Unlocking High-Salinity Desalination with Cascading Osmotically Mediated Reverse Osmosis: Analysis of Energy, Pressure, and Membrane Transport Properties

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ABSTRACT

Management and treatment of high-salinity brines (> ≈70,000 ppm TDS) have rapidly risen to be major environmental challenges. Prevailing thermally-driven desalination methods are highly energy-intensive. Reverse osmosis (RO) is the most energy-efficient and cost-effective technique for seawater desalination (≈35,000 ppm TDS), but are constrained to operating pressures of below ≈85 bar and is, hence, unsuitable for handling high-salinity brines. To overcome limitations of conventional RO, recently we proposed a novel cascading osmotically mediated reverse osmosis (COMRO) technology to extend membrane-based process to high-salinity desalination. The innovation utilizes the novel design of bilateral countercurrent (BCC) reverse osmosis stages to lessen the osmotic pressure difference across the membrane, thus depressing the hydraulic pressure needed (Fig. 1A), and simultaneously reduce the energy requirement. Our analysis shows that desalinating hypersaline feed at 70,000 ppm TDS to 50% recovery would require operating pressures of below 70 bar in COMRO. On the other hand, conventional single-stage RO would require an unfeasible hydraulic pressure of 137 bar, exceeding the common operating pressure limit. To produce 1 m^3 of freshwater, COMRO requires 3.35, 3.22, and 3.16 kWh energy with two, three, and four BCC stages, respectively (Figure 1B), achieving energy savings of up to 16.7% compared to conventional single-stage RO (ignoring the hydraulic pressure limitation). When COMRO is employed to boost the recovery of seawater desalination to 70% from the typical 35–50%, energy savings of up to ≈33% is achieved while operating at moderate hydraulic pressures below 80 bar (conventional RO would need 113 bar, in excess of the typical limit). We developed the governing flux equations based on advection and diffusion, and modeled water and salt transport in COMRO desalination. Membrane transport performance under hypersaline conditions are experimentally characterized to validate the model. Our study indicates that transport properties of the membrane active layer are detrimentally affected by atypically high salinities. This study highlights the encouraging potential of energy-efficient COMRO to access unprecedented high recovery rates and treat hypersaline brines at moderate hydraulic pressures, and builds up framework for understanding fundamental transport properties of COMRO in hypersaline desalination, setting foundations for advancing the promising technology.

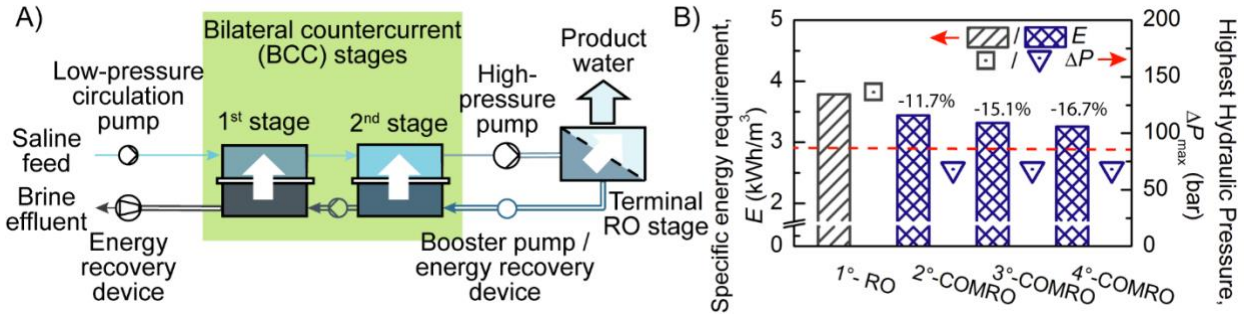


Figure 1. **A)** Schematic diagram of a 2-stage COMRO, comprising 2 BCC stages and a terminal RO stage. Input feed is diluted in 2 BCC stages (green shaded area) before directed to a terminal standard RO module to produce freshwater. The retentate stream is cycled back to the cascading BCC stages in countercurrent flow, and the applied hydraulic pressure of each stage drives water permeation across the membrane, concentrating the retentate stream to a hypersaline brine for discharge. Color intensity of the streams and stages represents salinity, while the white block arrows in the membrane modules indicate water permeation direction. Double and single lines denote pressurized and ambient pressure streams, respectively. **B)** Specific energy requirement, E (columns, left vertical axis), and highest hydraulic pressure, ΔP_{max} (symbols, right vertical axis), of conventional single-stage RO (1°-RO) and COMRO with 2–4 BCC stages (2°, 3°, 4°-COMRO) for desalination of hypersaline feed at 70,000 ppm TDS to 50% recovery. The red horizontal dash line denotes 85 bar (left vertical axis), which is the traditional operating pressure limit of RO.