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Pushing desalination recovery to the maximum limit: Membrane and thermal processes integration

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ABSTRACT

The economics of seawater desalination processes has been continuously improving as a result of desalination market expansion. Presently, reverse osmosis (RO) processes are leading in global desalination with 53% share followed by thermally driven technologies 33%, but in Gulf Cooperation Council (GCC) countries their shares are 42% and 56% respectively due to severe feed water quality. In RO processes, intake, pretreatment and brine disposal cost 25% of total desalination cost at 30–35% recovery. We proposed a tri-hybrid system to enhance overall recovery up to 81%. The conditioned brine leaving from RO processes supplied to proposed multi-evaporator adsorption cycle driven by low temperature industrial waste heat sources or solar energy. RO membrane simulation has been performed using WinFlow and IMSDesign commercial softwares developed by GE and Nitto. Detailed mathematical model of overall system is developed and simulation has been conducted in FORTRAN. The final brine reject concentration from tri-hybrid cycle can vary from 166,000 ppm to 222,000 ppm if RO retentate concentration varies from 45,000 ppm to 60,000 ppm. We also conducted economic analysis and showed that the proposed tri-hybrid cycle can achieve highest recovery, 81%, and lowest energy consumption, 1.76 kWh_{elec}/m^3, for desalination reported in the literature up till now.

1. Introduction

The economics of seawater desalination processes has been continuously improving as a result of desalination market expansion. The competition attracted many manufacturers to develop new processes and material for better recoveries. Lower operating cost has been achieved by efficient operation strategies and better recoveries and the capital investment dropped many folds due to competent system designs and material development [1–4]. Thermally driven (MSF & MED) and membrane separation (RO) processes are commercially available desalination technologies covering almost 90% of World market. Their share in desalination sector varies in different part of the World and it depends on feed water quality. Overall, RO processes are leading with 53% share followed by thermally driven technologies 33% and remaining is covered by other emerging processes such as ED, MD etc. In GCC, thermally driven processes contribution is the highest, 56% followed by RO 42% as shown in Fig. 1 [5,6].

Table 1 shows the feed water quality from different sea sources and desalination processes application ranges [5]. RO processes are dominating in brackish water treatment market because of low concentration but recent membrane development trend increasing its application for seawater desalination from 2.0 Mm^3/day to 3.5 Mm^3/day capacity. RO processes trend is expected to be strengthen in future due to highly efficient aquaporin and graphene membrane development and energy recoveries devices [6–8]. The RO processes recovery ratio for an average seawater (35,000 ppm) has been improved tremendously from 25% in 1980s to 45% in 2016 and even up to 60% with two stage system. Sever feed condition locations such as Arabian gulf, Red Sea and Mediterranean Sea restrict RO processes recovery below 30% and they require more pre-treatment processes [9]. RO processes are safe for marine life in terms of thermal pollution since brine is rejected at ambient temperature. However, the chemicals added for the pretreatment add toxic brine pollution to marine environment and also promote RO membrane cartridge fouling [10]. RO processes have five major components namely; (i) intake system, (ii) pretreatment facility, (iii) high pressure pumps, (iv) membrane filters and (v) post treatment and brine disposal facility. The overall RO processes cost distribution is shown in Fig. 2 [11,12].

SWRO process feed quality is controlled by suspended particles concentration and sparingly soluble salts saturation levels. The common indicators used in desalination industry for suspended particles concentration are turbidity and Silt Density Index (SDI) and sparingly soluble salts concentration is indicated by Langelier Saturation Index (LSI) and the saturation ratios [13–16]. The theoretical operational

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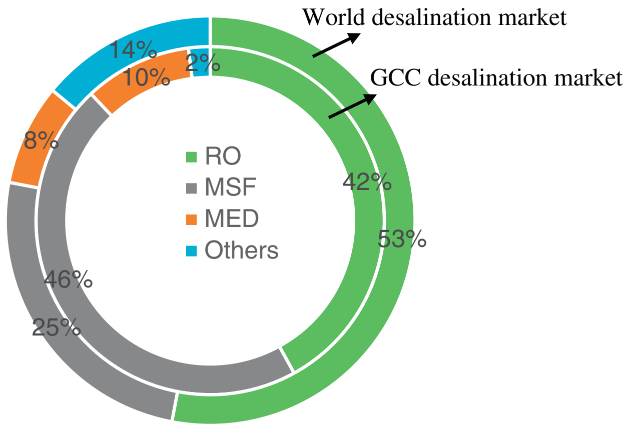

Fig. 1. Membrane and thermal processes contribution in the World and GCC desalination market [5,6].

Table 1
Sweater concentrations and appropriate desalination technologies [5].

Sea	Concentration (ppm)	Technology	Operation range (ppm)
Red Sea	40,000	Thermal processes	20,000–250,000
Mediterranean Sea	38,000	Electrodialysis	200–10,000
Black Sea	18,000	Reverse Osmosis	50–50,0000
Baltic Sea	8000	Ion Exchange	10–800
Average Seawater	35,000		

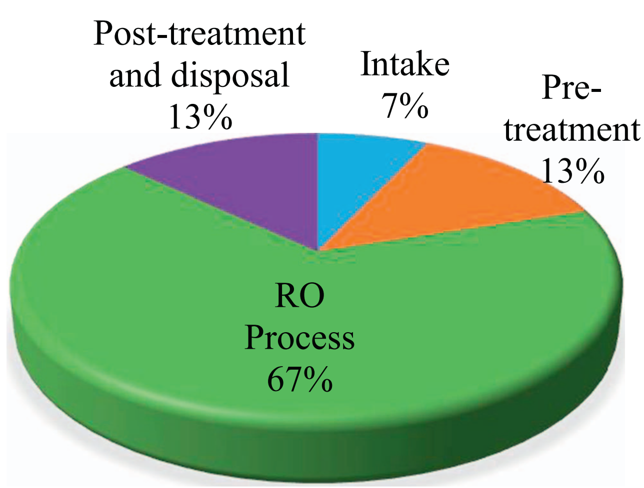

Fig. 2. Membrane processes overall cost distribution [11,12].

limits for turbidity and SDI are 1 and 4 respectively but for reliable operation the average values should be within 0.5 NTU and 2.5 SDI [17]. Continuous operation near limits may cause difficulties such as (i) scale formation when sparsely soluble salts solubility limit exceed, (ii) biofouling when secrete microorganisms polymers adhere to membrane surface, (iii) colloids agglomeration and cultivating by cross-linking with inorganic and organic polymers and attaching with membrane, (iv) seawater organic matter (SWOM) fouling due to phase separation when SWOM solubility limit exceeded [18,19]. In SWRO, biofoulant are the major foulants agents 48%, followed by inorganic colloids 18%, organic compounds 15%, silicites & silicates 13%, mineral deposits 6% and coagulants 5% [20]. Recently, microscopic algae in feed are reported as major threat to SWRO plants reliable operation. In 2008–2009, the red tide (also named as harmful algal bloom or HABs) event in the Gulf of Oman forced shutdown most of SWRO plants in the region due to pretreatment systems clogging that triggered membrane fouling due to sever feed quality. This incident cautioned water authorities and policy makers in countries relying largely on desalination that frequent HABs events can cause major problem with SWRO plants in future [21–26]. Presently, conventional pretreatment processes and intake pumping accounts for 20% of total SWRO energy consumption, as shown in Fig. 2, and yet they only reduced turbidity and SDI to some extent but these conventional processes are unable to remove particles and micro-organs [21,22]. Even though the World SWRO processes installation trend is increasing as shown in Fig. 3 [27], the reliability of continuous fresh water supply and percent recovery is still a question mark for GCC countries application. For maximum reliability and recovery, many hybrids of membrane and thermally driven systems have been proposed.

2. Desalination hybrids

Recently, hybridization trends of desalination technologies are evolving not only to improve processes performance by overcoming conventional methods limitations but also to maximize operational reliability and recovery. Helal et al. [28–30] investigated optimized minimum water cost for RO-MSF hybrid system with different configuration. They showed that MSF water production cost can be reduced 17 to 24% by hybridization. They also reported that hybrid system can boost recovery up to 40% as compared to 20% recovery of single stage SWRO. Hamed et al. [31] conducted extensive experimental study on tri-hybrid NF-SWRO-MSF system to investigate operational constraints and overall performance. They showed that brine after NF-SWRO can operate MSF unit at top brine temperature 130 °C safely because of low sulphate and calcium ions concentration that boost recovery ratio up to 69%. They also established a guideline for techno-economic viability assessment of trihybrid desalination system. Al-Mutaz et al. [32] presented MSF-RO hybrid performance combined with nuclear power plant. They showed that using MSF condenser cooling water as a RO feed can increase water production. They also summarized that, at constant pressure, membrane flux can increase 2.5% per degree feed temperature rise. Cali et al. [33] simulated 30,000 m^3/day and 100,000 m^3/day MSF-RO hybrid system integrated with co-generation plant for four different scenario in OPEC and non-OPEC countries. They concluded that water production cost is high in non-OPEC countries especially for small size plants. They simulated optimum design parameters to minimize water production cost. Cardona et al. [34] presented that RO & MSF series design can operate up to water conversion factor of 50% by maintaining MSF temperature below 120 °C to minimize $CaSO_4$ scale deposition. Al-Bahri et al. [35] analyzed feed temperature effect on RO-MSF hybrid operation. They concluded that for B10 membrane modules, optimum feed temperature ranges from 27 to 28 °C. Many other researchers [36–42] investigated technical and process feasibility of RO-MSF hybrid and showed that process hybridization can increase water recovery up to 50% and can reduce water production cost.

The hybridization of thermally driven systems such as MSF & MED with RO can improve system performance to some extent but overall recovery, 50% to 60%, is controlled by operational temperatures of MED/MSF. Top brine temperature is almost hit the limit, 130 °C, by using NF pre-treatment but lower brine temperature (LBT) is controlled by seawater cooling condenser at around 40 °C. Overcoming this LBT limitation can improve system performance tremendously without fouling and corrosion chances and can improve recovery to near crystallization range because of low operational temperature. Ng et al. [43] developed an innovative adsorption desalination (AD) cycle that can operate as low as 10 °C evaporator temperature using renewable energy or industrial waste heat from 60 °C to 80 °C for adsorbent regeneration. They calculated that specific electric energy consumption for AD cycle is about 1.38 kWh_{elec}/m^3. The detail of AD cycle can be found in the published literature [44–50]. Shahzad et al. [51–53] conducted theoretical study and simulation of AD cycle integration with MED to extend bottom brine temperature to as low as 10 °C as