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Seawater Reverse Osmosis (SWRO) desalination by thin-film composite membrane—Current development, challenges and future prospects

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ABSTRACT

Since the breakthrough discovery made by Cadotte and his co-workers in the 1970s, thin-film composite (TFC) membrane prepared using interfacial polymerization (IP) technique has experienced significant progress in composite membrane development and emerged as one of the most advanced technologies in water and wastewater purification processes. Nowadays, the most promising technology to desalinate seawater is reverse osmosis (RO), which is driven by a pressure gradient across a semi-permeable membrane. This technology has drawn great attention mainly due to its relatively low energy usage during operation as well as easy of operation and maintenance compared to other conventional technologies such as thermal desalination. On the basis of the brief introduction on TFC membrane, this paper will highlight the recent developments of RO TFC membrane and its challenges in seawater desalination process with respect to fouling problem, boron rejection and chlorine attack. Future directions in SWRO membrane research are also discussed to further expand research and development related to seawater desalination process.

1. Introduction

In the 21st century, the most crucial problem afflicting people around the world is global water scarcity. The rapid growths in population and economy have resulted in greater demand on the quantity and quality of drinking water, leading to catastrophic water shortage in arid and water-stressed region areas [1]. It is projected that by year 2030, the global needs of water would increase to 6900 billion m^3 from the current 4500 billion m^3 [2]. As a result, the present surface water resources will no longer be sufficient to meet the future needs for mankind.

With the fact that only around 0.8% of the total earth's water is fresh water [3], numerous researches were conducted in an effort to develop more sustainable technological solutions that would meet increasing water consumption. Of the technologies developed, desalting seawater to produce clean water for drinking, irrigation, industrial and urban development emerged as the most sustainable approach [4]. In general, desalination technologies can be categorized into two different mechanism separations, i.e. thermal and membrane-based desalination. The thermal processes include multi-stage flash (MSF), multiple effect distillation (MED) and vapor compression distillation (VCD), whereas membrane-based processes include reverse osmosis (RO), nanofiltration (NF) and electrodialysis (ED) [3]. Among these technologies, RO membrane desalination is the primary choice where it dominates up to 44% of the total world desalination capacity [3]. Fig. 1 presents the total amount of water produced by membrane desalination plants and thermal desalination. As can be seen, membrane desalination is projected to increase exponentially in the next 4 years whereas the growth of thermal desalination remained almost unchanged [5]. Fig. 2 on the other hand shows the global installed desalination capacity by water sources and the use of seawater as feed brine has contributed more than half of the total capacity produced worldwide [6].

Since the first invention of RO asymmetric membranes by Loeb and Sourirajan in the late 1950s, the membrane technology has shown significant progress in desalting seawater [7]. The improvements in technology as a result of the use of energy-efficient devices, innovative process designs and novel membrane materials have contributed greatly to the notable reduction in the cost of desalination. In 1998, the price of desalting 1 m^3 seawater using RO membrane was in the range of $1.00 to $2.00 [8]. The cost however has substantially dropped to $0.50–.70/$m^3$ over the last couple of years [9]. It is reported that the production cost of the world's largest SWRO desalination plant built in 2005 in Ashkelon, Israel was at $0.53/$m^3$ [3].

There are three major membrane producers supplying polyamide thin-film composite (PA-TFC) membranes worldwide. The commercial seawater membrane elements which manufactured by niche membrane producers such as Hydrautics, Dow (FilmTec) and Toray-Nitto Denko in general offer very high salt rejection (99.4–99.8%) at standard test conditions of 32,000 ppm NaCl solution at 5.5 MPa and 25 °C. In addition to the high selectivity, PA-TFC membranes also exhibit greater water permeability than those of typical asymmetric

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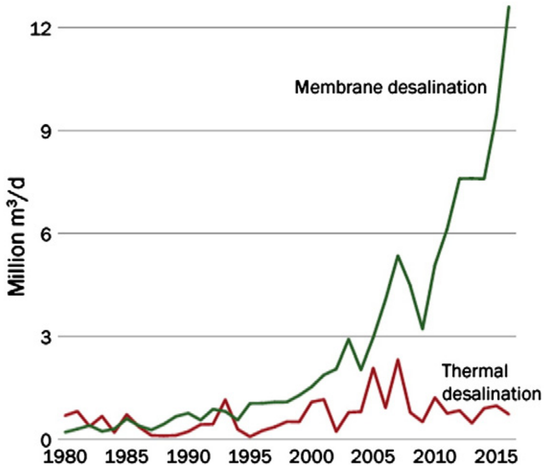

Fig. 1. Comparison between membrane desalination capacity and thermal desalination capacity from 1980 to 2016 [5].

membranes, making them remain as high-priority research domain in the past and present.

Several review articles can be found in the literature covering the development of composite RO and NF membranes [10–13]. These articles however did not address in detail the challenges faced by membrane desalination. Therefore, the aim of the present review is to bridge the gap of knowledge in seawater desalination using RO TFC membranes by providing an intensive coverage on membrane permeability and selectivity, in particular boron rejection during desalination process as well as fouling propensity and membrane degradation due to chlorine attack. It is important to review previous research works in order to provide an insight overriding the limitations of current RO membranes for the future development.

2. Preparation of thin-film composite membrane

In general, polymerization reaction takes place at the interface of the two liquids which are insoluble to each other. In order to establish a very thin PA active layer on top of a supporting membrane, the substrate typically will be first immersed into an aqueous solution consisting of amine monomer (mostly between 0.1 and 1% w/v) prior to immersion in second organic solution of acyl chloride monomer (between 0.05 and 0.2% w/v). The membrane is then subject to heat treatment at 70–90 °C to densify the polymerization properties of PA layer and/or enhance adhesion of PA thin layer to surface of support membrane. Due to the significant advantages of IP technique in optimizing independently the properties of skin layer and microporous substrate layer [14,15], a wide variety of TFC membranes have been successfully developed by many companies, allowing the applications of membranes for various industrial separation processes.

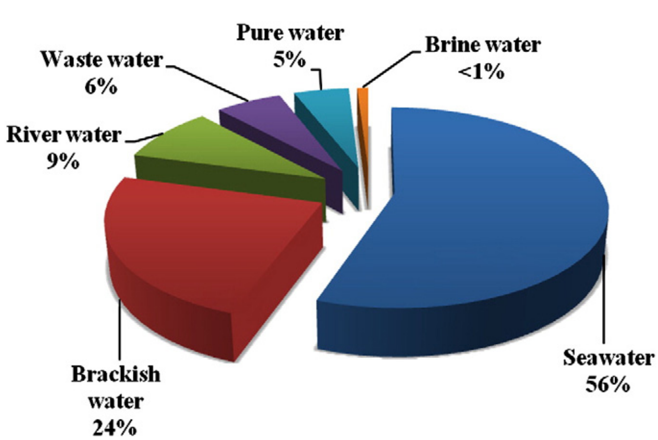

Fig. 2. The water sources used for global desalination processes [6].

Compared to asymmetric membrane, it is generally agreed that TFC membrane offers many advantages such as high water molecules transport rate, excellent mechanical properties (under high pressure of seawater desalination applications) and relatively stable over wide range of pH. A commercial FT-30 membrane developed by Filmtec Corporation for instance demonstrates up to 99.1% NaCl rejection with flux as high as 42.5 L/m^2 h at a pressure of 5.5 MPa [10]. Though TFC membranes show excellent performances with respect to flux and NaCl rejection, inadequate boron rejection efficiencies and its sensitivity to fouling and chlorine attacks are the main concerns in many industrial applications.

2.1. Challenges of RO TFC membranes in desalination industry

In desalination industry, beach wells (subsurface intakes) and open surface intakes are the two main feed water sources used in SWRO plants [3]. In general, beach wells which contain relatively low impurity content are considered when the total water production is below 4000 m^3/day. If more than 40,000 m^3 water/day is required to produce, beach wells intake is no longer applicable and open surface might be the ultimate solution to meet the requirement [3,16]. As a comparison, the concentration of total dissolved solids in open ocean intakes is relatively more consistent than that of beach well intakes, leading to more reliable desalination process [16].

As fouling problem is unavoidable in all pressure-driven membrane water separation processes, systematic identification on seawater components which contribute the most to membrane performance deterioration is highly recommended. In addition to fouling problem, inefficiency of RO membrane in boron removal coupled with sensitivity of PA selective layer to chlorine are the other main challenges encountered by SWRO. In view of this, the following subsections will discuss in detail all these challenges faced by RO TFC membranes in desalination process.

2.1.1. Fouling propensity

Fouling mainly refers to the deposition of foulants on top of the membrane surface or within the membrane pore and can be generally categorized into inorganic fouling, colloidal fouling, organic fouling and biofouling [17–20]. It must be pointed out that fouling portrays the prominent constraint in seawater desalination process. It deteriorates membrane performance and shortens its lifespan, leading to increased operation cost. For these reasons, membrane fouling control is highly recommended as an imperative way to control the economics of SWRO desalination process.

To date, biofouling which is denoted as the “Achilles heel” of membrane processes still remains one of the most technical challenges in SWRO desalination industry [21]. The adhesion of microorganisms and/or organic matters onto the PA surface promotes the development of microbial, which subsequently attributes to the formation of extra-cellular polymeric substances (EPS) on the membrane surface [22,23]. It is generally agreed that membrane resistance is increased following a biofilm formation, leading to lower water productivity. Experimental results revealed that biofilm formation could hustle the augmentation of dissolved ions on the membrane surface, resulting in remarkable increase in concentration polarization [22]. Besides, the accumulation of microorganisms such as bacteria, fungi and algae will produce acidic byproduct which is considered a major contribution for the deleterious membrane degradation [19,22]. In order to maintain water output, additional feed pressure is needed and this as a consequence results in higher energy consumption [22,23].

In the literature, many fundamental studies have been conducted to determine the mechanisms of membrane biofouling in seawater