



REVIEW ARTICLE

Materials and Corrosion in Seawater Reverse Osmosis Plants: A Review

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Abstract

Desalination is emerging as one of the most promising solutions to extraction and increasing global demand for drinking water. A water purification process called reverse osmosis (RO), in which dissolved solids are separated from solutions by partially permeable membranes. Advances in membrane technology have resulted in the removal of up to 99% of salts in seawater. However, the process and system of seawater treatment RO are associated with many problems, such as scaling and fouling of the membranes, corrosion of the pumps, valves and piping system due to the highly concentrated salt solution and high chemical consumption. Nowadays, these problems have become very critical as they severely affect the desalination process and also massively deteriorate the performance and lifetime of the system components and materials. To ensure that the desalination process is always the best option for a low-maintenance, highly efficient and cost-effective system and process, a comprehensive study of these problems is essential. Therefore, this article addresses the characteristics of metallic materials and corrosion problems in the reverse osmosis process of seawater desalination, as well as the best solutions to focus on and evaluate for an optimal seawater desalination process, and the selection of the category of duplex stainless steels suitable for seawater desalination plants to reduce maintenance, avoid plant shutdown and ensure plant safety.

Keywords: Corrosion, Desalination, Reverse Osmosis, Seawater, Duplex

Introduction

Desalination of seawater has become one of the most popular processes in practise and necessary to supply drinking water to many countries and industries. It plays an important role in social and healthy development, especially in Africa and some Middle Eastern countries suffering from freshwater scarcity. Desalination is a process of separating salt that reduces the amount of

salts from the brine water to a certain level. The product water from the desalination process is generally water with a dissolved solids content of less than 500 mg/l, suitable for most domestic, industrial and agricultural uses (Suwaileh et al., 2020). Generally, brine with a dissolved solids content of more than 50,000 mg/l is disposed of for evaporation in evaporation ponds or by discharge into deep wells (Panagopoulos et al., 2020).

Desalination technologies are divided into two classes, which are thermal desalination and membrane desalination. Thermal desalination technology is often referred to as distillation and is one of the oldest methods of treating brackish and seawater to convert it into drinking water. It is based on raising the temperature to reach the boiling point until it becomes steam, the steam is condensed to produce fresh water, while the salt remains (Shatat et al., 2012). The most common thermal desalination processes are multi-stage flash distillation (MSF), vapour compression evaporation (VC) and multiple effect distillation (MED) (Shatat & Riffat, 2014).

Membrane technology is widely seen as a solution to the problem of water scarcity because it is very efficient and uses less energy than distillation processes. Membrane is a semi-permeable barrier made from different polymeric materials (Rozali et al., 2022, Safari et al., 2022) which enable them to be used for various applications including reverse osmosis process (Sulaiman et al., 2020, Ali & Hassan, 2016). For certain configurations, membranes also supported by a network of fibres that is impermeable to solutes (Aliyu et al., 2018). Commonly, membrane technologies for the treatment of saline and brackish water include reverse osmosis (RO), ultrafiltration (UF) and nanofiltration (Obotey Ezugbe & Rathilal, 2020). Reverse osmosis seems to be the most promising membrane technology, as treatment with membranes results in very high quality of drinking water.

Manufacturers of seawater desalination plants are confronted with the problem of the high salt content of seawater in the range of 35,000-45,000 mg/l. Very high pressures (60-80 bars) are applied in reverse osmosis plants to complete the desalination process. Therefore, special corrosion-resistant materials such as Duplex SS or Super Duplex SS are needed to withstand the high salinity and pressure.

Reverse Osmosis Membrane

The RO membrane is a separation process that separates the water from the solutes in a pressurised salt solution. The high pressure pump forces the water to flow through a semi-permeable membrane (Subramani & Jacangelo, 2015). This is a simple process in which a fluid is forced through a semi-permeable membrane from an area of high concentration to an area of low concentration by raising the fluid pressure to a pressure higher than the osmotic pressure (Mohammadifakhr et al., 2020). The water therefore flows through the membrane in the opposite direction. Only pure water can pass through the membrane, but water with high salt content, called brine cannot pass through the membrane.

The membrane should be strong enough to withstand the entire pressure drop across it. For seawater, this pressure is between 55 and 75 bars, but for brackish water, it's between 14 and 25 bar, depending on the salinity. RO Membranes are manufactured in a variety of configurations, the most commonly used membranes for brackish water and seawater desalination due to their compact size, low price, large membrane surface area relative to volume and suitability for multiple applications are hollow fine fibre membranes (HFF) and spiral wound membranes (SW) (Stoica et al., 2018).

Reverse Osmosis Membrane Configuration

The RO membrane (type SW) has a three-layer structure, i.e. a thin polyamide layer (< 200 nm) applied to a porous polyethersulfone layer (~50 µm), which is on a non-woven backing. The top polyamide layer is responsible for water permeability and retention of dissolved contaminants,

while the other layers provide mechanical strength to the membrane (Ibrahim et al., 2020). In the construction of the spirally wound elements, several layers are laid in an alternating arrangement, as shown in Fig. 1. If keep this array throughout the stack, the retentate sides of the sequential membranes face each other. The edges of the sequential membranes are sealed by the glue so that only one side serves as an outlet for the permeate flow (Wan et al., 2017). The outer sides are separated by coarse lining joints to ensure the flow of the feed. Finally, a central core tube is connected to the outlet side of each of the resulting envelopes and spiralled around the tube.

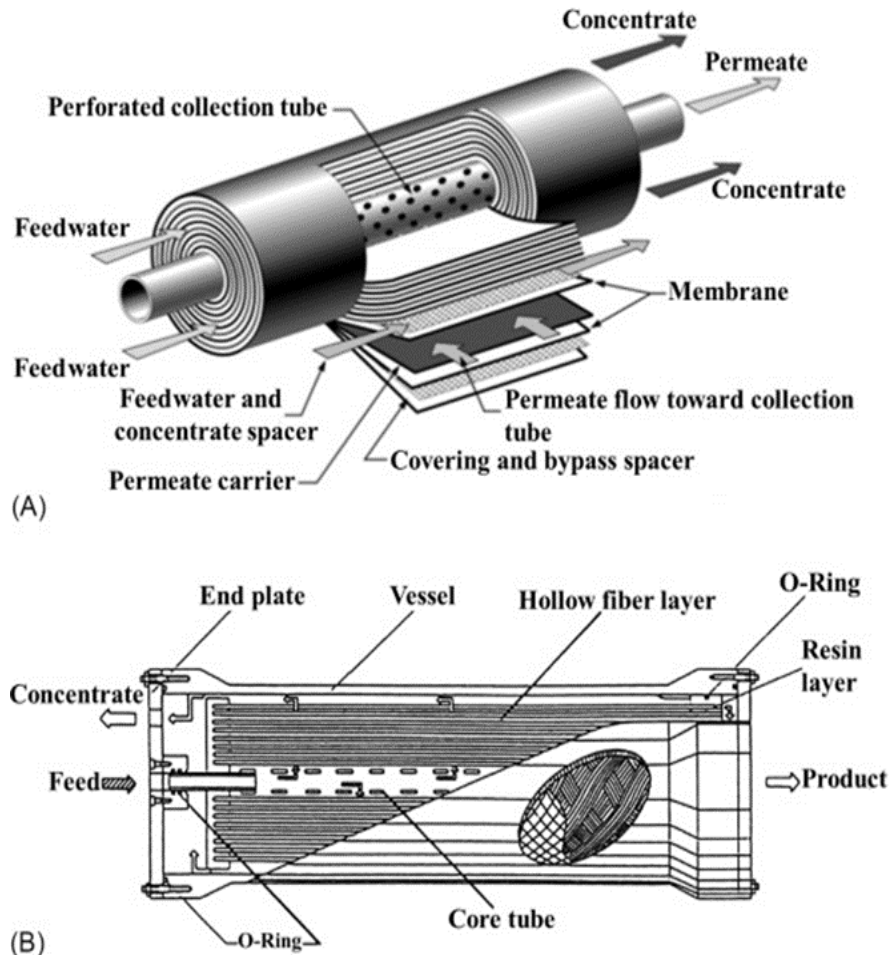


Figure 1. Flow through a spiral wound module in reverse osmosis membrane

Desalination Plant

Reverse osmosis is the best-selling desalination system on the world market that uses membranes. It is able to reject all dissolved organic matter in the water so that the product is a salt-free solution (Sanmartino et al., 2017). RO Membranes retain 96-99.5% of organic and inorganic solutes from the feed stream and discharge them into the reject stream, while the permeate can be considered high quality water (Sadrzadeh et al., 2015). The rejection of impurities by RO is based on their size and charge, and any impurity with a molecular weight bigger than 150-200 is likely to be rejected by a properly functioning RO system (Werber et al., 2018). The bigger the ionic charge of a pollutant, the more likely it is that it cannot pass the reverse osmosis membrane. Hence, RO is categorized as a concentration process, and has several

advantages compared to other applicable concentration technologies. If the ionic charge of the pollutant is large, it cannot pass through the RO membrane. Therefore, RO is categorised as a concentration method and has several advantages over other applicable concentration technologies.

RO is a very energy-efficient process, as it is usually operated at room temperature and does not require heating or cooling, as the removal of the solvent does not involve a phase change (Gude, 2018). In addition, RO is more economical for concentrating dilute solutions and at intermediate concentrations compared to other competing technologies (Vinardell et al., 2020). A typical RO system, shown in Fig. 2, consists of three main processes: Pre-treatment, salt separation and post-treatment stabilisation. In general, RO systems require less energy per unit of water extracted from the product than evaporative technologies, as they mainly require electrical energy for pumping and circulation, whereas evaporative systems need to generate steam in addition to electrical energy for pumping.

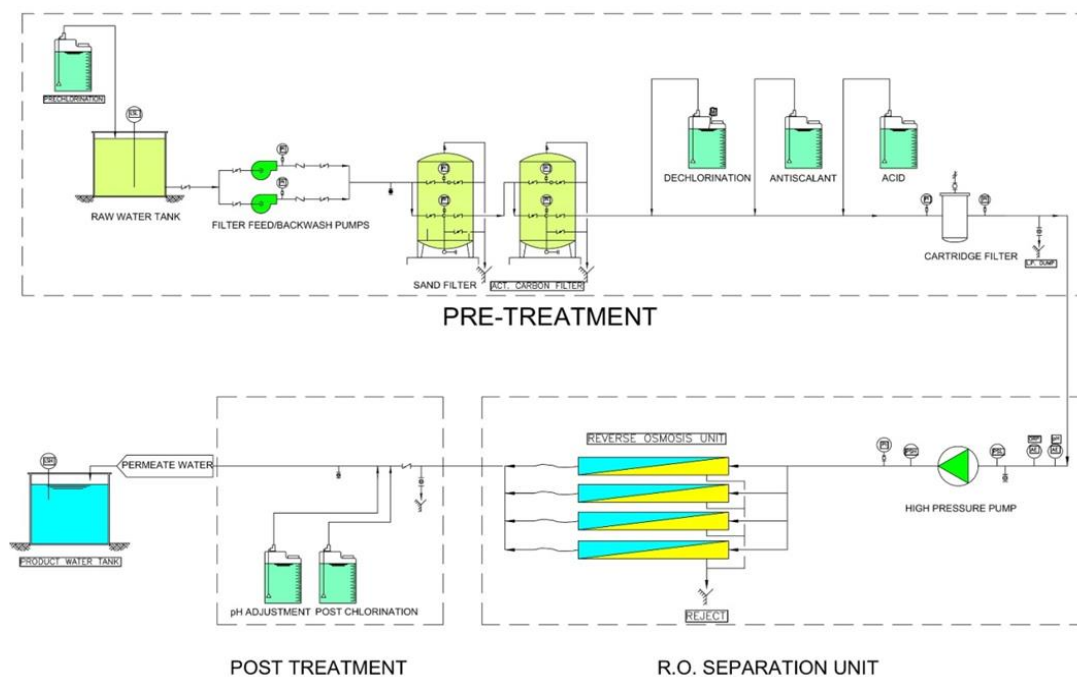


Figure 2. Components of the RO Desalination Process

Pre-treatment

The feed water is subjected to pre-treatment to make it suitable for the membranes. This involves removing suspended solids, adjusting the pH and adding a threshold inhibitor to prevent calcification (Al-Karaghoulis & Kazmerski, 2012). First, a sodium hypochlorite solution (NaOCl) is added to the raw water tank to kill microorganisms and bacteria. Then the raw water from a storage tank is passed through a multimedia filter and an activated carbon tank with the help of pumps. The first filter is sand supported by gravel to remove suspended solids, while the second is an activated carbon filter that removes a range of pollutants. The feed water enters the top of the tanks through the internal distribution, flows down through the sand bed or the carbon bed and becomes clearer as suspended solids are retained in the filter bed (Oliveira & Schneider, 2019).

Chlorine penetrating the membranes impairs their performance. Normally, sodium metabisulphite (SMBS) is added to the feed water to remove excess chlorine that has been added at the inlet for disinfection and may have passed through the dual multimedia filters (Al-Abri et al.,

2019). In addition, an antiscalant is added to the RO feed water to prevent the build-up of scale on the membranes caused by chemicals with scale potential such as CaCO_3 and CaSO_4 (Tay et al., 2018).

These deposits reduce the permeability of the membranes by clogging the pores, leading to fouling. In some cases, acid is added to further control the deposition of carbonate and sulphate deposits membranes. The pre-treated water is fed into a cartridge-wound polypropylene philtre located in a SS or PVC tank before finally being sent to the RO membranes. Pre-treatment of seawater is essential as seawater is known to contain many contaminants such as colloidal suspensions, substances of biological origin, silt, sand and other suspended solids. Therefore, the RO membrane is damaged by these problems because it is not designed to hold solid suspensions (Jacangelo et al., 2018).

Separation

The water is pumped over the surface of the membrane by the high-pressure pump, causing some of the water to flow through the membranes, as shown in Fig. 3. The operating pressures for brackish water desalination are 14 - 25 bar and for seawater desalination 55 to 75 bar (Dees et al., 2017). The RO membranes are equipped with pressure vessels (PV) that protect and hold the spirally wound RO membrane while the pressurised water flows through the membranes. The design pressure of the PV is 1200 psi for seawater and 300 - 600 psi for brackish water. At the pressure exerted on the membrane, a freshwater product stream and a concentrated brine reject stream are formed from the feed water. (Oren & Biesheuvel, 2018). The membrane acts as a semi-permeable barrier, allowing the selective passage of the desalinated product water (permeate) while preventing the passage of dissolved salts. At the pressure exerted on the membrane, a freshwater product stream and a concentrated brine reject stream are formed from the feed water. (Oren & Biesheuvel, 2018).

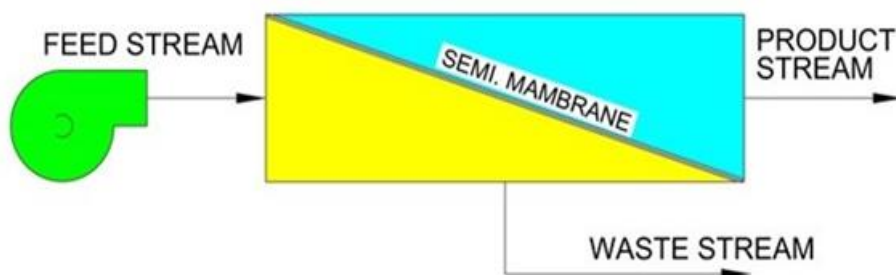


Figure 3. Schematic diagram representing a stage of membrane separation

Post-treatment

Due to the low salt content in the permeate water, it will be undrinkable, unhealthy and corrosive. The permeate must be re-hardened to prevent corrosion of the pipes in the distribution network, CO_2 and pH content must be adjusted to prevent scaling build-up, and the permeate water must be further disinfected (Duranceau, 2009). To reduce the aggressiveness of the treated water, post-treatment disinfection and conditioning (i.e. blending and remineralisation) must take place. Both processes are crucial for desalination (Rouina et al., 2016). Usually, the permeate water need to adjust the pH, and degassing before it is fed into the distribution system for use as drinking water (Yan et al., 2019). Normally, sodium hydroxide (NaOH) is added to the feed water to maintain the pH between 6.8 and 7.5.

Sodium hypochlorite is dosed into the product water stream to kill remaining bacteria and make the water proper for distribution via pipe supply network permitting it to contain a certain

minimum level of free residual chlorine. Another post-treatment stage is degasification of carbon dioxide, re-carbonation, aeration to remove hydrogen sulphide and disinfection using chlorine gas or calcium hypochlorite (Al-Hindi & Azizi, 2020). This is important for good taste of the water and to meet the final requirements for drinking water.

Problems in Seawater RO system and Possible Sustainable Solutions

Seawater desalination RO has gained in importance in the last ten years due to its higher water yield with simultaneously low energy consumption compared to other desalination processes. The electricity consumption of SWRO plants is about 3-6 kWh to produce one cubic metre of permeate water, while the production costs vary considerably depending on the capacity of the plant (Voutchkov, 2018). Obviously, water costs are relatively lower for large desalination plants. Moreover, water recovery in a single-stage SWRO system is between 40 and 50% (Song et al., 2015). Nowadays, the global freshwater desalination capacity has increased significantly in combination with lower unit costs. Interestingly, the RO freshwater desalination plants have the greatest potential for further improvement and expansion (Liyanaarachchi et al., 2014). Despite these technological advancements in SWRO, desalination industry is yet facing significant number of practical challenges, with RO membrane productivity decline due to scaling and fouling being the major one.

Fouling is the deposition of unwanted materials on the membrane. This includes scaling, organic fouling, and bio-fouling, which is caused by bacterial growth on the membrane surface and deposition of colloidal and suspended particles on the membrane surface, resulting in selectivity of a membrane and degradation of membrane flux. (Ruiz-García et al., 2017). This has a negative impact on the sustainability of the RO system in several ways, as hydraulic resistance increases. Over time, this leads to a significant decrease in permeate production at constant pressure, which requires costly pre-treatment, degrade permeate quality and increase the frequency of membrane replacement. This will increase in pure-water costs and energy consumption. Therefore, an important challenge is to investigate how to improve the processes of water reverse osmosis, through sustainable ways to deal with fouling and highly concentrated brine, and then to find solutions to the current problems faced by the seawater reverse osmosis projects in each process.

Scaling and Fouling

Scale formation and fouling in SWRO depend on the quality of the feed water. Scale forms when the concentration of various sparingly soluble salts, i.e. divalent and polyvalent salts, reaches their supersaturation limit (Lunevich et al., 2016). This causes them to precipitate on a surface of the membrane, which affects the permeate water quantity. Mostly, the deposits are Calcium Carbonate (CaCO_3), Calcium Sulphate (CaSO_4), Strontium Sulphate (SrSO_4), and Silicic Acid (SiO_2) and Barium Sulphate (BaSO_4) (Bello, 2017). In addition, the usual signs of membrane scaling are reduced salt rejection, reduced product flow and increased pressure drop in the last stage (Rouina et al., 2016). However, the application of anti-scalants agents is a widely used technique to prevent deposits caused by salts such as: silica, iron, barium sulphate, calcium carbonate, gypsum, etc. Common used anti-scaling agents, such as: organic polymers, organic phosphonates, surface-active reagents, and phosphates (Popov, 2016). In addition, scale formation caused by silica increases the complexity of SWRO process, which costly to remove even by using anti-scale agents. However, carbonate deposits can be avoided by adjusting the pH of the feed water between 5.0 to 6.5 (Sanciolo et al., 2014).

Purification is used to facilitate the redissolution of scales on the surface of the membrane. The cleaning procedure involves treating the scales with a strong acid (sulphuric acid, hydrochloric acid and nitric acid) to dissolve the scales, treating the scales with warm water at a temperature

of about 25° to 35°C and using large amounts of chemicals for long reaction times (Beyer et al., 2017). In SWRO, fouling of membranes occurs when pollutants are deposited on the surface of a filtration membrane, thereby impeding the flow of water through the pores of the membrane (Matin et al., 2021). The types of fouling are divided into particulate fouling due to suspended solids, inorganic fouling due to iron and manganese, organic fouling due to organic compounds and biofouling due to bacterial growth (Kucera, 2019). Fouling leads to higher operating pressure, a decrease in flux, higher energy consumption and frequent chemical cleaning which lead to a shorter membrane life. This makes SWRO desalination plants less reliable and membranes need to be replaced frequently.

Brine Disposal

Concentrate, reject line or brine has the same meaning in RO desalination plants. It is the by-product of the brackish water or seawater desalination process desalination process, which has a high salt content. In addition to high total dissolved solids (TDS) content, brine may also contain other constituents such as halogenated organic compounds, anti-pollutants, antiscalant agents, acid and corrosives (Shenvi et al., 2015).

Various disposal methods are currently practised, including direct discharge to the sea, injection into deep wells, discharge into sewers, surface discharge and evaporation ponds (Panagopoulos et al., 2019). The disposal of brine on land or in the sea poses a serious threat to the environment as it affects microalgae populations and plant life and leads to the formation of mud. The disposal of brine via evaporation ponds is commonly used for inland desalination plants RO in arid and semi-arid areas (Gorjian et al., 2019). However, evaporation ponds require big space, injection into deep wells can affect groundwater and surface discharge can affect soil and plant growth.

Reduction and Eliminating Brine Disposal

Various techniques are used to dispose of the saline water produced in desalination plants, in particular solar evaporation, injection into deep wells, surface water discharge, discharge to sewer, discharge to sea, and two-stage reverse osmosis. In solar evaporation, the brine is left in shallow evaporation ponds where the water evaporates naturally under the sun. The salt remains in the evaporation ponds or is removed for disposal (Katzir et al., 2010). Evaporation ponds are relatively simple to build and require little maintenance, no equipment is required other than the pump that delivers the wastewater to the pond, which keeps operating costs low (Ahmed et al., 2000). However, it is important to make evaporation ponds for the disposal of concentrates from desalination plants according to design and properly maintained and operated to avoid causing environmental problems, especially with regard to groundwater pollution (Morillo et al., 2014). Liners are very important in an evaporation pond and come at a high cost. They should be impermeable to prevent brine leakage and mechanically stable to withstand the stresses of salt removal (Afrasiabi & Shahbazali, 2011).

The most common method of waste disposal is injection into a deep well, as there are no technical difficulties here. However, the regulations for injection into a deep well are strict and the geology of the site is one of the most important factors to be decided. When water desalination plants are located relatively close to surface waters (rivers, lakes, lagoons and canals), discharging the water desalination plants into a surface water body is the most common practise for brine disposal. The costs for disposal are usually low, provided that the transport distances are not too long. The discharge of small brine into the sewerage system is sometimes possible if the brine mixture is not toxic (Afrasiabi & Shahbazali, 2011).

Two-stage RO desalination plants allow for higher water production and a lower amount of concentrate. In this technology, the high pressure pump is used for the first stage modules.

Then, the rejected brine of the first stage has a high pressure and then enters the second stage modules of RO to increase the recovery, but far from zero liquid discharge. Fig. 4 shows a typical diagram of a two-stage RO process for seawater. In general, the two-stages RO system is suitable for brackish water systems BWRO, but not for SWRO.

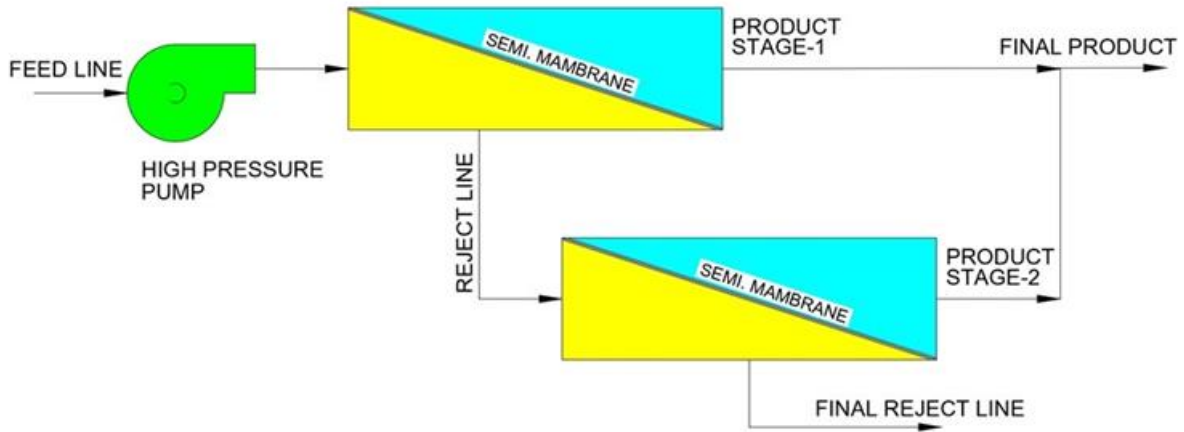


Figure 4. Schematic diagram of two stages of seawater membrane

Another method of effectively disposing of brine that reduces environmental impact is to dilute it with seawater or water consumed in other processes at the RO plant. Even the small amounts of brine pumped into the sea do not harm the marine environment. Concentrated water obtained from seawater desalination plants using reverse osmosis usually has a much higher salt content and a very large volume than in the sea. The disposal of this saline water poses an environmental risk if it is returned to the sea.

To determine the amount of brine in the return line (TDS reject), the recovery rate (RR%) need to be measured. The recovery rate (RR%) is the percentage of the feed water of the membrane system that exits the system as product water or "permeate":

$$RR\% = \left(\frac{Q_p}{Q_f} \right) \times 100 \quad (1)$$

Then,

$$TDS \text{ reject} = \frac{TDS \text{ feed}}{(1-RR)} \quad (2)$$

Where; Q_p : product flow ($\frac{m^3}{h}$), Q_f : feed flow ($\frac{m^3}{h}$), TDS Reject ($\frac{mg}{l}$), TDS Feed ($\frac{mg}{l}$).

For example, if:

$$TDS \text{ feed} = \frac{40,000 \text{ mg}}{l} \quad (3)$$

$$Recovery = 40\% \quad (4)$$

Then,

$$TDS \text{ reject} = \frac{40,000}{(1-0.4)} = \frac{66,666 \text{ mg}}{l} \quad (5)$$

Corrosion in Seawater Reverse Osmosis Processes

Corrosion is one of the biggest challenges in seawater desalination. This occurs due to the long-term erosion of seawater on pumps, valves and some equipment, resulting in reduced performance or failure of the plant. Therefore, the development of more corrosion-resistant piping materials or coating materials, valves and pumps is too important in desalination processes. More importantly, desalination plants create extremely corrosive operating environments as they process aggressive salt water under critical conditions. These include filtration, distillation, heat exchange, high pressure pumping, energy recovery, evaporation, agitation, high flow, etc. Therefore, metal corrosion causes pure economic losses. Therefore, it is important to address the study of corrosion and protection of metals in seawater desalination plants (Jordan et al., 2009).

The pipes, valves and pumps in desalination plants contain highly corrosive components such as: Iron oxides Fe_3O_4 and FeO , Iron hydroxides such as $\text{Fe}(\text{OH})_2$ and $\text{Fe}(\text{OH})_3$, Chromium oxides: Cr_2O_3 , Siderite: FeCO_3 and Carbonate or Sulphate green grates (Cui et al., 2016). The form and composition of corrosion in the pipes and fittings depends mainly on the quality of the water that comes into contact with it and on environmental factors, the most important is temperature (Ray et al., 2010). The oxygen creates by the different flow rates in desalination plants, which leads to an increase in corrosion in the piping system (Liang et al., 2013). The pH of salt water varies between 5 and 8 and the concentration of dissolved oxygen (DO), (the most important corrosive substance), varies between 4 and 6 mg/L depending on temperature and flow rate. Saltwater contaminated with hydrogen Sulphate H_2S is slightly acidic and attacks some corrosion-resistant alloys, so H_2S must be removed by mechanical or chemical methods (Schorr et al., 2012).

Corrosion Problems in Seawater Desalination

Factors that affect the life of materials exposed to seawater include salinity, conductivity, dissolved oxygen, temperature, pH, flow rates and pressure. Corrosion is an electrochemical reaction that occurs on the metal surface through reaction with the components of the salt solution. Salinity is the most important parameter that characterizes and defines salt water. It has a strong influence on the electrolytic and corrosive properties of seawater.

The measure of salinity is usually the total dissolved solids (TDS), expressed in mg/l. It is usually calculated from the measured chloride content or electrical conductivity. The salinity of the water directly affects the conductivity and the oxygen content of the water. The electrical conductivity of the water increases with increasing salinity in the water, but the oxygen content decreases with increasing salinity in the water.

The oxide layer on the surface of the metal is destroyed by the chloride in the seawater and forms a metal ion complex that generates hydrogen ions during the chemical interaction (Hou et al., 2018). Chlorine treatment is usually used in seawater desalination to prevent bio-fouling, the chlorine increases the corrosion potential of stainless steel and, depending on the concentration range and temperature of the water, can have a detrimental effect on local corrosion resistance, so that the main reason for the risk of crevice corrosion in desalination is chlorinated seawater (Bajpai, 2018).

Dissolved oxygen (DO) refers to the amount of oxygen contained in water. The oxygen concentration is high above the water surface because of the low solubility of oxygen in water. Reducing the rate of oxygen leads to less seawater corrosion (Al-Fozan & Malik, 2008). The more DO the seawater contains, the higher the electrode potential of the metal in the seawater and the faster the metal corrodes (Huang & Ji, 2018).

Some physical factors such as flow velocity, tides, temperature, etc. affect the corrosion of the metal surface. This physical factors cause DO diffuses faster to the cathode, increasing the

rate of corrosion of the metal. When the flow of seawater increased, the water and salt with high content of oxygen lead to fast corrosion of the metal. Therefore, the increasing of water pressure on the metal caused the corrosion. It has also been found that temperature speed up corrosion in the range between 10°C and 40°C. The pH value is a measure of the concentration of hydrogen ions in salt water.

The corrosion rate is high at a low pH due to acid corrosion, while it decreases at an intermediate pH of 8.5 to 12 due to the formation of a passive layer, and corrosion is severe at a higher pH due to alkali embrittlement effect (Paul, 2012). In general, the pH of seawater is beneficial for inhibiting corrosion of steel by seawater.

Corrosion-Resistant Materials and Equipment in Seawater Desalination

In the selection of materials for the proper operation of seawater desalination plants, corrosion resistance is the most important requirement to consider; therefore, corrosion-resistant and inhibitive alloys are used in these plants. There is a wide range of equipment that is assembled as shown in Table 1.

Table 1. Equipment in seawater desalination plants

Mechanical Equipment	Thermal Equipment
Pipes ,Tubes, Ducts and Frames	Evaporators
High pressure Pumps (H.P.P.) and Energy recovery devises (ERD)	Condenser and Diesel engines
Valves diverse types	Flash chambers
Fittings and flanges	Condensers
Filters diverse types	Steam generators
Compressors	Chlorinators
Instrumentation: Flow control, Pressure gauges, TDS and Conductivity maters	Storage tanks

This includes many storage tanks, pumps, heat exchangers and pipes (Valdez & Schorr, 2010). Carbon steel (CS), galvanised (GI) or cast-iron (CI) piping should not be used in desalination plants that come into contact with process salt water because of the risk of corrosion and the resulting contamination by corrosion products (Malik & Al-Fozan, 2011). The equipment in desalination plants is made of metallic and non- metallic materials that have adequate resistance to the fluids (liquids, vapours and gases) processed in the plants and the environment (Habib & Fakhral-Deen, 2001).

The most important factor when selecting materials is their resistance to corrosion. Corrosion resistant alloys (CRAs) used in the desalination industry are divided into two broad groups: Ni-containing alloys (e.g. Ni-based alloys, SS,7 and Cu-Ni alloys) and Titanium and Aluminium alloys (e.g. UNS A95052).

Their UNS designations are listed in Table 2. These metals can be used to reduce the need for additional corrosion protection. Meanwhile, non-metallic materials such as plastics: polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC) and composites, especially fibre-reinforced plastic (FRP), are mainly used for piping and storage tanks for low pressure stages in SWRO plants.

Table 2. Corrosion-Resistant Alloys (CRAs)

Alloy UNS	Designation
Aluminum-magnesium	A15052, A95054
Austenitic chromium-nickel steels	S30400, S31600, S31700
High-alloyed austenitic	S31254, N08020, N08028
Austenitic, casting	J92500, J92800, J95150
Duplex: ferritic-austenitic	S32250, S31803
Nickel-based alloys	N06600, N08825, N06030
Titanium	R50250, R52400

The main corrosion-resistant metallic materials used in the construction of desalination plants are:

Carbon Steel

Carbon steel (CS) is used effectively when strength and other property requirements are not critical and when high temperatures and corrosive environments do not play a major role in the selection of the material (Nogara & Zarrouk, 2018). It is the most important material for the construction of desalination plants, water reservoirs, tanks and pipelines. This is because of its low cost and the associated valuable mechanical properties, easy of fabrication and welding.

However, there are limits to the durability of CS due to its low corrosion resistance. In particular, CS pipes and pipelines are susceptible to erosion and corrosion damage due to the erosive and corrosive nature of seawater (Zeng et al., 2020). Due to its limited corrosion resistance, it should therefore be protected by cathodic protection through sandblasting, painting and coating for many structures that come into contact with liquid (Cheng et al., 2019).

Nickel-base Alloys

Nickel alloys are among the most important due to they resist corrosion in a variety of environments, including chloride-rich seawater. The higher content of nickel in alloys the higher the resistance to water line corrosion. They are divided into two groups: those consisting mainly of Ni and those containing chromium (Cr) as the main alloying element.

Nickel-based alloys also contain small amounts of manganese and iron. Their corrosion resistance depends on the presence of nickel and chromium oxides, which put them in a passive state (Cwalina, 2019). They are used in desalination plants for the manufacture of brine concentrators and high-pressure pumps.

Stainless Steel (SS), PREN

Many types of stainless steel (SS) are used for seawater desalination. SS should be carefully selected in desalination plants to avoid corrosion problems. The proper addition of Cr, Mo and Ni obviously has positive effects on the pitting and crevice corrosion resistance of SS in chloride environments (Combrade & Pierre, 2011). The corrosion value in SS is often characterised by a formula called PREN (pitting resistant equivalent number), which is as follows: $PREN = \%Cr + 3.3\%Mo + 16\%N$. It gives a quasi-linear relationship when plotted against the critical pitting

temperature (CPT) and/or crevice corrosion temperature (CCT) in oxidising media, with higher PREN values indicating better pitting corrosion resistance (Zhou & Engelberg, 2020). This relationship between the PREN and the pitting volume or crevice temperature allows a global material classification.

However, PREN should be used with caution as this figure does not take into account some other important parameters such as metallurgical quality (Larché & D  zerville, 2011). The composition of the main stainless steel grades used for SWRO plants is listed in Table 3 of ASTM A240/A240M (Standard specification for chromium and chromium-nickel stainless steel plate, sheet, and strip for pressure vessels and for general applications).

SS with PREN values below 30 are not suitable to resist local corrosion in seawater desalination plants. Most SW desalination plants using UNS S31603 (316L) or UNS S30403 (304L) SS have experienced severe pitting and crevice corrosion (Zhou & Engelberg, 2020). PREN 30-45 grades designated as Duplex SS (DSS) or Super-Duplex SS (SDSS) such as (S32550, S32750 & S32760) are mainly intended for use in extremely corrosive environments such as the oil and gas industry due to their excellent corrosion resistance and strength (Kannan et al., 2020).

Table 3. Composition of some stainless steel used in seawater application (Balanced Fe) from ASTM A240/A240M

N°UNS	Other designation	Cr	Ni	Mo	N	Other	PREN*	Type
S30403	304L	18-20	8-12	-	0.10	-	20-22	Austenitic
S31603	316L	16-18	10-14	2.0-3.0	0.10	-	24-29	-
N08904	904L	19-23	23-28	4.0-5.0	0.10	Cu 1.0-2.0	34-41	-
S31803	2205	21-23	4.5-6.5	2.5-3.5	0.08-0.20	-	31-38	Duplex
S32205	-	22-23	4.5-6.5	3.0-3.5	0.14-0.2	-	34-38	-
S32550	52N, 255	24-27	4.5-6.5	2.9-3.9	0.10-0.25	Cu 1.5-2.5	35-44	Super duplex
S32750	2507	24-26	6.0-8.0	3.0-5.0	0.24-0.32	Cu 0.5	38-47	-
S32760	Zeron100	24-26	6.0-8.0	3.0-4.0	0.20-0.30	Cu 0.5-1.0 W 0.5-1.0	37-44	-
S31254	254SMO	19.5-20.5	17.5-18.5	6.0-6.5	0.18-0.22	Cu 0.5-1.0	42-45	Super austenitic
N08367	A16XN	20-22	23.5-25.5	6.0-7.0	0.18-0.25	Cu 0.75	43-49	-
S34565	4565	23-25	16-18	4.0-5.0	0.40-0.60	Cb 0.10	44-51	-
S31266	B66	23-25	21-24	5.2-6.5	0.35-0.60	Cu 1.0-2.5 W 1.5-2.5	46-54	-

Stainless Steel Categories

Stainless steels are iron-based alloys. To be corrosion resistant and reveal their quality, they should contain minimum 11 to 13% by weight of chromium (Cr), at this minimum chromium content, a stable Cr oxide/hydroxide forms a reactive film on the surface of the steel. Stainless steels generally exhibit good resistance to general corrosion, although the passive film may dissolve at low pH and/or high chloride concentration (Esquivel & Gupta, 2020). The different classes of stainless steel are named after their main crystal structure, namely: austenitic (face-centred cubic (fcc)), ferritic (body-centred cubic (bcc)), martensitic (body-centred tetragonal) or duplex alloys, which contain almost equal proportions of austenite and ferrite, the structures being approximately 50/50 austenite and ferrite (Nakada et al., 2017). The physical properties are a combination of the austenitic and ferritic grades. The categories of Duplex SS are Lean Duplex SS – lower nickel and no molybdenum – 2101, 2102, 2202, 2304 (Table 4), Duplex SS – higher nickel and molybdenum - 2205, 2003, 2404, (Table 5) and Hyper Duplex – More Cr, Ni, Mo and N – 2707 (Table 6).

There are four categories of stainless steels, namely Martensitic SS, Ferritic SS, Austenitic SS and Duplex austenitic-ferritic SS. Martensitic SS alloys have a comparatively low chromium and high carbon content, and in some cases molybdenum may also be used, these SS grades are inherently magnetic (Cunat, 2004). In Ferritic stainless steels, the alloys have a comparatively high chromium content and a very low carbon content. Some ferritic grades contain up to 4% molybdenum and consist only of chromium as the most important metallic alloying element. Ferritic grades are magnetic and are chosen when the focus is not on toughness but on corrosion resistance, especially in seawater desalination plants (Cunat, 2004).

Austenitic stainless steels have comparatively very low carbon content, high Chromium content and a high Nickel content. The most important properties of these types of stainless steel are excellent corrosion resistance, toughness and ductility (Suba et al., 2019). Duplex austenitic-ferritic stainless steels have a comparatively high Chromium content, a very low Carbon content and a high Nickel content. These alloys can contain up to 4.5% Molybdenum (Mohammed et al., 2017). All the alloys have a mixed structure of austenite (50%) and ferrite (50%), and offer physical properties that reflect this structure. These alloys are magnetic and have higher tensile strength and yield strength than austenitic stainless steels (Cunat, 2004). Table 7 shows the chemical compositions for the four categories of SS.

Table 4. Chemistry of Lean Duplex SS: (High Cr, Low Ni, N=0.2, Little Mo)

Name	UNS No.	C	Cr	Ni	Mo	<u>N</u>	Other	PREN
2101	S32101	0.04	21	1.5	0.5	0.22	Mn=5	18
2102	S82011	0.03	21.5	1.5	0.5	0.21	Mn=2.5	26
2202	S32202	0.03	22	2	0.5	0.22	-	26
2304	S32303	0.03	23	4	0.5	0.12	-	19

Table 5. Chemistry of Duplex SS: (High Cr, Moderate Ni & Mo, N=0.16)

Name	UNS No.	C	Cr	Ni	Mo	<u>N</u>	Other	PREN
2003	S32003	0.03	20	3.5	1.7	0.16	-	30
2404	S82441	0.03	24	3.5	1.5	0.22	Cu	33

2205	S31803	0.03	21.8	5	2.8	0.12	-	35
2205	S32205	0.03	22.5	5	3.2	0.16	-	35

Table 6. Chemistry of Super Duplex SS & Hyper Duplex : (Higher Cr, More Ni & Mo, N=0.25)

Name	UNS No.	C	Cr	Ni	Mo	N	Other	PREN
2507	S32750	0.03	25	7	4.0	0.28	Cu= 0.5	43
255	S32550	0.03	25.5	5.5	3.4	0.20	Cu=2.0	42
Z100	S32760	0.03	25	7	3.5	0.25	Cu=0.75 – W=0.75	41
2707 Hyper Duplex	S32707	0.03	27	6.5	4.8	0.40	-	49

Table 7. Chemical compositions for SS categories

SS Category	Chemical composition	Chromium (Cr)	Carbon (C)	Nickel (Ni)
Martensitic SS	Fe-Cr-C-Ni-Mo	11.5-18%	1.2-1.5%	-
Ferritic SS	Fe-Cr-Mo	10.5-30%	< 0.08%	-
Austenitic SS	Fe-Cr-Ni-(Mo)	16-28%	< 0.08%	3.5-32%
Duplex-Austenitic-Ferritic SS	Fe-Cr-Ni-(Mo)-N	21-26%	< 0.03%	3.5-8%

Prevention and Corrosion Control in Seawater Desalination Plants

Methods to reduce corrosion begin with gathering information on the conditions of the desalination process and then evaluating the materials under consideration by screening the information previously gathered. This involves carrying out laboratory analysis and pilot-scale testing of suitable materials in the fluids and environments of the desalination process. Finally, the most suitable materials are selected on the basis of cost, accessibility, ease of manufacture, ease of maintenance and reparability (Aende et al., 2020). Experimental tests are conducted using SW in a desalination plant under the same operating conditions. Corrosion is monitored remotely and the corrosion rate is evaluated over relatively long periods of time. Based on this information, the metallurgical engineer can decide on the type and cost of corrosion protection measures. The following methods are commonly used to prevent metal corrosion.

Surface Treatment and Coating

Metallic coatings and non-metallic coatings are used to protect against corrosion through surface treatment (such as: sand blasting) and coating. However, it is not advisable in SW desalination plants, as the colour wears off quickly due to the chemical composition of the seawater and the inner metal begins to corrode. but only suitable for brackish water desalination plants.

High Grade Super Duplex Stainless Steel

Duplex stainless steel was developed to overcome the problems of 300 series stainless steels such as 316L and 317L (Reclaru & Ardelean, 2020). Duplex grades have better corrosion resistance than their austenitic equivalents, almost twice that of austenitic grades, and have higher strength, and have been successfully used in reverse osmosis (Saji et al., 2020). The microstructure of duplex steels consists of austenite pools surrounded by a continuous ferrite phase of about 40-50% ferrite, Duplex stainless steel is differentiated from austenitic stainless steel by a larger amount of Cr of about 19 to 32%, but less Mo of approx.<5%, and Ni content (Panagopoulos, 2020).

The use of duplex stainless steel is preferred for SW pumps because its corrosion-resistant properties are achieved with a lower alloy content than austenitic grades, which have similar performance, making duplex SS more cost-effective (Francis, 2020). In addition, the austenitic SS alloys are considerably more expensive than the duplex stainless steel alloys due to the higher Mo and Ni concentrations. The super duplex SS usually have a Cr content of 25% with the high alloy duplex steels being higher compared to the austenitic steels. It has been found to have higher strength and better resistance to pitting and crevice corrosion, since duplex stainless steel alloys are more durable than austenitic steel (Koyee et al., 2014). Pumps, valves and other equipment made of Duplex SS can be designed with slimmer castings to reduce the cost and weight of the component while maintaining its strength. Hence, the utilization of duplex stainless steel mostly in reverse osmosis desalination components such as seawater pumps, and other parts is becoming widespread. In addition, there is a collection of cast stainless steel that can be employed to replace copper alloys, but it is important to choose the proper stainless-steel grade for the service conditions.

Conclusion

Seawater desalination plants have a high salinity and high pressure makes corrosion resistance both exciting and alarming. Practical methods to minimise or prevent corrosion include the selection of suitable alloy materials. The risk of corrosion depends primarily on the material composition, metallurgy, operating conditions and design of the system in contact with seawater. Considering all these parameters, appropriate material selection should prevent corrosion problems. Moreover, many reasons for corrosion failures of stainless steel in RO operating systems are attributed to the wrong choice of stainless steel grade or to the specific aggressive conditions. Duplex grades have better corrosion resistance than their austenitic equivalents, almost twice that of austenitic grades, and have higher strength, and have been successfully used in reverse osmosis.

In seawater desalination RO, it is very important to pay more attention to corrosion and metal protection by selecting a corrosion-resistant metal for piping and pumps that is suitable for the high pressure required for the membranes and the high salinity of the seawater. Therefore, duplex stainless steel (DSS) or super duplex stainless steel (SDSS) are also too expensive, but it protects pumps, valves and pipes from corrosion and leakage, reducing the frequent shutdown of the seawater plant for maintenance. Therefore, SDSS offers the best combination of properties for seawater desalination plants.

As the salinity of the water increases, so does the corrosion. This defines the process of seawater corrosion, and selecting a certified SS welder with the best Duplex SS materials is critical for reduced maintenance and long life of seawater desalination plants. Finally, A long-term safe choice of materials, taking into account the material structure, is the best choice for continuous operation and the most economical choice. Therefore, selecting the right materials is the best solution in SW desalination plants, in SWRO desalination plants, Duplex SS or Super Duplex SS

are used in the high-pressure lines (after the high-pressure pump and the reject line), while PVC or Fiberglass are usually used for the low-pressure lines.

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