at one or several normalized feed and permeate flow rates. Previous researchers have reported the minimum SEC for one or several flow rates or a range of product water recoveries[5–20]. However, the global minimum SEC has not been identified along with SEC optimization via a general theoretical framework. Motivated by the above considerations, the current study revisits the problem of RO energy cost optimization when highly permeable membranes are used, via a simple mathematical formalism, with respect to the applied pressure, water recovery, feed flow rate, and permeate flow rate and accounting explicitly for the limitation imposed by the minimum required applied pressure. Subsequently, the impact of using an energy recovery device, brine disposal cost, membrane hydraulic permeability and pressure drop within the membrane module are discussed for one-stage RO. Additionally, an analysis is presented of the energy efficiency of a two-stage RO relative to one-stage RO following the formalism proposed in the present study.

In previous work[35], we systematically studied the effect of the thermodynamic restriction (i.e., the fact that the applied pressure cannot be lower than the osmotic pressure of the exit brine stream plus pressure losses across the membrane module) on the optimization of the specific energy consumption of an RO process[35]. Specifically, we computed the optimum SEC, corresponding water recovery, and permeate flux for single-stage and two-stage RO membrane desalination systems. We also studied the effect of energy recovery device, membrane cost and brine disposal costs on SEC. The developed approach can also be utilized to evaluate the energy savings of a two-stage RO system over single-stage RO and the drawback of extra membrane area consumption of two-stage over single-stage. In the present work, we extend our previous results[35] to include the effect of membrane salt rejection on SEC and to study the energy consumption optimization of a two-pass membrane desalination process as shown in Fig. . The two-pass configuration is a relatively new configuration used in seawater desalination in which the permeate water from the first-pass goes through a second-pass. Previous work on energy consumption optimization of two-pass membrane desalination has addressed a number of issues; specifically, Noronha *et al.* first studied the specific energy consumption optimization of a two-pass (called "product-staging" in their work) membrane desalination process with recirculation pumps for each pass' retentate stream but without energy recovery devices[36]. Based on their study, they argued that the lower the water recovery in the first-pass, the lower the specific energy consumption of the two-pass system. Later on, Cardona *et al.* compared the energy consumption of a two-pass membrane desalination process (called "double-stage" in their work) without energy recovery devices to a single-stage RO process without an energy recovery device and reported that two-pass has a potential for energy savings on the order of 13-15% when the overall water recovery is less than 50% and the salt rejection is 98.3%[37]. Both papers did not address the effect of thermodynamic restriction on the computation of the optimal solution.

The wide application of low pressure membrane modules, owing to the development of high permeability RO membranes, has enabled the applied pressure in RO processes to approach the osmotic pressure limit. Therefore, it is now possible to optimize RO mem-

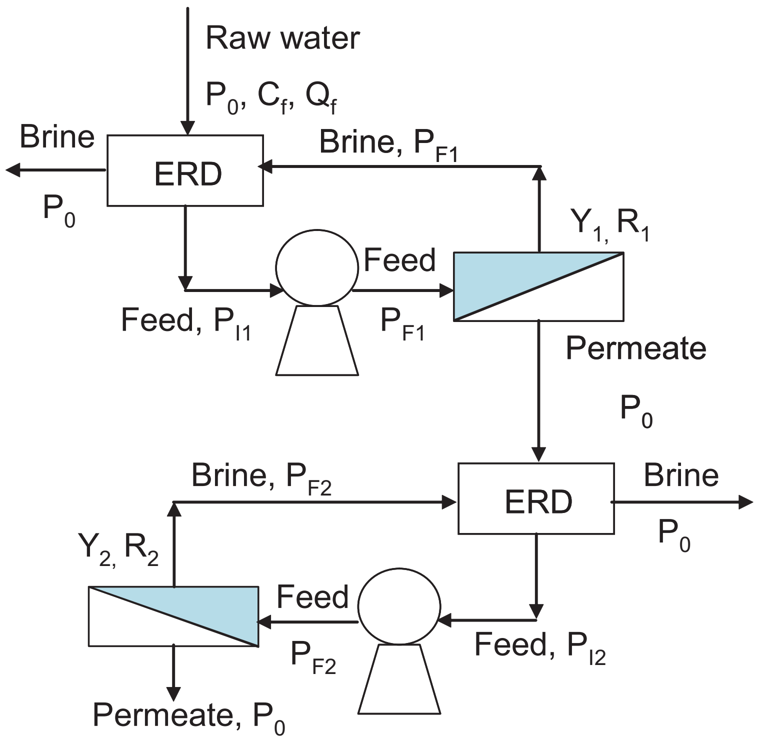

Figure 3: Schematic of a two-pass RO/NF process with ERDs.

brane processes with respect to product water recovery, with the goal of minimizing energy consumption, while considering constraints imposed by the thermodynamic cross-flow restriction and feed or permeate flow rate. In the present study, an approach to optimization of product water recovery in RO membrane desalination when highly permeable membranes are utilized was presented via a number of simple RO process models. The current results suggest that, it is indeed feasible to refine RO desalting so as to target the operation at the condition of minimum energy consumption, while considering the constraint imposed by the osmotic pressure as specified by the thermodynamic cross-flow restriction. The impact of energy recovery devices, membrane permeability, process configuration, brine management cost, pump efficiency, and frictional pressure drop can all be considered using the proposed approach as shown in a series of illustrations. Overall, as process costs above energy costs are added, the operational point for achieving minimum energy consumption shifts to higher recoveries. Although the newer generation of highly permeable RO membranes can allow high recovery operations, limitations due to mineral scaling and fouling impose additional constraints. The incorporation of these phenomena in an expanded optimization framework is the subject of ongoing research. To provide a clear picture to the problem of energy consumption optimization of two-pass reverse osmosis membrane desalination, the present work considers a systematic comparison of the SEC between single-pass and two-pass reverse osmosis systems and accounts for key practical issues like the effect of thermodynamic cross-flow restriction, energy recovery devices and concentration polarization.

References

[1] T. Manth, M. Gabor, and E. Oklejas. Minimizing RO energy consumption under variable conditions of operation. *Desalination*, 157(1-3):9–21, 2003.

[2] M. Busch and W.E. Mickols. Reducing energy consumption in seawater desalination. *Desalination*, 165:299–312, 2004.

[3] M. Wilf and C. Bartels. Optimization of seawater RO systems design. *Desalination*, 173(1):1–12, 2005.

[4] Srinivas (Vasu) Veerapaneni, Bruce Long, Scott Freeman, and Rick Bond. Reducing energy consumption for seawater desalination. *Journal AWWA*, 99:6:95, 2007.

[5] L. T. Fan, C. Y. Cheng, L. E. Erickson, and C. L. Hwang. The optimal design of desalination systems. *Desalination*, 3(2):225–236, 1967.

[6] L. T. Fan, C. Y. Cheng, L. Y. S. Ho, C. L. Hwang, and L. E. Erickson. Analysis and optimization of a reverse osmosis water purification system–part I. Process Analysis and Simulation. *Desalination*, 5(3):237–265, 1968.

[7] L. T. Fan, C. Y. Cheng, L. Y. S. Ho, C. L. Hwang, and L. E. Erickson. Analysis and optimization of a reverse osmosis water purification system–part II. Optimization. *Desalination*, 6(2):131–152, 1969.

[8] G. B. Hatfield and G. W. Graves. Optimization of a reverse osmosis system using nonlinear programming. *Desalination*, 7(2):147–177, 1970.

[9] R. Rautenbach and W. Dahm. Design and optimization of spiral-wound and hollow fiber RO-modules. *Desalination*, 65(1-3):259–275, 1987.

[10] S. Avlonitis, W. T. Hanbury, and M. B. Boudinar. Spiral wound modules performance. an analytical solution, part I. *Desalination*, 81(1-3):191–208, 1991.

[11] M. Ben Boudinar, W. T. Hanbury, and S. Avlonitis. Numerical simulation and optimisation of spiral-wound modules. *Desalination*, 86(3):273–290, 1992.

[12] S. Avlonitis, W. T. Hanbury, and M. B. Boudinar. Spiral wound modules performance an analytical solution: Part II. *Desalination*, 89(3):227–246, 1993.

[13] W. G. J. van der Meer and J. C. van Dijk. Theoretical optimization of spiral-wound and capillary nanofiltration modules. *Desalination*, 113(2-3):129–146, 1997.

[14] V. Geraldes, N. E. Pereira, and M. N. de Pinho. Simulation and optimization of medium-sized seawater reverse osmosis processes with spiral-wound modules. *Industrial & Engineering Chemistry Research*, 44(6):1897–1905, 2005.

[15] A. Villafafila and I. M. Mujtaba. Fresh water by reverse osmosis based desalination: simulation and optimisation. *Desalination*, 155(1):1–13, 2003.

[16] S.A. Avlonitis, M. Pappas, and K. Moutesidis. A unified model for the detailed investigation of membrane modules and RO plants performance. *Desalination*, 203(1-3):218–228, 2007.

[17] M. Wilf. Design consequences of recent improvements in membrane performance. *Desalination*, 113(2-3):157–163, 1997.

[18] J. E. Nemeth. Innovative system designs to optimize performance of ultra-low pressure reverse osmosis membranes. *Desalination*, 118(1-3):63–71, 1998.

[19] K. Fethi. Optimization of energy consumption in the 3300 m(3)/d RO kerkennah plant. *Desalination*, 157(1-3):145–149, 2003.

[20] J. Beca. Pharmaceutical discharge: Zero discharge for pharma plant. *Filtration & Separation*, 44(6):40–41, 2007.

[21] K. S. Spiegler and Y. M. El-Sayed. The energetics of desalination processes. *Desalination*, 134(1-3):109–128, 2001.

[22] L. Song, J. Y. Hu, S. L. Ong, W. J. Ng, M. Elimelech, and M. Wilf. Performance limitation of the full-scale reverse osmosis process. *Journal of Membrane Science*, 214(2):239–244, 2003.

[23] L. Song, J. Y. Hu, S. L. Ong, W. J. Ng, M. Elimelech, and M. Wilf. Emergence of thermodynamic restriction and its implications for full-scale reverse osmosis processes. *Desalination*, 155(3):213–228, 2003.

[24] L. Song and K. G. Tay. Performance prediction of a long crossflow reverse osmosis membrane channel. *Journal of Membrane Science*, 281(1-2):163–169, 2006.

[25] S.A. Avlonitis, K. Kouroumbas, and N. Vlachakis. Energy consumption and membrane replacement cost for seawater RO desalination plants. *Desalination*, 157(1-3):151–158, 2003.

[26] W. G. J. van der Meer, M. Riemersma, and J. C. van Dijk. Only two membrane modules per pressure vessel? hydraulic optimization of spiral-wound membrane filtration plants. *Desalination*, 119(1-3):57–64, 1998.

[27] W. G. J. van der Meer, C. W. A. Averink, and J. C. van Dijk. Mathematical model of nanofiltration systems. *Desalination*, 105(1-2):25–31, 1996.

[28] L. P. Wessels, W. G. J. Van der Meer, W. C. Van Paassen, and G. Vos. Innovative design of nano- and ultrafiltration plants. *Desalination*, 119(1-3):341–345, 1998.

[29] F. Maskan, D. E. Wiley, L. P. M. Johnston, and D. J. Clements. Optimal design of reverse osmosis module networks. *AIChE Journal*, 46(5):946–954, 2000.

[30] Y. Lu, Y. Hu, X. Zhang, L. Wu, and Q. Liu. Optimum design of reverse osmosis system under different feed concentration and product specification. *Journal of Membrane Science*, 287(2):219–229, 2007.

[31] N. G. Voros, Z. B. Maroulis, and D. Marinos-Kouris. Short-cut structural design of reverse osmosis desalination plants. *Journal of Membrane Science*, 127(1):47–68, 1997.

[32] N. Voros, Z. B. Maroulis, and D. Marinos-Kouris. Optimization of reverse osmosis networks for seawater desalination. *Computers & Chemical Engineering*, 20(Supplement 1):S345–S350, 1996.

[33] H. J. See, V. S. Vassiliadis, and D. I. Wilson. Optimisation of membrane regeneration scheduling in reverse osmosis networks for seawater desalination. *Desalination*, 125(1-3):37–54, 1999.

[34] A. Malek, M. N. A. Hawlader, and J. C. Ho. Design and economics of RO seawater desalination. *Desalination*, 105(3):245–261, 1996.

[35] A. Zhu, P. D. Christofides, and Y. Cohen. Effect of thermodynamic restriction on energy cost optimization of RO membrane water desalination. *Ind. Eng. Chem. Res.*, 2008.

[36] M. Noronha, V. Mavrov, and H. Chmiel. Simulation model for optimisation of two-stage membrane filtration plants–minimising the specific costs of power consumption. *Journal of Membrane Science*, 202(1-2):217–232, 2002.

[37] E. Cardona, A. Piacentino, and F. Marchese. Energy saving in two-stage reverse osmosis systems coupled with ultrafiltration processes. *Desalination*, 184(1-3):125–137, 2005.