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Desalination energy minimization using thin film nanocomposite membranes

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HIGHLIGHTS

- SEC of TFN RO membranes were compared with TFC RO membranes.
- TFN RO membranes exhibited up to 10% savings in SEC.
- Savings in SEC for TFN RO membranes was due to lower feed pressure requirements.

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ABSTRACT

In this study, thin film nanocomposite (TFN) reverse osmosis (RO) membranes were evaluated at a demonstration-scale facility to determine the specific energy consumption (SEC) during seawater desalination. Conventional (same element type within pressure vessel) and hybrid (high and low rejection elements within pressure vessel) configurations were evaluated and compared to commercially available thin film composite (TFC) RO membranes. The specific flux at 25 °C for TFN RO membranes was 1.72 lm^{-2} h^{-1}/bar when compared to 1.48 lm^{-2} h^{-1}/bar for TFC RO membranes. Utilization of TFN RO membranes resulted in reduced feed pressure requirements when compared to TFC RO membranes, resulting in energy savings up to 10%. In order to achieve the same permeate water quality, the SEC for a 2-pass RO system with TFN RO membrane elements in the first pass was 3.24–3.45 kWh/m^3. The SEC with TFC RO membrane elements for the same conditions was 3.60 kWh/m^3. Results presented in this study show a promise for the utilization of TFN RO membranes to reduce energy consumption and minimize operational costs associated with electricity usage.

1. Introduction

Many municipalities and water suppliers are considering seawater desalination to supplement inadequate freshwater sources due to increasing water demand. By the year 2016, the global water production by desalination is projected to exceed 38 billion m^3 per year, which is twice the rate of global production for the year 2008 [1]. Desalination processes are broadly categorized as thermal or membrane-based technologies [2]. Although thermal desalination has remained the primary technology of choice in the Middle East, membrane processes, such as reverse osmosis (RO), have rapidly developed since the 1960s [3] and currently surpass thermal processes in new plant installations [2]. More than 69% of the desalination production capacity in the United States is due to the use of RO membranes [2].

Seawater desalination is a promising option for a steady supply of high-quality water from the abundantly available source of ocean water, but the conventional RO process most widely used at present is energy intensive. Costs associated with electricity are up to 50% of the total cost of desalinated water [4]. Higher energy consumption also translates to a corresponding increase in greenhouse gas (GHG) emissions [5]. Reducing energy consumption is critical for lowering the cost of desalination and addressing environmental concerns about GHG emissions from the continued use of conventional fossil fuels as the primary energy source for seawater desalination plants.

During desalination with RO membranes, seawater is pressurized against a semi-permeable membrane that allows water to pass through while rejecting salt [6]. In order to produce desalinated water, the osmotic pressure of the source seawater and the concentrate generated during the RO process need to be exceeded [7]. The feed water to the RO is pressurized using a high pressure (HP) feed pump to supply the necessary pressure to force water through the membrane to exceed the osmotic pressure and overcome differential pressure losses through the system [8]. At present, typically, an isobaric energy recovery device

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(ERD) in combination with a booster pump is used to recover the pressure from the concentrate and to reduce the required size and energy use of the high pressure pump [8].

The energy required to desalinate seawater with RO can be expressed in terms of specific energy consumption (SEC) [8]. This is the energy required per unit output of product water from RO systems equipped with isobaric type energy recovery devices and can be calculated using the following equation [8]:

$$SEC = (E_{HP} + E_{BP} + E_{SP})/Q_P \quad (1)$$

where, SEC is the specific energy consumption (in kWh/m^3), E_{HP} is the high pressure pump-power consumed (in kW), E_{BP} is the booster pump-power consumed (in kW), E_{SP} is the supply pump-power consumed (in kW) and Q_P is the permeate flow rate expressed in m^3/h. The energy consumed by each of the RO system pumps is a function of the flow rate through the pump, pressure (total dynamic head) delivered by the pump, and the efficiencies of individual pump and motor [8]. Thus, by measuring the pressure and flow of the pumps along with the relevant motor and pump efficiencies, the SEC can be calculated.

A theoretical minimum energy is required to exceed the osmotic pressure and produce desalinated water. The energy needed for desalination using RO membranes is a function of the feed water recovery, intrinsic membrane resistance (permeability), operational flux, feed water salinity and temperature fluctuations, product water quality requirements and system configuration [4]. As the salinity of the source seawater or feed water recovery increases, the minimum energy required for desalination also increases. For example, the theoretical minimum energy for seawater desalination with 35,000 mg/L of salt and a feed water recovery of 50% is 1.06 kWh/m^3 [9]. The actual energy consumption is higher as actual plants do not operate as a reversible thermodynamic process [9]. For a similar TDS level, the lowest energy consumption reported for RO system (1st pass only) to desalinate seawater was 1.58 kWh/m^3 at a feed water recovery of 42.5% and a flux of 10.2 $lm^{-2}\,h^{-1}$ (lmh) [10]. In addition, pre- and post-treatments contribute to additional energy requirements [7]. Typically, the total energy requirement for seawater desalination using RO (including pre- and post-treatments) is on the order of 3–6 kWh/m^3 [11]. Thus, reducing the feed pressure requirement during desalination is a key to reducing energy consumption.

In the recent years, several novel membrane materials have been proposed to enhance water permeability and reduce energy consumption. Some of these promising membranes are based on graphene oxide sheets [12–14], carbon nanotubes [15–18] and aquaporins [19,20]. However, only membranes with TFN structure enhanced by zeolite nanoparticles have been commercialized to date.

Currently, TFC RO membranes are predominantly used for seawater desalination. These membranes consist of a three layer structure: a thin and dense active membrane layer (typically 100 nm in thickness), a thicker intermediate layer (approximately 40 μm) and a porous support layer [21]. A new generation of RO membrane elements, commonly referred as TFN RO membranes, has evolved based on the incorporation of nanoparticles within the active layer in order to enhance water permeability and maintain high solute rejection at the same time [22,23]. Initial development of TFN RO membranes utilized Linde type A zeolite nanoparticles within the active layer to enhance water permeability [24,25]. During commercialization of TFN membranes, alkaline earth metals, monohydrolyzed trimesoyl chloride (TMC) and other molecular additives were considered to enhance flux, maintain salt rejection and provide anti-fouling properties [26,27].

A recent study evaluated these commercially available TFN RO membranes for its performance and compared with TFC RO [28]. Results from this study indicated that the TFN RO membrane exhibited higher (twofold increase) water permeability when compared to TFC RO. However, the most important aspect of TFN RO membranes is the reduction in specific energy consumption (SEC) due to lower feed pressure requirements. The SEC of RO systems with TFN RO membranes has not been reported to date in the peer-reviewed literature. Thus, in this study, a demonstration-scale evaluation was performed to desalinate seawater using TFN RO membranes and the SEC was obtained experimentally and compared with TFC RO membrane of the same configuration and operational conditions. The specific objectives of this study were to: 1) evaluate the SEC of TFN RO systems at various operating conditions and 2) assess the performance of TFN RO membranes with respect to permeate water quality produced.

2. Materials and methods

2.1. Test site location and feed water source

Experimentation was conducted at West Basin Municipal Water District's Temporary Ocean-Water Desalination Demonstration Project site located at the L.A. Conservation Corps' SEA Lab facility in Redondo Beach, California. The feed water source was the Pacific Ocean with an open intake that utilized wedge wire screens as the first filtration step. The wedge wire screens were used to remove large pieces of debris and minimize impingement and entrainment of marine organisms. The seawater was then passed through a pretreatment process and a 2-pass RO system for desalination.

2.2. Description of treatment train

A schematic of the treatment train utilized for this study is shown in Fig. 1. The system capacity was 22.7 m^3/h and major process components of the treatment train included an Arkal microscreen disc filter, a General Electric (GE) ZeeWeed ZW1000 ultrafiltration (UF) membrane pretreatment system and a two-pass seawater RO system. After the wedge wire screens, seawater was passed through the Arkal disc filter system. The purpose of the 100 micron disc filters was to protect the UF system from damage caused by large particles, such as ocean life shell fragments. There were a total of 4 filters (2 duty and 2 standby) installed in a parallel configuration. The purpose of the UF system was to provide the required feed water quality to the RO system by removing suspended solids and maintaining a low turbidity (less than 0.1 NTU) and silt density index (SDI) (less than 2.5). The UF membrane had a nominal pore size of 0.02 μm and an outside-in geometric flow configuration. The membranes were suspended vertically in cassettes. A reverse (inside-out) flow backwash was implemented to remove foulants on the membrane surface. The backwash utilized UF filtrate water to remove any biofoulant layer. During the backwash cycle, coarse bubble aeration was also used to scour debris from the outside of the membrane surface.

The seawater RO system consisted of a two-pass system with 5 micron cartridge filters, an energy recovery device (ERD), clean-in-place (CIP) system and flush system. The 1st pass consisted of two 8-inch pressure vessels in a parallel configuration. Each pressure vessel was capable of accommodating 7 membrane elements. A Danfoss APP10.2 axial piston pump was used as the high pressure pump for the 1st pass RO system. A PX-45S ERD from Energy Recovery Inc. (ERI) was utilized for recovering the energy from the 1st pass concentrate stream. A Series 8500-2400 PX booster pump from ERI was after the ERD. A booster pump was used to boost the pressure on the high pressure portion of the system to make up the minor pressure losses that occur in the RO system, the ERD and associated piping. A portion of the 1st pass permeate (tail end elements) was sent to a 2nd pass RO system. The 2nd pass consisted of a two stage design where concentrate from the first stage was fed to the second stage and the first stage and second permeate streams were mixed together. The first stage had two pressure vessels in parallel, each containing either three or four 4-inch diameter brackish water RO elements.