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High Recovery Seawater Desalination by Energy-Efficient Reverse Osmosis (EERO) Processes

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Introduction

Challenge: Current single-stage reverse osmosis (SSRO) process requires high energy (or pressure) at high recovery, so typical recovery of SWRO is ~ 50%

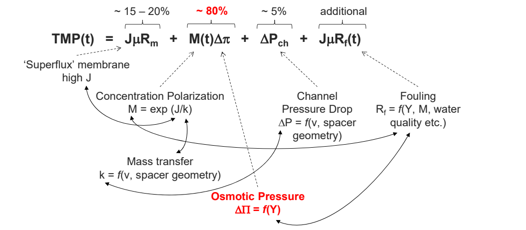

Fig 1. Pressure (Energy) requirement in RO process

Methodology

Energy-efficient reverse osmosis (EERO) through multi-stage processing and optimization to improve overall recovery at modest energy requirement

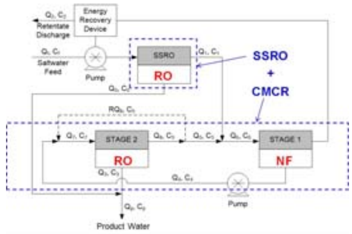

Fig 2. Schematic of 1-2 EERO process

Features of EERO Process:

- ❑ Capitalizes on SSRO performance by using its **brine as the feed** to a counter-current membrane cascade (CMCR)
- ❑ Reduces OPD by employing one or more **nanofiltration (NF) stages** in CMCR that provide retentate self-recycling
- ❑ **Permeate** from NF stage is further processed by RO stage to obtain product water while **retentate** from RO is **recycled** in CMCR
- ❑ All stages operated at **same osmotic pressure differential (OPD)** to avoid interstage pumping on retentate side and entropy-of-mixing effects

Results and Discussion

Process modeling and economic analysis:

Table 1. Mathematical model to account for Y, $\Delta\pi$ and SEC_{net}

Process	Y	SEC_{net}
SSRO	$1-\frac{K}{\Delta\pi}(C_f-C_0)$	$\frac{1}{Y_{SSRO}}\frac{\Delta\pi}{\eta_p}-\frac{1-Y_{SSRO}}{Y_{SSRO}}\eta_{ERD}\Delta\pi$
1-2 EERO	$\frac{Y_{SSRO}+1-Y_2}{2-Y_2}$ where $Y_1+Y_2=1$	$\left[1+\frac{1-Y_{SSRO}}{Y_2(1-Y_2+Y_{SSRO})}\right]\frac{\Delta\pi}{\eta_p}-\left[\frac{1-Y_{SSRO}}{Y_{SSRO}+(1-Y_2)}\right]\eta_{ERD}\Delta\pi$
1-3 EERO	$Y_{SSRO}+\frac{1}{2}(1-Y_{SSRO})$ where $Y_1+Y_2=1$, $Y_2+Y_3=1$	$\left[1+\frac{1-Y_{SSRO}}{Y_3(1-Y_3)(1+Y_{SSRO})}\right]\frac{\Delta\pi}{\eta_p}-\left[\frac{1-Y_{SSRO}}{1+Y_{SSRO}}\right]\eta_{ERD}\Delta\pi$

K : Conversion factor from concentration to osmotic pressure
C_f : Feed concentration
C_0 : Concentration of product water from SSRO
Y : Overall recovery; and with subscript SSRO, 1, 2, and 3 represents single stage RO, stage 1, stage 2, and stage 3 in the SSRO or EERO process
η_P : Pump efficiency
η_{ERD} : Energy recovery device efficiency
$\Delta\pi$: Osmotic pressure differential (OPD)
SEC_{net} : Net specific energy consumption

- o In 1-3 EERO, there are 3 stages in the CMCR with two NF stages and one terminal RO stage

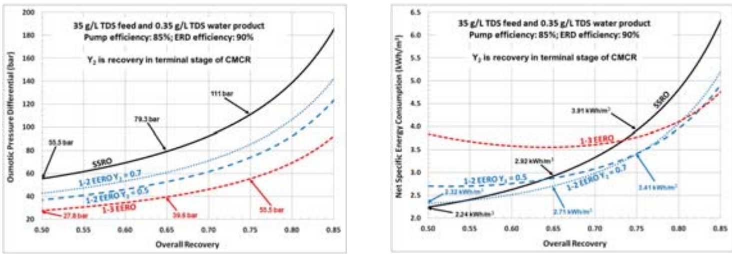

Fig 3. OPD and SEC_{net} vs. recovery for SSRO, 1-2 EERO and 1-3 EERO

Table 2. Performance metrics

Process	OPD (bar)			SEC_{net} (kWh/m³)			Fixed Cost (\$/m³)			Operating Cost (\$/m³)			Total Cost (\$/m³)		
	Recovery			Recovery			Recovery			Recovery			Recovery		
	50	65	75	50	65	75	50	65	75	50	65	75	50	65	75
SSRO	55.5	79.3	111	2.24	2.92	3.92	0.440	-	-	0.560	-	-	1.00 *	-	-
1-2 EERO	37.0	52.9	74.0	2.71	2.88	3.42	-	0.410	0.351	-	0.594	0.613	-	1.004	0.963
1-3 EERO	27.7	39.5	55.5	3.68	3.46	3.70	-	0.521	0.419	-	0.716	0.682	-	1.237	1.101

- o Most commercial membranes have a pressure limit of 69 bar (80 bar for some special membranes). Numbers highlighted in grey are for purpose of comparison and may not be applicable in practice.
- o * Annualized fixed, operating and total costs of water production for EERO processes at all recoveries normalized with respect to \$1.00/m³ for conventional SSRO at 50% water recovery, n = 20 and i = 7.5%
- o 35 g/L TDS feed and 0.35 g/L TDS water product; pump efficiency: 85% and ERD efficiency: 90%; No R_m, CP, ΔP_{ch}, fouling

- ❑ **Reduction in OPD and SEC_{net} of EERO compared to SSRO at same recovery**
  - ▪ 30 – 50% lower OPD at all recovery levels
  - ▪ Only able to lower the SEC_{net} above the 'critical' recovery due to pumping requirement to raise the pressure of the NF permeate to terminal RO stage
- ❑ **Competitive total cost of water production**
  - ▪ Potential savings in in fixed cost due to less pretreatment and brine disposal

Pilot test: CMCR in EERO process, capacity of 15 m³/d, SSRO brine as feedwater, no ERD, over 5 months

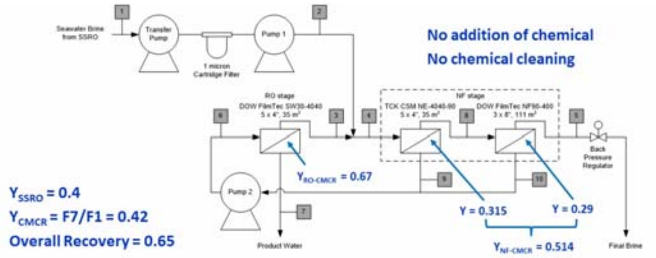

Fig 4. Schematic of CMCR in EERO process at Tuas R&D facility

Table 3. Process parameters and water analysis

Parameter	1	2	3	4	5	6	7	8	9	10
Pressure [bar]	atm	49.4±1.9	49.7±1.9	49.1±1.9	45.0±2.0†	49.8±1.9	atm	-	-	-
Flow [m³/d]	38.1±1.3	38.1±1.3	7.6±1.1	45.7±1.8	22.5±0.8	23.6±2.0	15.9±1.4	31.3±0.9	14.4±2.1	9.1±0.6
TDS [mg/L]‡	47600 ±2800	47600 ±2800			82000 ±8100	21900 ±1100	240 ±30			
TOC [μg/L]	2257 ±786	2257 ±786			3600 ±875	467 ±139	104 ±39			

† The pressure drop to 45 bar due to the change in pressure vessel size from 4" to 8"
‡ expressed as NaCl; seawater TDS = 28000 mg/L, Y_{SSRO} = 0.4

- ❑ **Energy consumption of 1-2 EERO at 65% recovery (with HP 85%, ERD 90%)**

$$= \frac{(11.5+4.3)\times 49.1}{(4.6+2.9)\times 0.85\times 36} - \frac{4.0\times 49.1\times 0.9}{(4.6+2.9)\times 36} = 2.73\ \text{kWh/m}^3$$

2.30 kWh/m³ (only consider thermodynamic limit)

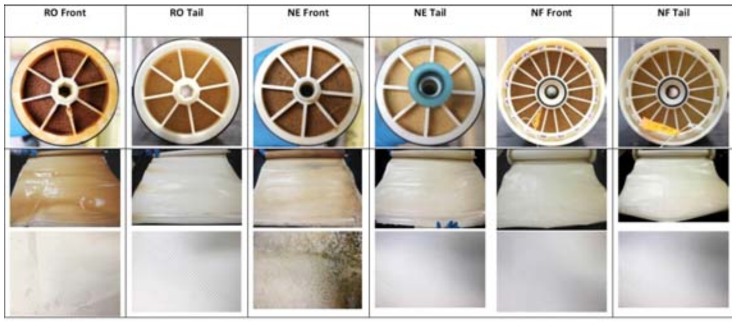

Fig 5. Membrane autopsy

- ❑ **Modest membrane fouling** observed with 1st NF element suffered the most severe (bio)fouling

Conclusions

EERO Process:

- ❑ Can achieve higher overall water recoveries at a significantly reduced osmotic pressure differential (OPD) and at a competitive specific energy consumption (SEC_{net})
- ❑ Offers potential savings in the total cost of water production
- ❑ Pilot test of CMCR in the 1-2 EERO process was demonstrated using SSRO brine as feed water; an overall recovery of 65% can be achieved at 2.73 kWh/m³

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This research grant was supported by the Singapore National Research Foundation (NRF) under its Environment and Water Research Program and administered by PUB.