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Reverse osmosis seawater desalination: current status of membrane systems

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ABSTRACT

Reverse osmosis is currently the most important and commonly used desalination technique. The objective of this paper is to review the history of reverse osmosis membranes, to outline the current state of the art and insight into the tendencies being. The current market of RO membranes is focused on thin-film composite polyamide membranes, which are made of three layers and with an average molecular weight cut-off of 100–150 Da in order to obtain a high salt rejection. Until reaching current RO membranes, there have been numerous developments, highlighting the development of NS-100 membranes by Cadotte in 1977 and subsequent optimization of the manufacturing conditions. Other improvements were surface modification and membrane post-treatment actions. The most common configuration used in desalination plants are polyamide spiral wound membranes (SWM), which involves several flat sheet membranes that are glued together pairwise on three sides with the fourth side left open. The membrane elements are connected in series using interconnectors and installed into a pressure vessel. Current research regarding SWM is focused on providing greater surface area within the same volume. Another point of interest is to achieve a high retention of boron to comply with current legislation.

Keywords: Reverse osmosis; Desalination; Membranes

1. Introduction

Desalination is the process by which brackish water or seawater can be turned into a fully usable water resource, both for human consumption and for irrigation and industrial purposes. Nowadays, desalination is an increasingly common solution to supply freshwater in many regions of the world where this resource is scarce. Among all desalination technologies, seawater reverse osmosis (SWRO) is the most internationally widespread technology [1].

Reverse osmosis is the passage of water through a semipermeable membrane from a solution of high salinity to another one with lower salt concentration, overcoming the osmotic pressure due to a driving force (usually using a feed pump). As a result, the salt is retained by the membrane.

Reverse osmosis is currently the most important desalination technique and is expected to continue to

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do so, due to continuous process improvements that reduce costs that are leading to increased commercial interest in this technology. These developments are based mainly on development of new membrane materials, in addition to module designs, process design, pretreatments, energy recovery or reducing energy consumption. In fact, in addition to ongoing research into conventional polymeric RO membrane materials, nanotechnology has opened the way to incorporating nanomaterials into RO processes. The beneficial outcomes are shown quantitatively in Fig. 1 [2].

2. Background

The current market of RO membranes is focused on thin-film composite (TFC) polyamide membranes. These membranes are made of three layers, as shown in Fig. 2:

- An ultrafine active barrier layer on the upper of the membrane (~0.2 μm). This layer is made of polyamide or aromatic polyamide (PA).
- A microporous interlayer (~40 μm).
- A polyester web acting as structural support (120–150 μm). This layer is made of different materials, and it involves lots of possibilities in the design of suitable membranes for each application. Nevertheless, supporting layer is usually a micro–ultrafiltration membrane made of polysulfone [2–4].

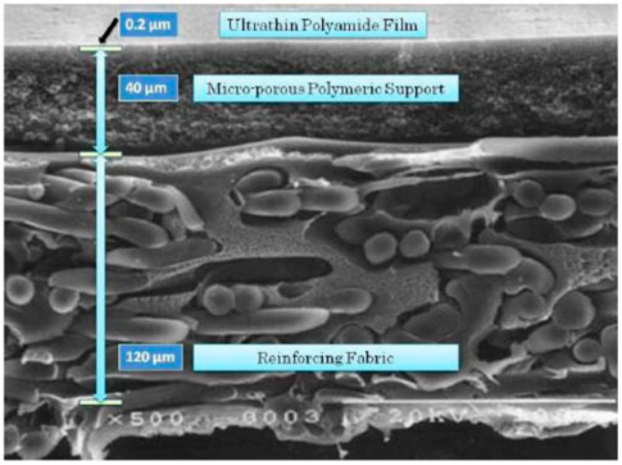

Fig. 2. Structure of typical RO membrane [5].

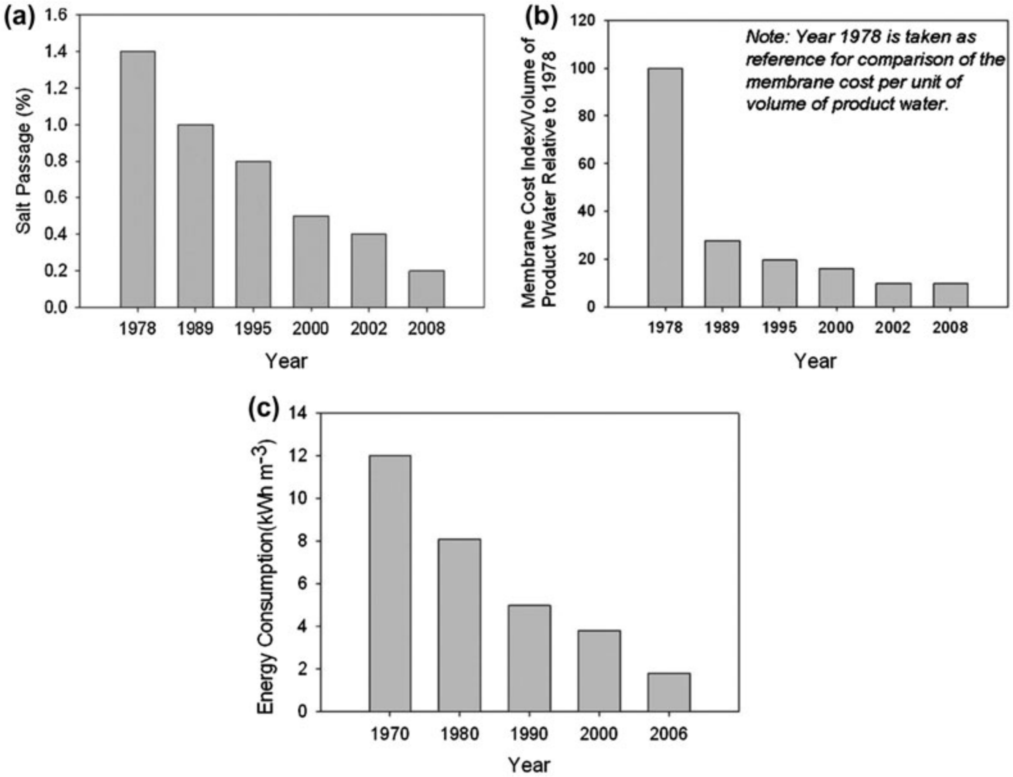

Fig. 1. (a) Improvement in salt rejection; (b) reduction in membrane cost; (c) reduction in energy consumption of RO [2].

According to Lee et al. [2], the reason why a polysulfone microporous interlayer is added between active/barrier and supporting layer is that polyester supporting web cannot act as direct support of active layer because it is too irregular and porous. Thus, this interlayer makes possible that active layer withstands high pressure. Furthermore, Fritzmann et al. [3] stated that the supporting layer protects the membrane from ripping or breaking, while the active layer/barrier is responsible for almost all resistance to mass transport and the selectivity of the membrane. Membranes featuring this combination of active layer and supporting structure are called asymmetric membrane [3].

Lee et al. [2] specified that although RO membrane pore size is between 0.1 and 1 nm, for achieve a salt rejection higher than 99%, this size is usually less than 0.6 nm. On the other hand, Shon et al. [6] and Gautam and Menkhaus [7] exposed that the molecular weight cut-off for reverse osmosis membranes is established around 100 Da. In reality, the main mechanism for the rejection of the small molecules by the RO membranes is not the size exclusion rather it is electrostatic interactions between membrane surface and charged molecules. Fritzmann et al. [3] and Humplik et al. [8] published that for efficient desalination, reverse osmosis membranes, should in general display high flux and high rejection. To achieve high water flux, high membrane permeability is desired while maintaining high salt rejection; also, high permeability requires very thin membranes. Today, extremely thin membranes, which guarantee high permeability and therefore high flux, consist of a very thin active non-porous layer and a porous supporting layer for mechanical stability. These membranes are fabricated using interfacial polymerization, this method is based on the use of polysulfone as a support layer and this one allows membranes withstand the alkaline conditions created by the use of caustic as acid acceptor in the interfacial polymerization process [2,9].

The major technological milestone in the history of RO processes was the development of NS-100 membranes [10]. This membrane which results from the reaction of polythylenimine with toluene was the first successful non-cellulosic membrane with comparable flux and monovalent salt rejection. It demonstrated superior rejection of organic compounds, as Bartels [11] stated, and good stability in high temperature, acidic and alkaline environments. On the other hand, these membranes have virtually no resistance to chlorine and a pronounced surface brittleness as a result of a highly cross-linked structure [2]. PA-300 and RC-100, another two commercialized products formed by interfacial polymerization of polymeric amines, showed better properties respect to NS-100 [12], and this improvement allow them being installed in important desalination plants.

Initial attempts at interfacial polymerization of monomeric amines produce membranes with poor salt rejection performance. For this reason, Cadotte [13] optimized the polymerization conditions and discovered that using monomeric aromatic amines and aromatic acyl halides containing at least three carbonyl halide groups it was possible to obtain membranes with excellent permselectivity. Cadotte [9] patented it and concluded that the best results were obtained with trimesoyl chloride [14]. As result, membrane FT-30 was prepared by the interfacial reaction between 1,3-benzenediamine and trimesoyl chloride. The development of FT-30 brings with it the discovery of the "ridge and valley" structure, a very unique surface characteristic [4]. Studies have shown that this rough "ridge and valley" surface feature is related to the increased effective surface area for water transport and thus water flux [15]. The aromatic polyamide structure of FT-30 provides a wide pH operating range and high degree of resistance to compression, thermal, microbial and chemical resistance, as well as a high degree of tolerance to chlorine which is sufficient to withstand accidental exposure to this chemical [16]. These properties have resulted in a series of products based on this membrane which have been commercialized by The Dow Chemical Company©. Besides, other similar products commercialized, i.e. by Hydranautics© or Toray Membrane America©, Industries were released by the success of FT-30 [17–23]. In conclusion, this membrane has significant impact on the design of RO desalination elements [2].

In 1985, Sundet created a membrane that excels in both flux and salt rejection, showing superior resistance to fouling and chlorine due to its relatively neutral surface charge and stronger polyamide-urea bond linkage. This membrane, designated X-20, was the result of patent of the use of isocyanato aromatic acyl halides (e.g. 1-isocyanato-3,5-benzenedicarbonyl chloride) as cross-linking agents for 1,3-benzenediamine [17].

After the success of the introduction of cross-linked fully aromatic polyamide TFC RO membranes into the market, research and development towards new polymeric materials for RO membranes has declined severely. Current products from major manufacturers of RO desalination membranes are still based on the original chemistry discovered during the 1980s [2].

Nevertheless, the performance of RO membranes has been improved, and it is the results of surface modification, and closer monitoring of interfacial polymerization reaction parameters, as well as a more effective design of the module structure. Thus, water permeability has been at least doubled, and the recovery of freshwater can be over 60% [24–26].

Another major improvement in membrane systems is the application of a post-treatment to chemically modify the membrane surface properties. Much of membrane post-treatment research is focused on hydrophilization, which can improve its permeability and chlorine resistance.

Various water soluble solvents such as acids and alcohols have been used to treat the membrane surface. A ternary mixture of ethanol–water–inorganic acids has also been used to improve flux and rejection due to the partial hydrolysis and skin modification initiated by the alcohol and acid [27].

In 1998, Mickols patented post-treatment of a membrane surface with ammonia or alkyl compounds [28]. By soaking composite membranes in solutions containing various organic species, we can improve the flux a 70%, as Kuehne et al. [29] reported. Other surface modification techniques including the use of free radical-, photochemical-, radiation-, redox- and plasma-induced grafting are currently used to covalently attach some useful monomers onto the membrane surface which have been covered in. Another area of intense research study is the optimization of interfacial polymerization reaction mechanisms including kinetics, reactant diffusion coefficients, reaction time, solvent solubility, solution composition, nucleation rate, curing time, polymer molecular weight range and characteristics of the microporous support [2].

With respect to composite membranes properties, Fritzmann et al. [3] stated that composite membranes are chemically and physically more stable, display a strong resistance to bacterial degradation, do not hydrolyse, are less influenced by membrane compaction and are stable in a wider range of feed pH (3–11). Besides, they have an improved chemical resistance, a good tolerance against impurities, a good durability and easily cleaning [2].

However, composite membranes are less hydrophilic and have a stronger tendency for fouling than CA membranes [3].

3. Characterization and analysis of membranes

In order to characterize membrane properties and morphology, new techniques and methods are being developed to achieve a better understanding of the molecular, microcrystalline and colloidal levels of the polymeric membrane [30].

The knowledge about new techniques of analysis and the choice of most appropriate method for studying each of the parameters, it is important to correctly monitor the status and performance of the membranes.

The solute permeation performance is the most important characteristic of membranes and hence characterization based on molecular transport is essential. For this study, scanning electron microscopy (SEM) and atomic force microscopy (AFM) are the two most common microscopic methods used. SEM allows the direct observation of membrane morphology and fouling layer. SEM can easily be combined with an energy-dispersive X-ray spectroscopy (EDS), which enables analysis of elemental composition of the spot being imaged by SEM. Another benefit of SEM is that the foulants do not have to be removed from the membrane in order to be analysed. SEM-EDS is often used as a combined tool that can provide detailed information on the size, shape, structure and chemical composition of membrane material and foulants. SEM-EDS may also be used to characterize very thin fouling layer, such as microbiological fouling, membrane scaling or membrane degradation and defects [31].

Recently, it has been developed the environmental scanning electron microscope (ESEM), it is a special type of low-vacuum SEM, which does not require coating and hence no artefacts are produced during preparation when membrane samples are completely dried. Field emission scanning electron microscopy (FESEM) and transmission electron microscopy (TEM) provide qualitative information on surface roughness and deposition of foulants. AFM allows the measurement of membrane surface roughness, pore size and its distribution, surface change during fouling and interaction forces between the permeate and the membrane surface and provides morphological images by scanning a nanometerscale sharp tip over the surface [31,32]. Among the spectroscopic methods applied are infrared (IR) spectroscopy, Rutherford backscattering spectroscopy [33,34], X-ray photoelectron spectroscopy (XPS or ESCA) and Raman spectroscopy (RS) [30].

Khulbe and Matsuura [32] presented a complete review of the RS, electron spin resonance (ESR) and AFM methods. They concluded that RS is most adequate in obtaining information on crystalline structure of the macromolecules and change of polymeric structure in membrane, ESR on the mobility of molecules in membrane polymer matrices and membrane pores and the mechanism of membrane fouling and thin-layers coating and AFM for three-dimensional display of membrane surfaces.

4. Membrane configurations

The most common configuration used in desalination plants are polyamide spiral wound membranes (SWM) [2]; this configuration, as shown Fig. 3, consist of several flat sheet membranes that are glued together pairwise on three sides with the fourth side left open and a permeate spacer in between both to form a membrane pocket. Each pocket is connected to the permeate collector tube with its open end. The membrane pockets are rolled around the tube with feed spacers between each pocket, in such a way as to obtain the enough free space for the feed water flow. Thus, alternating feed and permeate channels are created. The element thus formed is covered externally with a coating made of epoxy–fibreglass.

The membrane elements are connected in series and installed into a pressure vessel (PV), cylindrical vessels capable of withstanding high operating pressures. The feed, as shown Fig. 4, comes into the first module on one side and flow parallel to the direction of the permeate collector tube. The feed is partly forced through the membrane; this water follows a spiral path and is collected by the permeate collector tube. The rest of the feed flows parallel to the permeate collector, removing the salt to the retentate in the opposite side of the PV. As a result, the salinity of feed water increases and travel from the end of this element to the entry of the next one. The permeate in the central tube can be collected at any one to the sides of this one, according to design requirements [3,5,35].

Membranes do not retain 100% of salts, so permeate has a little content of salts, depending on the concentration of salts in the feed flow rate, concentration of salts in the retentate, temperature in the feed flow rate, the type of membrane element and the configuration of the plant [35].

These membranes are easily scale up and replaced and generally, it is the most economical module configuration to produce from flat sheet TFC membrane.

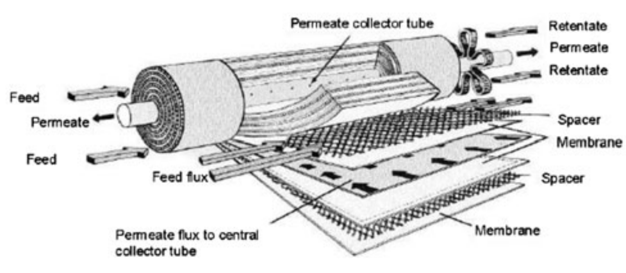

Fig. 3. Flow through a spiral wound module adapted from [3].

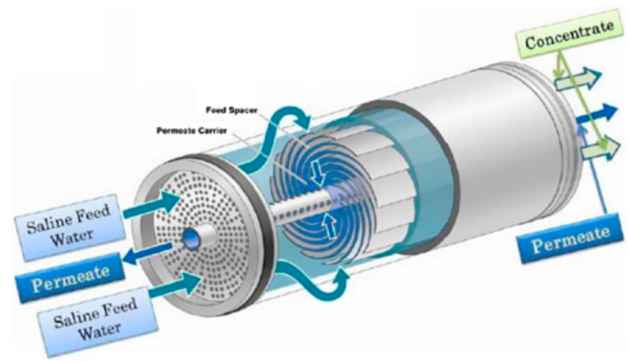

Fig. 4. Flow patterns in SWM element [5].

Beside, it offers good permeability conditions, a considerable fouling control, a higher productivity and salt rejection. Also, SWM element offers high specific surface area. Nevertheless, current research is focused on offers a higher filtration with the same volume [1–3].

The membrane elements are connected in series using interconnectors and installed into a PV, as shown in Fig. 5. Although recovery rate depends on mainly osmotic pressure, it also depends directly on the length of the membrane elements, so these ones have a determinate length (usually 1 m). For obtaining a suitable recovery rate (for seawater it is stated in 45%), it is necessary to install 6, 7 or 8 elements in series per each PV [1,35,36]. Furthermore, number of membrane elements installed inside a PV cannot be increased indefinitely due to the difficulty of moving elements through the PV during loading, the feed temperature variation and the potential subsequent elements impact damage [1].

Fritzmann assured that these PVs are commercially available for desalination plants up to 65–80 bar [3].

As we will later on explain, recovery rate in each membrane element is about 8%. The retentate of each one is the feed of the next one, so the permeate flow is calculated by the following mass balance suggested by the authors:

$$P = R \cdot A \cdot (1 + (1 - R) + \ldots + (1 - R)^{n-1}) \quad (1)$$

where P: Permeate flow.

R: % Recovery.

A: Feed flow.

n: No. of membranes in series.

Spiral wound RO membrane is available in 2.5´´, 4´´, 6´´, 8´´, 16´´ and 18´´ size, but the most widely used size for seawater is 8´´ [1,5]. Peñate and García-Rodríguez [1] exposed that within large desalination

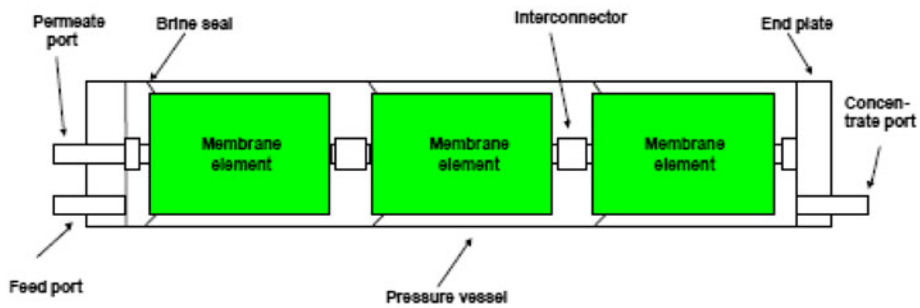

Fig. 5. Pressure vessel [36].

plants, there is poor economy of scale for the 8-inch diameter membranes because the number of elements, PVs, piping and connections must increase in direct proportion to the increase in flow capacity. For this reason, in 2005, a consortium of membrane suppliers comprised by The Dow Chemical Company©, Hydranautics©, Toray Membrane America© and Trisep Corporation© evaluated new industry standard for RO elements of larger diameter than the current 8-inch diameter standard. Bartels et al. [37] exposed the influence of module diameter on cost concluded by this consortium. Savings from increased module diameter were expected via a reduction of system footprint, number of housings, piping interconnections and seals between the modules [3].

Hallan et al. [38] showed that large diameter spiral wound modules enable significant reductions in RO plant capital cost and lifecycle cost. It was concluded that the optimum diameter was 16-inch considering that despite the cost savings, there is a risk associated with working even higher modules and PVs. Aforementioned diameters allow membrane active area and module productivity increase to 4.3 times respect to standard SWRO modules. On the other hand, Koch Membranes© determined that 18-inch will be the optimum diameter. As a result, The Dow Chemical Company©, Toray Membrane America© and Hydranautics© 16-inch diameter × 40-inch length RO elements, and Koch Membranes© has developed 18-inch diameter × 60-inch length RO elements [1].

In the same way, Gotteberg [39] showed this theory with a practical case. As she stated, a typical system with 8´´ elements would use 25 PVs and 175 elements. That same system with 18´´ elements would use only five PVs and 25 elements. The number of element O-rings is reduced by a factor of 14, which reduces the risk of downtime due to O-ring failures. The floorspace requirement for the 18´´ system is approximately 50% of that for the 8´´ system, which reduces building size and hence civil costs associated with the project. Also, the reduction in number of connections and size of the membrane rack allows for some potential savings in capital cost [1]. On the other hand, element size is limited by manufacturers' abilities to make elements as long as possible and with as large a diameter as possible, the ability to obtain a PV for that diameter, and the ability to handle the large element because of the increased weight of these ones [39].

Finally, Bartels et al. [40] reported that over the past years seawater elements have been made with increased area. Advances in membrane technology include both higher rejection and higher permeable membranes too. These advances allow system designers more options for cost savings and reduction of energy consumption.

With respect to current membrane supplies, we can single out five of them: Koch Membrane Systems, Inc.©, Toray Membrane America©, Hydranautics a Nitto Denko Corporation©, The Dow Chemical Company© and CSM Products—Woongjin Chemical Co Ltd ©. The most representative parameters are shown in the Tables 1(A), 1(B) and 1(C):

Permeate flux: Parameter obtained by dividing the permeate flow by the membrane area.

% Salt rejection: This parameter is the ions rejection capacity of the membrane. This percentage is determined using the concentration of salts in the feed line flow rate and in the permeate/product line.

$$\%\ \text{Salt rejection} : (\text{TDS-feed} - \text{TDS-product})/(\text{TDS feed}) \times 100 \quad (2)$$

TDS: Total dissolved solids

% Recovery rate: Ratio between the product flow rate and the feed flow rate.

Table 1(A)
Characteristics of different SWRO membrane types

Membrane suppliers	Type	Operating pressure (bar)	Maximum operating pressure (bar)	Permeate flux per unit area ($m^3/d/m^2$)	% Salt rejection	% Recovery rate (per element)	Active area (m^2) (per element)
Hydranautics'	SWC-4014	55	81.2	0.90	99.40	10	1.56
	SWC5-LD-4040	55	81.2	0.89	99.70	10	7.43
	SWC4-LD (Low fouling technology)	55	81.2	0.66	99.80	10	37.1
	SWC4 MAX	55	81.2	0.67	99.80	10	40.8
	SWC4B	55	81.2	0.66	99.80	10	37.1
	SWC5-MAX	55	81.2	0.92	99.80	10	40.8
Dow Chemical Company	SW30-2,540	55	N-A	0.93	99.40	8	2.8
	SW30-2514	55	N-A	1.00	99.40	2	0.6
	SW30-2521	55	N-A	0.92	99.40	4	1.2
	SW30-4021	55	N-A	0.97	99.40	4	3.1
	SW30-4040	55	N-A	1.00	99.40	8	7.4

Active area (m^2): It is the part of the total area useful to reject salts.

5. Reverse osmosis plants design

5.1. Internal-staged design

The essential point in the current plant design which uses similar membrane elements in the PVs is the difference in production of the membrane elements depending on their location inside the PV. Critical flux defines the flux at which concentration polarization leads to severe fouling and it should be taken into account for the design and choice of a membrane [41]. Goosen et al. [41] exposed that the highest flux along a PV occurs in the first element due to minimum osmotic pressure, so this element is most prone to bio- and colloidal fouling and critical flux must not be exceeded there. However, flux along the PV decreases because of increasing osmotic pressure due to increase in salt concentration. Using equal membrane elements causes a reduction in productivity from PV inlet to outlet [3].

Fritzmann et al. [3] stated that in 2005, it was suggested a new design approach, which involved the use of a seawater membrane element as a first element and high-flux membranes towards the end of a PV can lead to significantly higher recoveries at the same feed pressure and to large energy savings. Overall, water production cost was estimated to be reduced by 9–15% on average.

Peñate and García-Rodríguez [1] referred to this aforementioned concept, which consists in using different membrane models in the same PV, called in this case Hybrid membrane Inter-stage Design (HID), in order to reduce the lead/tail flow imbalance. They agreed that the effects of decreasing net driving pressure along the PV on permeate flux can be diminished by placing a low-flux element in the lead position, followed by high-flux elements in the rest of the PV. The HID in conventional SWRO plants proves that there is a significant reduction in the permeate costs in the different HIDs in comparison with standard designs [42]. The same design concept is known as "Internally Staged Design" by Dow Chemical Company©, who has patented this PV design concept for their membranes [43].

One inconvenience for the implementation of this innovation is that not all the manufactures are using the same interconnection of endcap elements. According to Peñate and García-Rodríguez [1], the use of special feed spacers can improve the membrane performance minimizing pressure drop across the element. These spacers have larger open cross-section of feed channel than traditional aforementioned spacers, thus reducing pressure drop and allowing more effective cleaning, reducing the biofouling process. With higher cross-flow velocity using large pores, low-pressure drop is possible getting lower fouling. This is useful for example surface brackish waters characterized by high-colloidal materials and prone to biofouling. Feed spacers used in most RO spiral wound

Table 1(B)
Characteristics of different SWRO membrane types

Membrane suppliers	Type	Operating pressure (bar)	Maximum operating pressure (bar)	Permeate flux per unit area ($m^3/d/m^2$)	% Salt rejection	% Recovery rate (per element)	Active area (m^2) (per element)
Koch Membrane Systems	FLUID SYSTEMS TFC–HF 4´´ ELEMENT	51.75–65.55	69	0.96	99.30	7	6.9
	FLUID SYSTEMS TFC–HF 8´´ ELEMENT	51.75–65.55	69	0.97	99.50	7	37.2
	FLUID SYSTEMS TFC–HF MegaMagnum® ELEMENTS	51.75–65.55	69	0.93	99.50	11	283
	FLUID SYSTEMS TFC–SW 4″ ELEMENT	51.75–65.55	82.75	0.72	99.50	7	6.9
	FLUID SYSTEMS TFC–SW 8″ ELEMENT	51.75–65.55	82.75	0.73	99.50	7	31.1–37.2
	FLUID SYSTEMS TFC–SW MegaMagnum® ELEMENTS	51.75–65.55	82.75	0.71	99.50	11	283
Toray Membrane America	TM820R-400	55	83	0.87	99.80	8	37
	TM820R-440	55	83	0.87	99.80	8	41

elements will range between 0.66 and 0.86 mm thick. Traditionally, these spacers are made from polyolefin materials which tolerate both high and low pH required during cleaning. The operation at low fouling rates will reduce cleaning costs and should also reduce overall operating costs and total plant costs [44]. For that some new materials are being developed. Polypropylene is being tested as spacers in RO membranes. This polymer is ubiquitous in membrane filtration as a feed spacer due to its high chemical stability, low cost and versatile properties.

In this way, Fritzmann et al. [3] stated that besides providing a flow path for the feed along the membrane leaf, they also create eddies, which reduces concentration polarization and thus increases mass flow through the membrane. By this way, feed spacers significantly reduce fouling potential and it was found that they may enhance critical flux by a factor of two. However, feed spacers inevitably increase feed channel pressure drop and for feed channels below 0.6 mm, excessive loss of productivity has been found due to a strong decrease in transmembrane pressure difference. Optimal feed channel height was found to be between 0.6 and 1.5 mm [3].

An optimization of spacers can lead to reduced pressure loss and decreased fouling which leads to cost savings when operating SWMs, an increased productivity and allows to operate at higher critical and water fluxes in the PV [1,3,44].

5.2. Array configuration (Matrix)

RO desalination plants capacity for seawater is determined by the number and position of PVs, as well as the number of membrane element in each PV.

Desalination plants based on RO membrane technology have usually multiple stage processes. There are three basic plant designs, and a selection of a proper design will depend on plant capacity and production requirements. The simplest plant design uses the series array configuration, which consist of several SWM (Spiral wound modules) elements connected in series, often in the same housing, depending on the available space; as mentioned before, usually 6–8

Table 1(C)
Characteristics of different SWRO membrane types

Membrane suppliers	Type	Operating pressure (bar)	Maximum operating pressure (bar)	Permeate flux per unit area ($m^3/d/m^2$)	% Salt rejection	% Recovery rate (per element)	Active area (m^2) (per element)
Toray Membrane America	TM820E-400	55	83	0.76	99.75	8	37
	TM840 M-1760	55	83	0.71	99.8	8	164
	TM820 M-400	55	83	0.71	99.8	8	37
	TM820 M-440	55	83	0.71	99.8	8	41
CSM Products	RE16040-SHF	55	82.7	0.92	99.7	8	148.6
	RE16040-SHN	55	82.7	0.63	99.75	8	148.6
	RE8040-SHA	55	82.7	0.74	99.75	8	34.4
	RE8040-SHF400	55	82.7	0.99	99.7	8	37.2
	RE8040-SHA400	55	82.7	0.76	99.75	8	37.2
	RE4040-SHN	55	82.7	0.65	99.75	8	6.9
	RE2521-SHN	55	82.7	0.77	99.75	4	1.1

elements are loaded into one housing. This design is limited by the feed fouling potential and restrictions on pressure head loss, which defines the maximum housing length (Fig. 6) [3,44].

For higher plant through-put, multiple housings are used in parallel. If feed-side flow rates are significantly reduced by permeation and fall below minimum requirements, the tapered array configuration can be applied to reduce cross-sectional membrane area proportional to decreasing flow rates.

Interstage pumps, so called booster pumps, are used to boost the pressure and so improve mass transfer when pressure loss along the housings and increasing concentration on the feed side reduce pressure driving force to very low levels.

The number of parallel PV of a specific stage and element number per housing are mainly based upon the maximum allowed pressure, defined by the membrane manufacturer to avoid membrane damage, the maximum and minimum flow rate through a SWM element and the targeted overall recovery.

Higher flow rate would result in excessive pressure loss along the modules. Besides, a restriction on flow rate in terms of minimum flow is necessary to avoid excessive concentration polarization, which would cause permeate flux reductions, increased fouling potential and lower rejection rates [3,44].

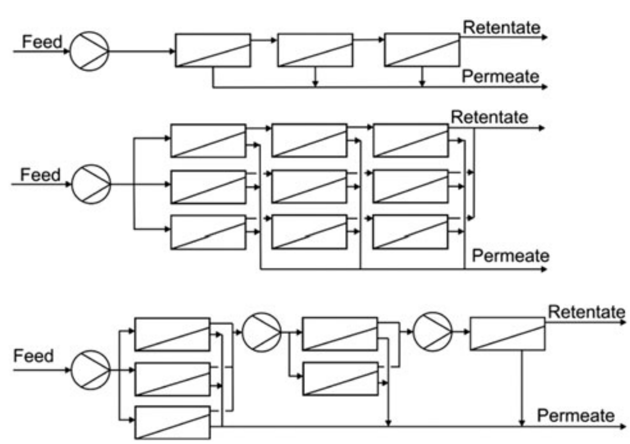

Fig. 6. Series array configuration. Parallel array configuration. Tapered array configuration [44].

On the other hand, other authors claim that the simplest configuration consists of several PV installed in parallel (Fig. 7) [35].

The permeate that leaves membrane elements contains certain amount of salts, due to RO membrane elements retentate never reach 100%. Consequently, desalinated water produced has a different concentration, according to feed water concentration, temperature, type of membrane or the design of the plant. In seawater RO plants, permeate concentration is between 200 and 300 mg/l of salts. WHO recommends a concentration of chloride of less than 250 mg/l for drinking water [45]. If a reduction of saline content is required, is necessary a different configuration with two or more passes (Fig. 8).

In these installations, the required permeate quality is relatively high, mainly related to Boron limitation, and a second-pass is needed in order to further treat the permeate water obtained in the first-pass. With the installation of high productivity modules in the first-pass, the feed pressure and thus the total energy consumption of the plant can be significantly reduced. Due to the lower rejection of these modules compared with standard seawater modules, the required size of the second-pass may increase. However, the benefit obtained from the reduction of the operation expenses compensates the increase in the capital expenses [1].

5.3. Energy recovery devices

Energy recovery devices (ERD) use in general the remaining energy of the brine, which otherwise would be wasted, to apply part of the necessary pressure to the feed, becoming a major reason for the decreasing cost for seawater desalination. Depending on overall recovery and efficiencies of ERD and pumps, this can substantially reduce energy requirements of an RO plant [3].

ERD can be divided into two groups:

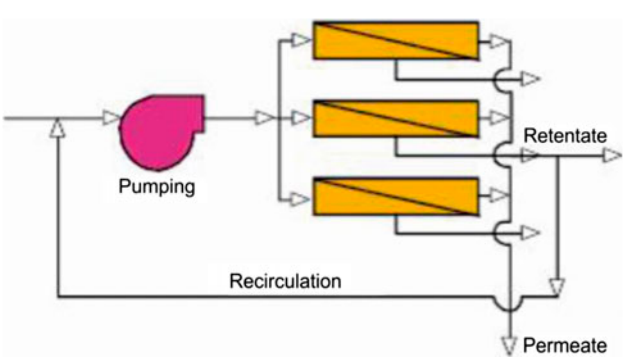

Fig. 7. Simplest configuration. Several PV installed in parallel [35].

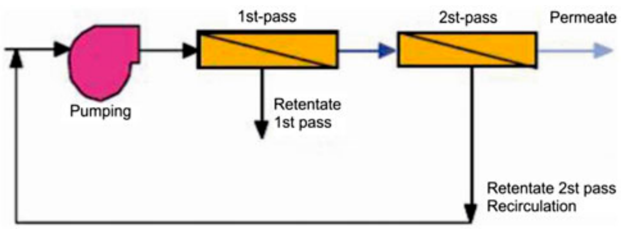

Fig. 8. Configuration with two passes [35].

(1) Pressure exchangers, which directly transfer pressure from the brine to the feed achieving efficiencies of around 96–98%. The general principle of pressure exchanger systems is the following: feed water is led into a duct, which is then closed by a valve. Another valve opens and gives way to brine at elevated pressure entering the duct, this way pressurizing the feed. Feed at elevated pressure exits the duct, mixes with feed from the high-pressure pump and is led to the RO stage. In a RO desalination process, using pressure exchanger systems, only part of the overall feed needs to be pressurized in the high-pressure pump. Due to pressure loss in the RO systems and piping, feed leaving the pressure exchanger needs additional pumping prior to the RO stage [3].

(2) Turbine systems, which convert potential energy from the brine to mechanical energy either supplied to the feed pump as auxiliary power supply or directly to the feed water. Turbine ERDs are either the Pelton wheel or the turbocharger system. Both of them work at efficiencies of up to 90%.

In Pelton wheel type ERDs, the high-pressure concentrate enters the turbine through the inlet nozzle. The high-pressure water stream drives the rotor which then produces rotating power to a shaft connecting turbine and high-pressure pump, thus assisting the main electric motor in driving the high-pressure pump.

Turbochargers consist of a pump and a turbine section combined in one housing. Both pump and turbine sections contain a single-stage impeller or rotor. Hydraulic energy from the brine stream is converted to mechanical energy by the turbine rotor. The pumping section re-converts the mechanical energy back to pressure energy supplied to the feed stream. The process pumping section consists of two steps. At first, all feed is pressurized by high-pressure pumps driven by an electric motor to an intermediate pressure level. The feed pressure is then further increased by the turbocharger to the RO stage inlet pressure. Turbochargers are the dominant technology despite the fact that pressure exchangers offer significant advantages in terms of efficiency [3].

According to Fritzmann et al. [3], pressure exchangers require additional auxiliary equipment such as high-pressure circulation pumps. Thus, equipment and maintenance costs of pressure exchangers exceed those of a turbine system. Other disadvantages of the pressure exchanger systems are increased salinity of the feed due to mixing of brine and feed water, causing higher osmotic pressures in the RO stage.

On the other hand, pressure exchangers maintain a very high efficiency even if membrane recovery is changed or if changes occur due to aging, fouling or seasonal variation of temperature and salinity. Turbine systems suffer stronger reductions in efficiency if operated outside the actual design point.

6. Desalination trends

New legislation of freshwater supply requires reduce the boron content in the permeate or, in other words, a higher boron rejection. For this reason, manufacturers work in developing membranes which comply this legislation and some desalination plants are adopting alternatives or complementary processes [1].

Typical boron concentrations in seawater by far exceed required values and usually are about 4.5 mg/l. For humans, boron can represent reproductive dangers and has suspected teratogenic properties. The WHO, therefore, limits boron content in drinking water to 0.5 mg/l, while the EU suggests concentrations below 1.0 g/l. In addition, boron at elevated concentrations may be harmful to crops when desalinated water is used for irrigation purposes. Although boron as a trace element is vital for plant growth, it can lead to foliage damage [46]. Therefore, typical tender documents display boron limits in the RO permeate that lie between 0.3 and 1 mg/l [3].

According to Lee et al. [2], the highest boron rejection membrane offered in the market can only achieve 93% boron rejection at optimum conditions. Membrane manufacturers work in developing membranes with high boron rejection due to the requirement to reduce the boron content in the permeate to comply new legislation of freshwater supply. This also causes some plants to adopt alternative or complementary processes to the RO. Rodrigo and Peñate [47] expose the different alternatives that are being used, thus generating an extra cost for the water production. They stated that the most selective membranes exhibit a stabilized boron rejection close to 90% [1].

According to Fritzmann et al. [3], under standard test conditions (32 g/l NaCl, 8% recovery, 55 bar feed pressure), SWRO high-rejection membranes display a boron rejection between 88 and 91%.

Actual rejection not only depends on pH, but on various parameters such as temperature and salt concentration. At higher pH, rejection strongly increases due to a shift to the charged form. A shift to pH 10 elevates rejection of SW membranes to about 99% and at pH 11 to 99.5%. Removal of boron with RO membranes, therefore, requires elevated pH values. In a single-pass RO operation, high pH is however problematic due to high alkalinity resulting in an excessive consumption of caustic and high hardness which could cause precipitation of scaling layers. Increased pH is therefore used primarily in double-pass operation at the second RO pass (Fig. 8). Alternatively boron selective resins can be used instead of a second RO stage [3].

The main options for boron removal are a design involves a single-pass RO with high boron rejection membranes, a design which consist of a SWRO followed by boron selective ion-exchange resin or a SWRO followed by electrodialysis reversal [3].

On the other hand, current research regarding SWMs is focused on providing greater filtration surface within the same volume [1]. Furthermore, While RO systems have already been commercialized; improving water flux, salt rejection and resistance to fouling and degradation of the membranes are required to advance this technology to meet future needs. Higher permeability membranes may enable operation closer to the ideal osmotic pressure, thereby, decreasing the energy cost for a given membrane area and capacity; alternatively, such membranes may reduce capital cost or plant size by requiring less membrane area for a given desalination capacity [8]. Furthermore, higher salt rejection can possibly reduce the number of RO passes necessary to achieve appropriate product water quality. Reduction in fouling, particularly via the development of chlorine-tolerant membranes, is important because it directly reduces the costs of membrane replacement, backwashing chemicals and energy to overcome the additional osmotic pressure [2]. However, the coupling between flux, salt rejection and other properties such as mechanical stability and fouling resistance requires careful optimization of the membrane material, which is particularly challenging as improving one factor tends to adversely affect the others [8].

Additionally, as we have read previously, significant improvement in the rejection of low molecular weight compounds, especially boron species, is necessary [2].

Finally, current research effort has focused on improving new materials too. In particular, nanostructured materials, which will probably form the basis for new reverse osmosis membrane materials. As we have said previously, since the building of the first RO desalination plant, only polymeric membranes have been employed for industrial use and membrane modules have been improved only by increasing membrane area per module. So, it is appropriate look forward to the novel nanostructured materials that will shape future trends in reverse osmosis membranes research. In fact, advances in nanotechnology have led to the development of nanostructured materials which may form the basis for new RO membranes. Thus, nanotechnology has opened the way to incorporate new materials into RO processes [2].

Firstly, inorganic membranes, made mainly from zeolites, offer higher tolerance to a variety of feed waters and harsh cleaning methods [48]. Secondly, two carbon-derived materials as carbon nanotubes, exhibit high permeability and high rejection rate [49] and graphene, with high breaking strength and impermeability to molecules as small standard gases [50]. Finally, a novel concept of membranes called mixed matrix membrane which combines organic and inorganic material and the benefits of each one [2].

Li and Lee [51] reported that research efforts are focussed on developing new materials that were less vulnerable to fouling and were easy to regenerate.

Humplik et al. [8] affirmed that advances in nanotechnology have enabled unprecedented control on the fabrication of nanostructured materials, and in particular, makes possible to create well-defined, size-selective and nanostructured filtration membranes.

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