Seawater Desalination by Reverse Osmosis: Current Development and Future Challenges in Membrane Fabrication – A Review

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SUMMARY

Seawater reverse osmosis (SWRO) is the key technology driving an energy-efficient and cost-effective desalination process. At the center of this technology are the thin film composite (TFC) membranes, which not only promise a stable operation but also high separation performances. The objective of this review is to consolidate recent advances in SWRO membranes from the standpoint of membrane materials, fabrication methodologies and applications. First, the thermodynamic limit and energy consumption of SWRO desalination are reviewed, before we discuss the current status of SWRO membranes, highlighting the four main challenges to date – permselective tradeoff, relatively low single-pass boron rejection, membrane fouling and poor chlorine resistance. Thereafter, a comprehensive review of the membrane development is presented based on findings reported in research papers and patents. Lastly, we put together an outlook, featuring our perspectives on SWRO membrane development.

KEYWORDS

Membrane fabrication, Permeability-selectivity tradeoff, Reverse osmosis, Seawater desalination, Upper-bound relationship

INTRODUCTION

Desalination has evolved into an alternative water supply in the last 40 years in response to the increasing freshwater scarcity. Seawater desalination is based on reverse osmosis or thermal technologies, with the former seawater reverse osmosis (SWRO) being dominant in the market due to its better energetics and lower footprint [1]. At the core of SWRO is the membrane unit, which comprises semi-permeable membranes capable of separating salts from water. In a typical RO process, seawater is pressurized (~55-70 bar) against the membrane that enables the selective transport of water over salt. As a consequence of the high pressure needed, the power consumption by the high-pressure pumps is the highest in an SWRO process. It is therefore imperative to develop robust and high performance SWRO membranes in order to minimize the energy consumption and capital cost of SWRO [2]. The focus of this paper targets a holistic review of SWRO membrane fabrication works in order to facilitate the resolving of various challenges in SWRO desalination. Although SWRO membranes are constantly evolving due to advancement by key membrane manufacturers, there have not been many reports on the progress of SWRO membrane development. Furthermore, due to the fact that SWRO membrane developments are mostly reported in patents, which are much less paid attention by the academic community, we attempted to incorporate SWRO membrane fabrication techniques from both research journal papers and patents to address this gap between conventional wisdom and reality. This review is expected to provide a big picture mapping for SWRO membrane researchers in academia and industry [3].

METHODS

The review starts with a revisit of the current trends in SWRO, including the energy consumption and thermodynamic limit of seawater desalination, water production costs and fundamental chemistry of SWRO membranes. Then, the current challenges, including permeability-selectivity tradeoff, insufficient boron rejection, poor chlorine resistance and membrane fouling, encountered in SWRO membrane fabrication and application are briefly discussed. Subsequently, the recent developments in SWRO membrane fabrication are reviewed under the themes of enhancing membrane permselectivity through the optimization of the support and selective layer, and methods to increase the boron rejection and chlorine resistance as well as fouling resistance. Whenever possible, the factors and mechanisms governing the fabrication of SWRO membranes are compared with brackish water RO (BWRO) membranes, so as to identify the key differences in fabrication approach for SWRO and BWRO membranes. In particular, the current status of SWRO membrane industry is highlighted. Finally, based on all the SWRO membrane performance data collated in this work, a new upper bound relationship specifically for SWRO membranes is proposed for future benchmarking. Prospective research needs and directions are also recommended to path future works in the fabrication of SWRO membranes.

RESULTS AND DISCUSSION

Our new upper bound features a new limit based entirely on SWRO data (Fig. 1). In addition, we have added TFC membranes performance results from patents to supplement those from commercial TFC membranes and the literature to provide the reader with the most complete collation of data for an accurate definition of the upper bound limit centered on the SWRO process. The new upper bound for SWRO demonstrates an unequivocal tradeoff, similar to those reported for TFC membranes for RO and NF processes. A stark difference between our upper bound as compared to others is the significantly lower limit, suggesting that performance benchmarking of TFC membranes is more befitting for SWRO.

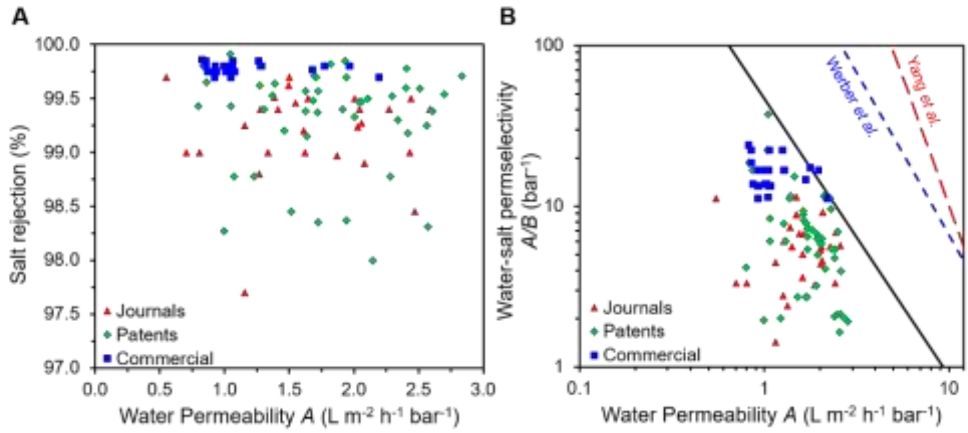

Fig. 1. Performance data of all the SWRO membranes summarized in this work, including journal papers, commercial and patents (sample size: 105). Raw plot of **(A)** water permeability and NaCl rejection and log-log plot of **(B)** water permeability and water-salt permselectivity ratio *A/B*. The new SWRO upper-bound relationship (black solid line) is proposed based on the empirical data summarized.

We envision a technology roadmap for the next-generation membranes (Fig. 2), integrating functional designs for practical solutions to alleviate the Achilles heels of SWRO membranes. As shown in the roadmap, we highlight to the reader the strategies which we feel will create impact in the short term for SWRO, and those that will require a longer term duration. Firstly, the use of filler (nano)materials to realize high-performance, high boron rejection, anti-fouling, and chlorine resistance TFN membranes is an attractive approach commonly adopted in the literature. While a breakthrough in materials for SWRO is definitely a quantum leap, there are by no means a lack of novel materials to try. Novel materials, such as carbon-based nanomaterials, MOFs, covalent-organic frameworks (COFs), zeolites, and MXenes have demonstrated promising results for SWRO. However, there remains few TFN membranes that can reach a NaCl rejection capacity of 99.8%. We attribute this to potential problems, such as materials dispersion inhomogeneity, poor particle size distribution control, compatibility issues with the PA matrix, and the lack of understanding of the roles played by the materials, which result in the formation of a PA selective layer that is deficient in handling seawater. Hence, we consider the scouting of cutting-edge materials and perfecting them for high-performance TFN-SWRO membranes will be a long-term endeavour (Fig. 2).

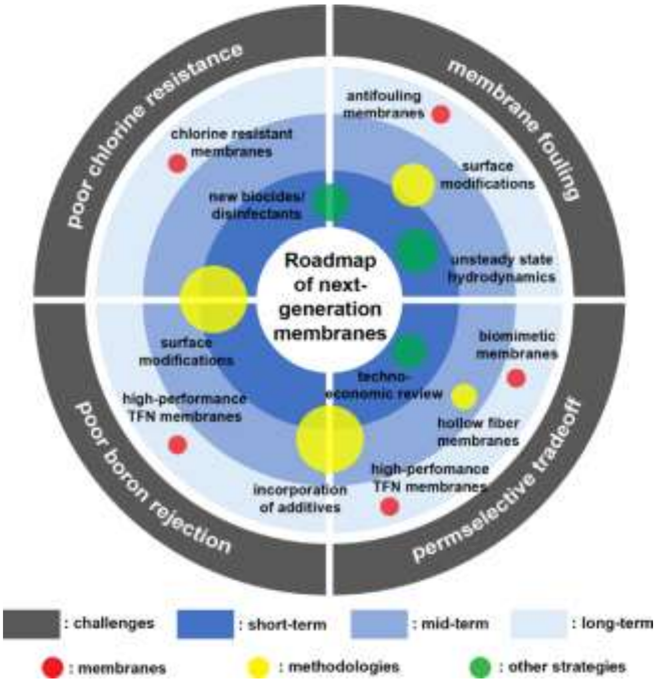

Fig. 2. Technology roadmap of the SWRO membrane fabrication, showing different short- and long-term strategies. The size of the circle represents the impacts they are likely to make towards next-generation SWRO membranes.

CONCLUSIONS

In summary, we have reviewed recent progress in TFC membrane development for SWRO, focusing on the four main Achilles heels, namely permselective tradeoff, insufficient single-pass boron rejection, membrane fouling and poor chlorine resistance. Membrane design and fabrication strategies to optimize support and selective layers of TFC membranes for improving membrane performances are evaluated, and surface-centric strategies to modify PA active layers for mitigating poor boron rejection, membrane fouling and chlorine resistance are discussed. SWRO will likely remain as the most efficient technology for seawater desalination. Moving forward, we need to discriminate TFC membrane designs that are unique to SWRO, owing to the different challenges faced in processing SWRO feed. This will allow us to better single-out effective strategies to improve TFC membrane performances for SWRO. Overall, by initiating stronger efforts in elevating membrane materials and fabrication methods to address these Achilles heels of SWRO, we are in a better position to say that next-generation SWRO membranes will be more competitive in meeting the growing demands of seawater desalination, delivering drinking water that is safe, accessible and sustainable for the benefit of all mankind.

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