Membrane desalination technologies in water treatment: A review

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Abstract

One of the most pressing problems worldwide is inadequate access to potable water. Many technologies have been applied to address this through research to find robust but inexpensive methods of desalination that offer high fluxes and use less energy, while reducing chemical use and environmental impact. Membrane desalination technology is universally considered to solve water shortage problems due to its high efficiency and lower energy consumption than distillation methods. This review focuses on the desalination performance of membrane technologies with consideration of the effect of driving force, potential technologies, membrane types, flux, energy consumption and operating temperature, etc. Pressure driven membrane processes (MF, UF, NF, RO), and their fouling propensity and major drawbacks are discussed briefly. Membrane characteristics and the effects of operating conditions on desalination are also covered. Organic-hybrid and inorganic membrane materials can offer advantages, with high flux, good selectivity, and useful chemical and thermal resistance.

Key words: desalination, flux, fouling, membrane, pervaporation, potable water

INTRODUCTION

Accessibility to fresh water is threatened in many areas of the world. It is worsened by population movements and industrial development, climate change and drought (Shannon et al. 2008; Swenson et al. 2012; Zhao & Ho 2014; Akther et al. 2015; Burn et al. 2015; Sari & Chellam 2016; Von-Kiti 2016). Although 71% of the earth’s surface is covered with water in the seas and oceans, with ice at the poles (Von-Kiti 2012), the problem persists because 97% of it is too saline for consumption. To curb and subdue ever increasing needs for potable water, schemes like water recycling and seawater desalination have had to be used (Jiang et al. 2017). The commonest way of treating salinity is by using membrane technologies.

A membrane is a thin sheet of natural and/or synthetic material, usually supported by a fibrous network impermeable to substances in solution. The most commonly used membrane technologies for treating saline and brackish water include forward osmosis (FO) (Sahebi et al. 2015; Majeed et al. 2016), reverse osmosis (RO) (Greenlee et al. 2009), membrane distillation (MD) (Mericq et al. 2010), pervaporation (PV) (Swenson et al. 2012), microfiltration (MF) (Voutchkov 2010), ultrafiltration (UF) (Sun et al. 2015) and nanofiltration (NF) (Chollom et al. 2015). The characteristics and morphology of the membrane affect its contaminant rejection, fouling propensity and water permeability (Tijing et al. 2015).

Membrane science and technology present new processes and systems, and modified design production cycles. Membrane processes are more efficient than traditional separation methods such as sedimentation and filtration.

This paper is a review of water treatment processes, especially membrane-based technologies. Some membrane module types are discussed and various types of membrane-based separation technique are reviewed. The effects of operating conditions on these processes are also reviewed, as well as their
separation performance and other parameters. Finally, some of the qualities of hybrid organic-inorganic materials with potential for use in advanced membranes are assessed.

Overview of membrane technology processes

Nowadays, there are many types of seawater desalination technology – including RO, etc, and thermal processes like multi-effect distillation (MED), membrane vacuum distillation (MVD) and multi-stage flash distillation (MSF). Osmosis is the movement or diffusion of water molecules from a region of higher to lower concentration through a semi-permeable membrane, until equilibrium is established. RO desalination uses the principle to remove salt and other impurities from water by using a series of semi-permeable membranes (Nair & Kumar 2013; Goh et al. 2016; Kaplan et al. 2017).

FORWARD OSMOSIS

Osmotic processes are governed by the difference in solute concentration across semi-permeable membranes that reject the solute (Cath et al. 2006).

Osmotic pressure ($\pi$) is the pressure needed to inhibit pure solvent from crossing into a given solution by osmosis, and is related to the solution’s concentration. FO depends on the osmotic pressure differential, instead of a hydraulic pressure differential as in RO. The FO process results in concentration of a feed stream and dilution of a highly concentrated stream (referred to as the draw solution).

The concentrations are related according to Equation (1). (Lee et al. 1981)

$$J_v \Delta p = A (\Delta \pi - \Delta P) \Delta P$$

(1)

which can be transformed to (Cath et al. 2006)

$$J_v = (\sigma \Delta \pi - \Delta P)$$

(2)

where $J_v$ is the water flux, $A$ the water permeability constant of the membrane, $\sigma$ the reflection coefficient, and $P$ the applied pressure. For FO, $P$ is zero; for RO, $P > \Delta \pi$.

With the use of a minimum amount of energy, FO draw solutes can be regenerated. FO membrane fouling can be reduced if the membrane support surface prevents reverse/backward flux of draw solutes (Cath et al. 2006).

While different types of osmotic agent can be employed, draw solutions are cheaper and can be regenerated using existing technology. Draw solutions, of course, must be stable, non-toxic and inexpensive, and have a neutral pH to avoid forming precipitates (Cath et al. 2006; Achilli et al. 2009; Subramani & Jacangelo 2015).

Concentration polarization (CP) is similar in all membrane separation processes. The concomitant concentration gradient at the membrane-solution interface enables selective species transfer across a semi-permeable membrane (Pendergast & Hoek 2011).

The use of small molecules and ions in draw solutions reduces internal concentration polarization (ICP) but results in reverse salt diffusion. This is a topic for future research in FO desalination, to minimize solution reversal and maintain high forward flow. ICP, membrane fouling and reverse solute diffusion are all determined by the draw solute properties (Baker 2012).

FO membrane applications include seawater desalination (Goh et al. 2016), wastewater treatment (Shaffer et al. 2015), water purification (Shannon et al. 2008), pharmaceutical applications (Khawaji et al. 2008), food processing and power generation (Shaffer et al. 2015).

FO attracted attention from different disciplines because of its wide applicability. It is not robust in application, however, and lacks membrane modules, so more research and development is needed to
improve both hollow-fiber and flat-sheet FO membrane modules to enable processing at high flow rates, with maximum solute rejection, and chemical and mechanical stability, as well as ICP. A draw solution is needed to induce high FO process performance (Lee et al. 2010; Chekli et al. 2015; Kaplan et al. 2017).

The FO process has the advantage of operating under low or no hydraulic pressure, and the resistance to flow arises from the membrane modules and system (Achilli et al. 2010). Cath et al. (2006) found that hydration bags were available commercially, and required no power with lower fouling tendencies, even when used with muddy water. They also noted that the treated water was free of microorganisms, as well as ions and macromolecules.

Finally, water production and draw solution recovery will be improved and become sustainable, if FO-hybrid systems are incorporated with renewable energy (Akther et al. 2015). Thermodynamic principles show that FO needs little energy input to achieve separation because the process occurs spontaneously (Baker 2012).

REVERSE OSMOSIS

In RO processes, increasing the external pressure above the water’s osmotic pressure will overcome it. As a result, water flows in the opposite direction across the membrane, leaving dissolved salts behind so that that solution becomes more concentrated. No heat or phase transformation is required (Akther et al. 2015).

When ionic aqueous solutions of different concentrations are separated, an inherent phenomenon – the osmotic pressure – drives water from the solution with lower concentration to dilute the more concentrated solution, so that the ionic concentrations on either side of the membrane become equal (Greenlee et al. 2009). Application of hydraulic pressure to the concentrated liquid so that it exceeds the osmotic pressure causes water molecules to pass through the membrane to the more dilute side. This enables the separation of water from ions and low-molecular weight organic constituents (Bush et al. 2016).

RO seawater desalination plants have four stages: pre-treatment, high pressure pumping, membrane separation and post-treatment (Ayyash et al. 1994). Of these, only the membrane separation section is considered here.

Hollow fine fiber and spiral-wound membranes are the most commercially successful module types (Bou-Hamad et al. 1998). Hollow fine fiber membranes are made from cellulose triacetate and polyamide material, and held in U-shaped pressure vessels. Like spiral-wound membranes they offer the advantages of high water flux, high salt rejection, robust public health rule compliance and environmental safety (Ayyash et al. 1994; López-Ramírez et al. 2006).

Despite the advantages and potential of RO membranes, they also have limitations, such as poor permeate flux, low selectivity, moderate durability, potential for fouling, and high equipment and operating costs, which make the process uneconomic (Wenten & Khoiruddin 2016).

Attempts have been made since the mid-twentieth century to improve RO processes, and reduce both the capital and operating costs, mainly through improvements in membrane technology. These advances have typically included improved flux, longer life, improved salt passage, better resistance to compression, and higher possible recovery (Subramani & Jacangelo 2015).

RO is considered the most effective membrane desalination technology by many authors, even though it has membrane fouling and operating cost problems. Pressure driven, membrane-based technologies (RO, NF, UF) all suffer from fouling, which affects desalination and other water treatment procedures, and comprises deposition on the membrane surface and/or in its pores, reducing its salt rejection and water flux performance (Tijing et al. 2015; Majeed et al. 2016).

Micro-organism colonies and the deposition of unwanted materials are the main fouling problems in RO secondary treatment processes. If not managed, they can cause serious membrane damage and
increase operating costs, while reducing performance. Micro-organism colonies can damage cellulose acetate membranes irreversibly (Shannon et al. 2008). Polyamide membranes cannot be biodegraded but there is propensity for membrane performance to be affected (López-Ramírez et al. 2006).

**MEMBRANE DISTILLATION**

This technique is driven thermally, using the difference in partial vapor pressure created at the liquid-vapor interface by the temperature gradient (Tomaszewska et al. 1995). MD separates water vapor from aqueous solutions at low temperatures (Abu-Zeid et al. 2015). As a result of vaporization, pure water distillate forms and the solution in the feed vessel becomes more concentrated.

MD membranes are porous and hydrophobic. Most are polymeric, including, but not limited to, polypropylene (PP), polytetrafluoroethylene (PTFE) polyvinylidene fluoride (PVDF), zeolite and ceramic materials. The process operates at between 50 and 80 °C, and can be powered using waste heat or solar energy. It can operate at very low pressure compared to pressure driven membrane techniques like RO and use very concentrated feed solutions because of the low concentration polarization effect. The potential value of MD membrane separation is well established and documented (Al-Ansari et al. 2001; Alkhudhiri et al. 2012).

In contrast, MD membranes serve as a support between the input (feed) and output (permeate) sides of the process. Mass transport and separation are membrane characteristic functions only in MD, where the membrane acts as a support. Mass transfer arises from the vapor pressure gradient between the input and output streams.

MD is a relatively new, low cost process and is being investigated worldwide. It has low energy requirements, unlike RO, distillation or other hydraulic separation processes, leading to useful energy savings (Lawson & Lloyd 1997).

MD, while operating at low temperature, offers almost 100% salt rejection and high output (permeate) flux, without susceptibility to salt concentration, etc. (Maab et al. 2013). It is a rising desalination technique for producing potable water from seawater, but is associated with high energy consumption because of significant heat loss by conduction through the membrane (Lee et al. 2015).

The MD membrane acts as a liquid-vapor interface support, unlike RO, MF and UF membranes, which serve a real role in separation. The MD membrane acts neither as a sieve nor in differentiating between solution composition concentrations. Because of this, such membranes can be made from chemically resistant polymers like PTFE, PP and PVDF, and have large diameter pores that are not fouled easily (Lawson & Lloyd 1997).

The MD concept can take various forms. The aim is to generate a vapor pressure gradient to move vapor across the membrane. The methods used to achieve lower vapor pressure on the permeate side include: (a) direct contact MD (DCMD); (b) air gap MD (AGMD); (c) sweeping gas MD (SGMD); and, (d) vacuum MD (VMD). Each method has its own advantages and disadvantages, which are functions of the feed solution to be processed (Imdakm et al. 2007).

MD is driven thermally, and operates at pressure gradients ranging between zero and a few kilopascals – i.e., lower than pressure driven processes like RO. Because of this, the costs of equipment and process safety are low (Lawson & Lloyd 1997). MD can be compared with pressure driven processes like UF, MF, and RO, because they have common applications (Lawson & Lloyd 1997).

**DIRECT CONTACT MEMBRANE DISTILLATION**

In DCMD the (saline) feed water temperature must be above 80 °C and separated from the cold permeate by a porous, hydrophobic membrane (Maab et al. 2013). DCMD uses high porosity
membranes with pore sizes ranging between 0.1 and 0.6 $\mu$m. If the solution pressure is below the breakthrough pressure, hydrophobic membranes of this level of porosity will not be wetted by aqueous non-wetting solutions – e.g., saline water – under constant operating conditions (Sirkar & Qin 2001). Vapor from hot brine is transferred through the membrane pores, along with heat, to the cold distillate side by conduction through the pores. Heat is lost by evaporation. DCMD performance is maintained by minimizing conductive heat transfer. Thermal conduction through polymeric membrane walls always exceeds thermal conduction through vapor space, which implies that high porosity, thick walled membranes have less tendency for conductive heat loss (Li & Sirkar 2005).

The film condensate and cooling surface are the process effects in DCMD, because the two are in direct contact with the membrane (unlike in AGMD).

**Air gap membrane distillation**

In AGMD, a thin air gap is created between the membrane and the cooling surface. The membrane and air gap allow vapor molecules to pass across and condense on the cooling surface (Lee et al. 2010; Wang & Chung 2015). The air gap provides some resistance to vapor transfer.

The water flux from AGMD is less than that from DCMD formations (Warsinger et al. 2015). The integrated cooling plate in AGMD has enabled extensive studies of multi-effect or multi-stage membrane modules with improved thermal efficiency (Wang & Chung 2015, 2016).

**Sweep gas membrane distillation**

In SGMD an inert gas is introduced to sweep into the permeate stream and collect vapor molecules from the membrane surface. Usually, the vapor is cooled outside the membrane configuration in a different condenser (Burn et al. 2015). The equipment can be expensive (Wang & Chung 2015).

**Membrane vacuum distillation**

In MVD, the feed temperature and vapor pressure are the operating variables affecting the permeation flux. Other operating conditions have less effect. The materials used for MVD membranes are the same as those for MD, but differ in configuration. In MVD, hydraulic pressure is applied using a pump to establish a vacuum on the permeating region of the membrane. There is no heat loss and condensation occurs away from the membrane area (Achilli et al. 2010; Alkhudhiri et al. 2012). Banat & Simandl (1999) and Imdakm et al. (2007) report that membrane parameters such as pore size, tortuosity, membrane thickness, pore size distribution and porosity all influence performance significantly, and fulfill a high driving force across the membrane and permeate flux in MVD. The process requires relatively low membrane mechanical properties and good salt rejection can be achieved for non-volatile solutes (Abu-Zeid et al. 2015). MVD is a current desalination technology with relatively low energy demands. It is a trans-membrane process utilizing the vapor pressure differential that can be sustained on the membrane’s permeate side (Pérez-González et al. 2012). In MVD, the cold distillate efflux is created on one side of the membrane, with a vacuum used to extract the vaporized water (Li & Sirkar 2005). The extracted vapor is liquefied in a different condenser, unlike DCMD.

**MEMBRANE MODULES**

**Plate and frame**

In plate and frame membrane modules, the spacers lie between pairs of equal flat sheets. This type of membrane is usually used in laboratory set ups for simplicity. Plate and frame modules are applicable
to MD for water treatment and desalination (Alkhudhiri et al. 2012). Figures 1 and 2 illustrate the modules and their operation.

**Figure 1** | Schematic model of plate and frame membrane module.

**Figure 2** | Plate and frame membrane module operation.

**Hollow fiber**

This type of module – Figure 3 – has hollow fibers aligned and secured in a tubular shell. The feed enters via the shell and the filtrate comes out through the membrane. In their independent studies, Laganà et al. (2000) and Fujii & Kigoshi (1992) used this module to treat apple juice and alcohol, while Elimelech et al. (1997) treated saline water using a capillary, polypropylene membrane.

**Figure 3** | Cutaway model of hollow-fiber membrane module.
Hollow fiber membrane modules have the advantage of high packing density and low energy consumption. The disadvantages are high fouling tendency, maintenance needs and a likely requirement for replacement after damage (Kennedy et al. 2008).

**Tubular membrane**

This is a tube-shaped membrane structure, placed between parallel cylinders of hot and cold fluid. The tubular membrane module has the advantages of low fouling tendency, easy maintenance and good contact area, which make it attractive in commercial applications. It is also applicable to MD but has the disadvantages of high operating costs and low packing density. Ceramic membranes have been used to treat aqueous NaCl− in many MD set ups – DCMD, AGMD and VMD – with salt rejections exceeding 99% (Cerneaux et al. 2009; Alkhudhiri et al. 2012).

**Spiral wound membrane**

Spiral wound membranes are made so that a flat sheet and spacers are packed and wound around a punctured collection area. The feed solution crosses the membrane axially, and the filtrate moves radially to the center, exiting through the collection area. Spiral wound membranes – Figures 4 and 5 – have low fouling tendency, moderate energy consumption and reasonable packing density. Microfiltration processes operate in two basic ways, crossflow and dead-end flow, and both are applicable to MD. Crossflow is used, for instance, where the feed is driven tangentially to the membrane, with the treated water passing through the membrane while the feed solution recirculates (Kennedy et al. 2008).


**Pervaporation**

PV is one of best desalination processes for sea- and brackish waters, because it offers high salt rejection (Wang et al. 2016). Extensive work has been done in both academia and industry to establish a thin film composite membrane (TFC) to improve performance and selectivity, as well as resistance to chlorine, solvents and fouling (Lau et al. 2012). In PV, the membrane functions as a molecular sieve between the feed and permeate, unlike in MD where it acts simply as a support (Semiat 2008). Polyethylene and cellulose were used in the 1960s for membrane technology, but since the turn of the century, zeolites have started to attract researchers’ attention. PV membrane desalination using organic and inorganic...
membranes has reached an advanced stage, where novel hybrid membranes from organic-inorganic sources and TFCs with high water flux have been developed (Lau et al. 2012; Wang et al. 2016).

With continuous developments in membrane materials in both industry and academia, membranes are expected to continue being the most viable alternative in producing cheap fresh water from seawater for the future.

**Microfiltration/ultrafiltration/nanofiltration**

These processes differ mainly in the membrane pore size. MF membranes have larger pores and tend only to reject relatively larger micro-organisms than UF membranes, whose pore size is considerably smaller. UF can reject bacteria and soluble super molecules. NF, sometimes referred to as ‘loose RO’, membranes are new and their application is limited to RO (Chollom et al. 2015).

MF and UF low pressure membrane technology was established in the 1960s for water treatment and purification. Their membranes have pore sizes between 0.08 and 0.5 mm, and 0.001 and 0.01 mm, respectively. MF enables effective separation and treatment of colloidal suspensions, while UF is used to separate or treat solutions/suspensions of moderate molecular size (Buffel et al. 1998; Wu et al. 2017).

MF is a water management process wherein polluted solutions are treated with a membrane with a particular pore size. It enables micro-organisms and suspended solids to be separated from a feed solution, and is usually applied concurrently with other separation technique like RO and UF (Chollom et al. 2015).

Progress made in UF and MF membrane applications for water treatment led to a breakthrough in membrane pre-treatment in seawater desalination (Busch et al. 2010; Voutchkov 2010). Several considerations emphasize the need to consider MF/UF rather than conventional pre-treatment. These include the ability to cope with difficult waters, reliability, ease of design and operation, and lower operating and capital costs (Busch et al. 2010; Wu et al. 2017). Pre-treatment using UF and/or MF can be limited by fouling and result in poor desalination plant yield. However, RO membrane biofouling may not be mitigated because of poor salt rejection by UF and MF membranes.

NF is capable of separating colloidal particles ranging between UF and RO, and has a pore size of 0.5 to 5 nm. It is pressure driven and can effectively withstand differential pressures of 500 to 2,000 kPa, below RO operating pressures but producing high permeate flux (Chollom et al. 2015). NF processes can restrain both divalent (Ca$^{2+}$, Mg$^{2+}$) and monovalent (Na$^+$, K$^+$ and Cl$^-$) ions.

NF is applied in a similar way to RO but differs in network structure. It is widely used in water softening and removing organic matter, as well as for wastewater treatment and recovery (Elimelech et al. 1997; López-Ramírez et al. 2006).
Laws and regulations concerning treatment to yield potable water with minimal health risks often lead nowadays to NF and low-pressure RO processes being considered for surface water treatment. The combination of such pre-treatment processes has led to the development of a new technological concept called an integrated membrane system (IMS). The application of IMS will mitigate membrane fouling problems (Kennedy et al. 2008).

IMS could affect the yield of desalination processes because, for instance:

1. The quality of MF/UF filtrate is good and changes little with time, and can reduce the colloidal fouling and turbidity load on RO.
2. The frequency of colloidal fouling of RO/NF is reduced.
3. The concentrates from MF/UF can be discharged easily compared to those from chemically upgraded, traditional, pre-treatment operations (Kabsch-Korbutowicz 2005).

**Membrane integration in desalination processes**

Integration of desalination membrane operations can lower salt discharge and improve water reclamation (Godino et al. 1996). Numerous studies report that incorporating MD/NF or MD/RO improves effectiveness and economic feasibility with respect to energy consumption and flux (Yun et al. 2006; Qu et al. 2009; Ji et al. 2010; Mericq et al. 2010; Taylor et al. 2015). De Andrés et al. (1998) report that yield/flux rose by 7.5% and energy efficiency improved by 10% as a result of incorporating MD with MED. A fouling problem is likely from integration of MD into desalination operations because of the deposition of inorganic species – e.g., \( \text{Ca}^{2+} \) – on the membrane surface (Wang & Chung 2015).

In freeze desalination (FD), fresh water is extracted by collecting and melting frost crystals from saline water (Manwell & McGowan 1994; Guan et al. 2012). While FD recovers little water, Wang & Chung (2012) suggest that recovery and effectiveness could be improved in an FD-MD desalination technique, with the MD process concentrating the saline reject from FD. Both processes combined yield salt-free water with a recovery rate of 71.5%.

**MEMBRANE CLASSIFICATION**

**Organic membranes**

Organic membranes are either cellulose-based or composed of modified organic polymers – e.g., PE-based ion-exchange membranes (Xie et al. 2011a), or membranes based on polyether-amide (Zwijnenberg et al. 2005), polyether-ester (Xie et al. 2011a), cellulose (Xie et al. 2011a), polyester (Wang et al. 2016), nanofiber composites (Krzeminski et al. 2017) or poly(vinyl alcohol) composites (Wang et al. 2016).

Common organic membrane materials referred to are:

- polyethylene (PE)
- polytetrafluoroethylene (PTFE)
- polypropylene (PP)
- cellulose acetate (CA)
- polyacrylonitrile (PAN)
- polyimide (PI)
- polysulfone (PS)
- polyethersulfone (PES)

Many organic membranes find applications in different water treatment processes as shown in Table 1.
Inorganic membranes

Research into PV using inorganic membranes like zeolites is currently attracting wide attention. Inorganic membranes offer good thermal and chemical stability (Zou et al. 2011), good separation and low fouling propensity. Beyond this, their inflexible ceramic form and so-called ‘definite porosity’ mean that they can be used in separation processes based on the shapes and sizes of the molecules. Membrane morphology plays an important role in desalination separation processes (Wang et al. 2016).

Zeolites are the best inorganic membrane materials, with porosities between 0.3 and 1.3 nm. Mal-ekpour et al. (2008) synthesized zeolite A and ZSM-5 on an alumina support membrane, and established a perfect MFI membrane using the template-free and Si/Al ratio secondary growth method.

Wang et al. (2016) used a silicalite-zeolite membrane. Salt rejection increased with the aluminum/silica ratio from 97 to more than 99%, with zeolite membrane Al/Si ratios between 20 and 500. RO Na\(^+\) rejection of 17% was recorded using a ZSM-5 zeolite membrane with an Al/Si ratio of 100, while negative Na\(^+\) rejection was found with other membranes. Membrane thickness and hydrophobicity can affect water flux with varying Al/Si ratios in PV processes as the surface charge is not correlated to Al/Si ratio.

Molecular sieving is the ideal technique for seawater desalination by size exclusion using inorganic porous membranes. Sometimes higher membrane flux rates are achieved with concentrated salt than fresh water, as a result of ion exchange between the membrane and feed solution (Wang et al. 2016).

Wang et al. (2016) also reported the transfer of small amounts of salt through inorganic and polymeric membranes. More research is needed to find better methods of handling this in PV desalination.

Table 1 | Typical organic membranes, with process types, driving force, technology, membrane type and permeation fluxes

<table>
<thead>
<tr>
<th>Process</th>
<th>Driving Force</th>
<th>Potential use</th>
<th>Membrane material</th>
<th>Typical fluxes</th>
<th>Temperature</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>RO</td>
<td>Induced pressure</td>
<td>Desalination</td>
<td>PA, CA</td>
<td>90 L/m²·h</td>
<td>60 °C</td>
<td>Greenlee et al. (2009); Pérez-González et al. (2012); Antony et al. (2016)</td>
</tr>
<tr>
<td>FO</td>
<td>Osmosis</td>
<td>Desalination</td>
<td>Cellulose triacetate (CTA)</td>
<td>3.1 L/(m²·h)</td>
<td>50 °C</td>
<td>Wang et al. (2014); Sahebi et al. (2015); Majeed et al. (2016)</td>
</tr>
<tr>
<td>MD</td>
<td>Thermal</td>
<td>Desalination, brine concentration</td>
<td>polyvinylidene difluoride (PVDF), PTFE, and PP</td>
<td>n.r.</td>
<td>50 °C–80 °C</td>
<td>Al-Ansari et al. (2001); Alkhudhiri et al. (2012); Maab et al. (2015); Wang &amp; Chung (2015)</td>
</tr>
<tr>
<td>PV</td>
<td>Thermal</td>
<td>Desalination</td>
<td>PVDF, Polyether amide</td>
<td>0.03 L/m²·h</td>
<td>90 °C</td>
<td>Swenson et al. (2012); Zhu et al. (2014)</td>
</tr>
<tr>
<td>MF</td>
<td>Induced pressure</td>
<td>Desalination</td>
<td>PTFE, Acrylonitrile polymer</td>
<td>n.r.</td>
<td>25 °C</td>
<td>Kennedy et al. (2008); Bush et al. (2016)</td>
</tr>
<tr>
<td>UF</td>
<td>Induced pressure</td>
<td>Desalination</td>
<td>PTFE, PVDF and CTA, regenerated cellulose</td>
<td>91.2 × 10³ L/m²·h</td>
<td>75 °C</td>
<td>Kennedy et al. (2008); Busch et al. (2010); Chekli et al. (2015)</td>
</tr>
<tr>
<td>NF</td>
<td>Induced pressure</td>
<td>Desalination</td>
<td>CTA</td>
<td>≤17.4 L/m²·h</td>
<td>25–55 °C</td>
<td>Noghabi et al. (2011); Chekli et al. (2015)</td>
</tr>
<tr>
<td>ED</td>
<td>Electric current</td>
<td>Brackish water desalination</td>
<td>CTA</td>
<td>≤3.5 L/m²·h</td>
<td>Ambient temperature</td>
<td>Greenlee et al. (2009); Pérez-González et al. (2012); Burn et al. (2015)</td>
</tr>
<tr>
<td>MED</td>
<td>Thermal</td>
<td>Desalination, brine concentration</td>
<td>PVDF, PTFE, and PP</td>
<td>n.r.</td>
<td>50 °C</td>
<td>Maab et al. (2013)</td>
</tr>
</tbody>
</table>
Energy consumption and salt rejection efficiency

RO system energy consumption ranges from 6 to 8 kWh/m³, depending on salinity and system size, with efficiencies of up to 99.75% (Lee et al. 2011; Mayere 2011), because the feed must be pressurized above the brine’s osmotic pressure for the system to perform at its best.

The energy consumption and efficiency of FO are lower than for RO because FO is not energy driven. As a result, its efficiency is only moderate (Chung et al. 2012; Kaplan et al. 2017).

MSF energy consumption is in the range 2.5 to 5 kWh/m³, with moderately high efficiency (Blank et al. 2007; Semiat 2008).

MED requires energy in the range 2 to 2.5 kWh/m³ and achieves salt rejection exceeding 90% (Blank et al. 2007; Semiat 2008; Thiel et al. 2014; Chekli et al. 2015; Kaplan et al. 2017).

While PV, MF, UF, and NF are not energy driven they have salt rejection efficiencies of between 90 and 99.99% (Zwijnenberg et al. 2005; Blank et al. 2007; Kennedy et al. 2008; Semiat 2008; Ge et al. 2011; Chekli et al. 2015; Fasano et al. 2016; Kaplan et al. 2017).

Inorganic membrane materials

The basic materials employed for inorganic membranes are:
1. Aluminum oxide (Al₂O₃), and
2. Zirconium oxide (ZrO₂) as well as, for trial purposes
3. Stainless steel (S/S), and

Inorganic membrane materials have greater mechanical strength, and thermal and chemical resistance than organic membranes. These are often offset, however, by their inherently higher capital costs.

Hybrid organic–inorganic membrane modification

The advantages offered by zeolite membrane processes in seawater desalination include high flux and ion rejection, and good selectivity (Zhu et al. 2014). Membrane fouling can increase operating costs significantly due to increased energy demand, while reducing productivity and permeate quality (Jiang et al. 2017). Fouling can be controlled by pre-treatment, foulant removal and membrane cleaning, and/or maintenance, as well as reducing membrane lifetime (Achilli et al. 2009; Tang et al. 2016; Jiang et al. 2017).

Recently, a novel hybrid membrane has been established comprising a combination of organic and inorganic phases bonded together chemically. It is stable and has good permeation flux. It was synthesized using a sol-gel mechanism to produce PVA with organic silica spread on it (Xie et al. 2011b). This improved the PVA’s stability in water and effectiveness in PV desalination. If the silica content is increased during PVA/maleic anhydride/silica membrane synthesis, from zero to 10%, the flux increases from 4.29 to 5.51 L/m²·h, at 22 °C and a vacuum of 800 Pa. This might be attributable to the increase in free volume caused by the size of the silica nanoparticles (Xie et al. 2011b). When the feed temperature was increased to 65 °C, the flux rose to 11.7 kg/m²·h (Xie et al. 2011a). The hybrid membrane is robust because of the chemical and thermal stability of the inorganic (zeolite) phase.

CONCLUSIONS

Many studies have been carried out or continue into simplifying and enhancing membrane desalination technology. As reported above, different technologies use different membrane materials and driving processes – e.g., pressure, osmosis and heat.
Effort is warranted to develop inorganic zeolite and hybrid membranes to a size sufficient for desalination. Organic–inorganic hybrid materials have already been shown to have real potential as membranes. Incorporation of desalination techniques with other separation processes – e.g., MF and UF pre-treatment – may enhance performance and improve the operating economics.

The hybrid organic–inorganic membrane technology developed recently could be used to enhance water treatment. More research is needed into the incorporation of both organic and inorganic materials in water treatment technologies.

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REFERENCES


