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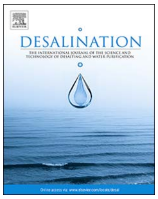

Engineering advance

Biomimetic membranes: A critical review of recent progress

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ABSTRACT

A membrane material that can concurrently provide commercially acceptable levels of water permeability, high salt rejection, and of sufficient stability to withstand mechanical and chemical stresses seems to be necessary to guarantee the energy and environmental sustainability of desalination systems and other membrane separation processes. Recent developments in desalination have shown that bio-inspired membranes are moving steadily in this direction. Sustainable desalination via aquaporin-based bio-inspired membranes is elucidated in this paper in terms of recent commercialization exploitation and progress towards real operations. Current large-scale applications, viable opportunities, remaining challenges and sustainability of operations, in terms of comparison with established technologies, are discussed in this paper. The major drawback of aquaporin-based membranes, which has been highlighted repeatedly in recent studies, is the stability of the membranes during real operations. This review is focused on recent solutions provided by scientists towards the mitigation of these problems and commercialization of aquaporin-based membranes.

1. Energy requirement as a major barrier to sustainable desalination

1.1. Current status of desalination energy requirements

The Earth's surface is composed of 71% water, of which only 1% accounts for accessible fresh water and 97% is seawater. The most threatening challenges of the 21st century are water scarcity, climate change and accelerated population growth. The latter two challenges only exacerbate the former: water scarcity is an alarming threat to our sustainability and requires immediate action. According to data obtained by UNICEF and WHO, about 1.1 billion people are without access to clean drinking water [1]. The demand for potable drinking water is increasing with the global population (Fig. 1), leading to a decrease in the available freshwater resources per capita.

For improved water sustainability, new purification methods and increased water resources are urgently required. Water desalination is one way to provide potable drinking water. Thermal processes and membrane desalination are the most common methods of modern desalination. Thermal processes, such as multi-stage flash, multi-effect distillation, vapor compression, and humidification dehumidification, usually follow the concept of evaporation and condensation of water. Membrane desalination technologies, such as reverse osmosis (RO), forward osmosis (FO), electrodialysis (ED), and nanotechnology-based processes, use membranes as salt rejection barriers to desalinate water. Membrane technology is advantageous compared to thermal processes because of comparatively low energy usage [3].

Energy is the single biggest cost component in desalination, accounting for up to half of the total cost of fresh water production [4,5]. The increasing trend in energy demand for desalination will continue into the future if necessary steps are not taken (Fig. 2). Therefore, this major problem will result in a drastic increase in global energy usage as a result of surging desalination capacity.

The energy required for desalination has considerably decreased in recent years as a result of development of energy recovery devices, more efficient of pumps and membranes, and development of improved configurations [7,8]. However, when the magnitude of the world's total desalination capacity is taken into consideration the total energy cost is still considerable. For the desalination step alone, high-performance membranes which are capable of desalinating seawater through an RO process at an energy level of 1.8 kWh/m^3 (just above the thermodynamic minimum) and 50% freshwater recovery have been demonstrated [9]. The question to ask is: which step in the overall desalting system requires the most attention in order to optimize energy effi-

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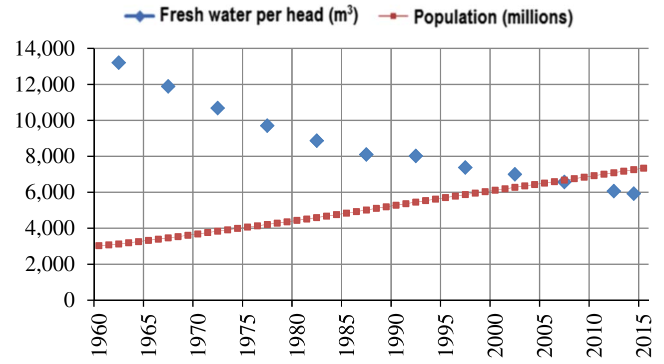

Fig. 1. Decreasing available fresh water resources per head and rising total population [2].

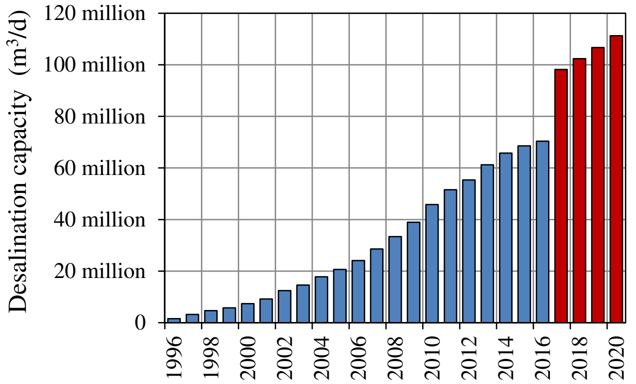

Fig. 2. Annual online desalination capacity (in blue color) and total predicted contracted capacity for 2017–2020 (in red color) [6]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

ciency? The various steps that contribute to the energy costs of desalination are outlined below.

(1) Intake step:
The energy required for the feed intake to the pretreatment step depends on the feed quality, source and geographical location. Intake sources may include open surfaces, subsurfaces, such as underground wells, and effluents from power plants [10]. The energy required for feed intake may become higher if there are regular impingements and entrainments of biological species from the source in the intake system [7]. However, this energy cost can be minimized if the sharing of intakes between new and existing plants is encouraged.

(2) Pre-treatment step:
The pre-treatment step prevents regular membrane fouling and unnecessary process shut-downs by removing particulate matter, organic substances, inorganic salts, and turbidity from the feed water. Current commercial desalination processes would not run smoothly and flow channels would become plugged in minutes if they are not fed with pretreated water. However, the pre-treatment step requires a large amount of energy and materials [11].

(3) Desalination step:
The hypothetical lowest energy required by the desalination step is the Gibbs free energy of mixing or energy required to achieve salt rejection via thermodynamic reversibility [12]. This energy is ensured by the osmotic pressure of the feed solution and it is highly dependent on the feed salinity and fresh water recovery. However, the actual energy required for the desalination step is higher than the thermodynamic minimum of about 1.06 kWh/m^3 because of pressure losses [9], which are due to friction to flow contributed by the membrane channels and their tortuosity, layer of foulants on membrane, frictional losses in the pipelines, concentration polarization, and inefficiencies of inflow pumps [13–16]. Therefore, the water permeability of the membrane is the ultimate determinant of the actual hydraulic pressure required to achieve a particular recovery at standard process conditions.

(4) To reduce the gap between the actual energy and the theoretical minimum energy required for the desalination step, the following approaches have been suggested: the use of multi-stage systems to recover residual energy from the concentrates; use of energy recovery devices, hybridization of two desalination technologies to utilize the comparative advantages; use of waste heat from boiler blowdown or cooling water effluent for thermal distillation; and utilization of salinity gradient power [17].

(5) Post-treatment:
Post-treatment involves disinfection, adjustment of pH and hardness, removal of some trace pollutants such as boron and chlorides, and re-mineralization so that the final product water can be able to provide some health benefits. Post-treatment consumes a considerable amount of energy in current large-scale desalination plants because in many cases, membranes, pumps and other mechanical equipment are involved [10,18].

(6) Concentrate management:
The reject brine from desalination is a critical environmental issue because of its huge volume [19,20]. This is due to the residual pretreatment chemicals and high salinity and temperature of the disposed brine. Also, the heavy metal content in the reject brine due to pipe corrosion constitutes serious environmental risks. The characteristics of the reject brine depend on the quality of the supplied and generated water, the techniques used for pre-treatment, and the desalination process employed [21]. The energy required for the concentrate treatment depends on the deployed technology, as thermal crystallizers and brine concentrators are known to use a considerable amount of energy [22]. However, this may be effectively controlled by mixing concentrate streams with low-salinity effluents such as cooling water to ensure safe discharge to a water body, optimizing fresh water recovery through a multi-stage desalination step and recovery of valuable products from the concentrate [17,23–25]. In addition, the generation of electric power from the osmotic potential of reject brine could open another vista of opportunities for renewable energy generation via pressure-retarded osmosis (PRO) [26].

Of all the steps in a desalination system, pre- and post- treatment account for the highest proportion of energy, most especially for seawater desalination [18], with intake, pre- and post- treatment, and brine management normally consuming more than 1 kWh/m^3 [27]. Thus, the actual overall energy usage for desalination is 1.5–2 times higher than what is calculated by theoretical thermodynamics [28]. In fact, the energy requirements of some recent plants are 3–4 times more than the theoretical minimum [9]. Some RO plants (using seawater as feed) are now operating at applied pressure that is only about 10–20% greater than what is thermodynamically required for the desalination step [8,9]. From these estimations, suggestions that research focus should be directed towards pre- and post- treatment steps mainly have been made because inefficiencies in these steps might double the thermodynamic energy requirement.

However, the desalination step influences the energy requirements of the pre- and post- treatment steps. An efficient desalination step that is highly resistant to fouling and scaling from feed contaminants and can provide high water flux and salt rejection with high quality permeate would significantly reduce pre- and post- treatment energy costs. A lot of work has been done with regards to improving membranes and desalination stages to tolerate the harsh conditions of the feed saline water with minimal fouling [29–32]. Between 2016 and 2020, an estimated 18.4 million m^3/d is expected to be added to the world's contracted desalination capacity