Desalination and Water Treatment
www.deswater.com
51 (2013) 2030–2040
February

doi: 10.1080/19443994.2013.734483

Water desalination and challenges: The Middle East perspective: a review

Manjula Nair[a,*], Dinesh Kumar[b]

[a]*American College of Dubai, P.O Box 36778, UAE*
Email: manjula.nair@acd.ae
[b]*Department of Chemistry, Banasthali University, Rajasthan 304022, India*

Received 25 April 2011; Accepted 12 August 2012

ABSTRACT

The Gulf countries are located in the arid and semi-arid regions where rainfall is scanty and evaporation rates are high. Surface water is limited and there are no perennial streams. The increase in population and socio-economic development has led to an imbalance between supply and demand. These countries depend mainly on desalination to meet the growing water needs. This paper reviews the history of desalination and the desalination processes used—multistage flash distillation (MSF), reverse osmosis (RO), multieffect distillation and electrodialysis. An overview of these processes and the challenges faced—like scaling of tubes in MSF and membrane fouling in RO—is discussed. This review also highlights the present trends in water pre-treatment and integrated membrane systems. The depletion of fossil fuels makes it imperative to consider alternate energy sources like solar and nuclear energy. Future prospects for integrated desalination techniques which could result in reduction of cost of desalinated water are outlined. The paper mainly focuses on RO and MSF as these are the most popular commercial processes used in the Gulf region.

Keywords: Desalination; Reverse osmosis; Multistage flash distillation; Multieffect distillation; Electrodialysis; Pre-treatment; Membrane fouling; Corrosion; Scaling; Nanofiltration

1. History of desalination

Desalination occurred on earth millions of years ago—the natural process of water evaporating from the surface of the sea and condensing to form rain. The freezing of seawater near the Polar Regions wherein the ice crystals formed are from pure water, as salt is excluded from the crystal growth is another example. The first references to the use of desalination occur from 300 BC to 200 AD. In an account by Alexander of Aphrodisias (320 BC), it is mentioned that sailors at sea boiled seawater and suspended sponges from the mouth of a brazen vessel to absorb the vapour. The water condensed was drawn off the sponges and referred to as sweet water. The French explorer, Jean De Lery, reported the successful desalination of seawater during a voyage to Brazil in 1565. In 1627, after the Dark Ages, Sir Francis Bacon suggested the use of sand filters for desalination which paved the way for further advances in this area. The advent of steam power in the mid-eighteenth century and the understanding of the thermodynamics of steam processes were significant in the development of desalination technology. Throughout the early 1900s, evaporation and condensation continued to be the common desalination methods. The Second World War saw an increased demand for potable water for

*Corresponding author.

Table 1
Top 10 countries employing desalination [3]

S.No.	Country	Total capacity (Million m^3/d)	Market share (%)
1	Saudi Arabia	9.9	16.5
2	USA	8.4	14.0
3	UAE	7.5	12.5
4	Spain	5.3	8.9
5	Kuwait	2.5	4.2
6	China	2.4	4.0
7	Japan	1.6	2.6
8	Qatar	1.4	2.4
9	Algeria	1.4	2.3
10	Australia	1.2	2.0

Table 2
Top 10 countries employing seawater desalination [3]

Rank	Country	Capacity (Million m^3/d)	Market share (%)
1	Saudi Arabia	7.4	20.6
2	UAE	7.3	20.3
3	Spain	3.4	9.4
4	Kuwait	2.1	5.8
5	Qatar	1.4	3.9
6	Algeria	1.1	3.1
7	China	1.1	2.9
8	Libya	0.8	2.3
9	USA	0.8	2.2
10	Oman	0.8	2.2

troops stationed in the arid regions. Commercial desalination plants started making their appearance in 1960 and most of these were based on thermal processes. Multistage flash distillation (MFD) processes became popular and many commercial plants were set up using this technique, especially in the Arabian Gulf [1]. Membranes entered the desalination market in the late 1960s and were initially used for brackish water treatment. The next decade saw the use of reverse osmosis (RO) membranes in seawater desalination [2]. By the 1980s, desalination became a totally commercial enterprise and developments in both thermal and membrane technology led to an exponential growth in world desalination capacity. Worldwide distribution of desalination capacities is given in Tables 1 and 2.

2. Role of desalination in the Middle East

The expected population growth and the expected desalination capacity in the Gulf countries by 2012 are represented in the Table 3.

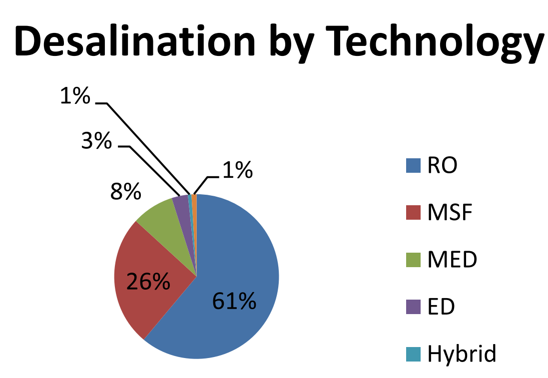
The ground water resources in the Gulf are of two types—shallow aquifers which are renewable and deep aquifers which are non-renewable. The shallow groundwater aquifers are the only renewable water source in the Gulf. The amount of groundwater abstraction is far greater than the amount of recharge. Excessive use of groundwater to meet the growing water needs has resulted in decline in groundwater levels [5]. Many water wells in Bahrain, Qatar, UAE and Oman have had to be abandoned because of excessive pumping and lack of replenishment from natural rainfall, resulting in seawater intrusion [6]. The Gulf countries depend largely on non-conventional resources like desalination and treating wastewater to meet its water requirements. A number of wastewater treatment plants are being set up and water from these plants are used for irrigating parks, gardens and landscaping [7].

3. Desalination techniques

The word "desalination" means the removal of salts and other minerals from brackish water or seawater to make it suitable for human consumption. There are three types of desalination processes:

- Thermal processes which include MSF distillation, multieffect distillation (MED) and mechanical vapour compression.
- Membrane processes which include RO and electrodialysis (ED).
- Process acting on chemical bonds like ion exchange processes.

Of the above, ion-exchange processes are used mainly for industrial applications which require extremely high-quality water. This method is not suitable to treat brackish water or seawater and is not discussed in this paper.



Though RO accounts for over 60% of the world desalination technology, thermal processes like MSF and MED continue to dominate in the Middle East

Table 3
Predicted increase in population/desalination capacity [4]

Country	2002		2025	
	Population × 1,000	Desalinated water production (million m^3)	Population x 1,000	Desalinated water production (million m^3)
Bahrain	677	122.7	1,483	161.96
Kuwait	2,165	589.1	4,744	749.34
Oman	2,518	67.93	5,517	114.13
Qatar	599	194.32	1,312	252.61
Saudi Arabia	21,930	1,063.3	48,051	1,690.6
UAE	2,444	812.61	5,355	1,357.1

due to the large base of thermal desalination units, with proven high operational reliability and the convenience of their integration with power plants [8].

4. Overview of the desalination methods

4.1. MSF method

4.1.1. Process description

The principle of this method is to boil seawater in a number of stages in a closed vessel under low pressure and then condense the water vapour for producing drinking water. In this method, water is made to boil at a temperature below its boiling point—this is referred to as “flashing effect” [9].

There are two types of MSF plants—Once through and brine recycling (BR).The latter is the more popular method in the UAE as it is suited to the large daily and seasonal temperature fluctuations. The BR type has three sections:

- Heat input section.
- Heat recovery section.
- Heat rejection section.

MSF is a desalination unit that begins with heating water and ends with condensing water. It can have up to a total of 40 stages [10].

The condenser, known as the heat rejection section, consists of two to three stages. Cold seawater flows through the heat exchanger tubes of the heat rejection section, beginning with the last stage, which has the lowest absolute temperature. The vapour which condenses on the outer surface of the heat exchanger tubes, gives its latent heat to the seawater flowing through the tubes. The temperature of the seawater increases as it flows from one stage to the other. The seawater leaves the heat rejection section and splits up into a make-up feed stream and a rejected stream. The make-up stream is doused with chemicals and it enters the last evaporation stage. A portion of the brine is also mixed with the feedwater. As the feedwater flows through the stages in the heat recovery section, it is heated up by the latent heat of the steam that is constantly condensing. Finally, the feedwater is heated in the brine heater by using externally supplied steam. This raises the feedwater to its highest temperature called “top brine temperature” (TBT). The TBT ranges between 90 and 110°C.

It is then passed through the different stages where flashing takes place. The steam generated by flashing is converted to fresh water by condensing on the tubular heat exchangers that run through each stage. The pure water vapour is sucked due to vacuum through demisters which remove any droplets of brine. The water vapour comes in contact with cold condenser tubes and condenses to form pure water which is collected in trays. Vacuum increases through successive stages so that water boils at lower temperatures.

At each stage, the concentration of brine increases due to water being vapourised. The concentrated brine remaining at the end of the process is rejected as blow-down (Fig. 1).

4.1.2. Challenges

The main challenges associated with MSF are:

(1) Scale deposition due to precipitation of Ca and Mg salts on the heat exchanger tubes [12].

There are two types of scales observed—Alkaline scales and non-alkaline scales. The alkaline scales are $CaCO_3$ and $Mg(OH)_2$, while the non-alkaline scale is $CaSO_4$.

Mechanism of scale formation:

On heating, the bicarbonate ions in seawater decompose as follows:

$$2HCO_3^- \rightarrow H_2O + CO_2 + CO_3^{2-}$$

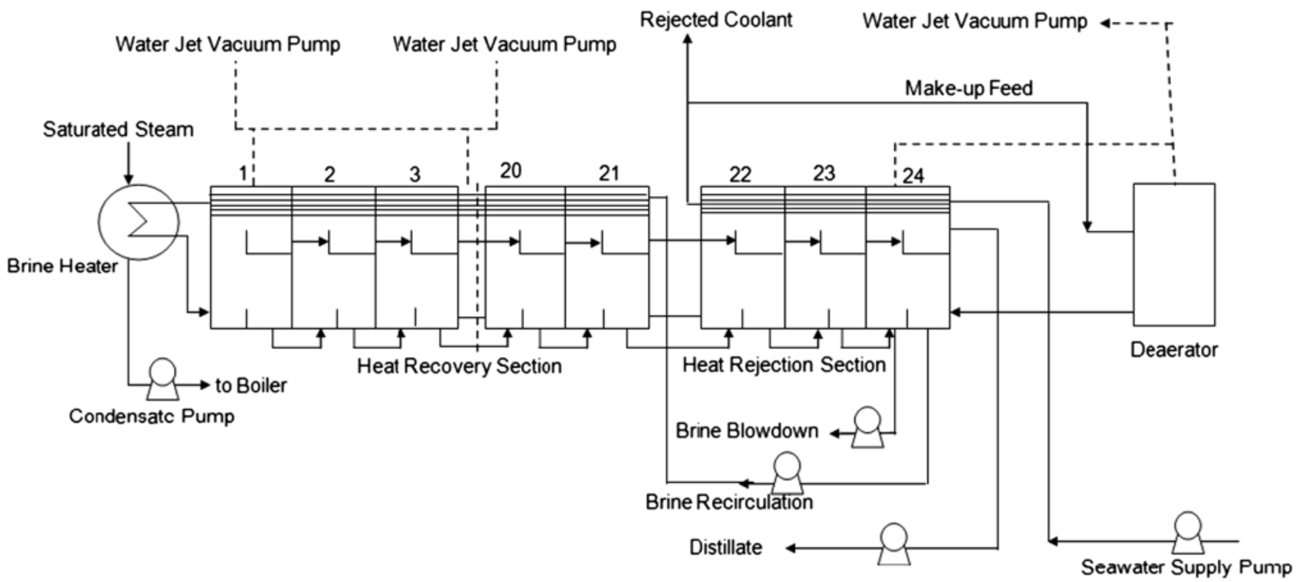


Fig. 1. MSF desalination unit [11].

The carbonate ions then react to form hydroxide ion as shown below:

$$CO_3^{2-} + H_2O \leftrightarrow 2OH^- + CO_2$$

The Ca and Mg ions in seawater combine with OH^- and CO_3^{2-} [13].

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3$$

$$Mg^{2+} + 2OH^- \rightarrow Mg(OH)_2$$

It is found that up to 90°C, $CaCO_3$ is the predominant scale formed; while between 95 and 100°C, the predominant scale is $Mg(OH)_2$. The non-alkaline scale, calcium sulphate, exists in three forms i.e. anhydrite ($CaSO_4$), hemihydrates ($CaSO_4$·½ H_2O) and dihydrate ($CaSO_4 \cdot 2H_2O$). Most of the deposited calcium sulphate is in the form of the hemihydrate. Unlike the alkaline scales, the sulphate minerals are insoluble in common chemicals and are undesirable for the smooth working of the MSF plant. A study of the solubility of the three forms of calcium sulphate can be used to estimate under what conditions the MSF plant could operate efficiently. Decreasing the TBT helps to curb scale formation, however, this affects the system performance and the productivity.

(2) Corrosion: MSF plants are subject to corrosion due to their operation in aggressive environment consisting of seawater and non-condensable gases like oxygen and CO_2. The flash chambers are highly prone to corrosion as they are exposed to flashing brine and subject to attack by chloride [14]. Pitting corrosion is also observed in condenser tubes, resulting from the formation of small micro galvanic cells [15].

(3) Energy intensive process: MSF plants require both thermal and electrical energy with relatively high specific energy consumption as compared to RO and MED.

It is estimated that the unit water cost for water produced by MSF in the Middle East is US $0.52 per m^3 [16].

(4) MSF requires a larger footprint in terms of land and material [17].

4.2. MED

MED is the oldest desalination process and was popular until around 1960 when MSF started dominating the desalination market [18].

4.2.1. Process description

Like MSF, MED takes place in a series of vessels (effects) at reduced ambient pressure in the various effects. The feedwater is sprayed onto the evaporator surface (usually tubes) in thin films to promote rapid boiling and evaporation. The surfaces in the first effect are heated by steam from turbines of power plants or a boiler. The surfaces of all other effects are heated by the steam produced in each preceding effect. The steam produced in the final effect is condensed in a separate heat exchanger called the final condenser, which is cooled by the incoming seawater, thus preheating the feedwater. The number of effects range from 4 to 14 and the performance ratio is around 10–18 [19]. MED consumes less power than MSF and it also has a better performance ratio.

MED can be used in small- to medium-sized plants and can operate at a top temperature of 70˚C, which reduces the scaling problem. But this increases the need for additional heat transfer area and adds to the size of the plant. Developments in MED process include coupling of thermal vapour compression with MED and use of Aluminium for heat transfer tubes leading to reduction of unit water costs. MED can be used even for the harsh Gulf waters. This has led to the installation of two MED units each of 5 MGD capacity at Al Layyah in Sharjah [20]. The Al Taweelah MSF plant introduced 14 MED into its existing MSF plant. Each consists of six effects. The process couples thermal vapour compression with MED with falling film evaporation [21].

4.2.2. Challenges

The two main concerns associated with this process are scaling and corrosion. Calcium carbonate deposits are formed on the condenser tubes. This results in a decrease in distillate production and rise in specific heat consumption.

4.3. Reverse osmosis

4.3.1. Process description

RO is a membrane-based process and does not involve phase change. It is a physical process that uses the osmosis phenomenon. Osmosis occurs when a semi-permeable membrane (allows the passage of water, not solute) separates two aqueous solutions of different concentration. At equal pressure and temperature on both sides of the membrane, water will diffuse through the membrane resulting in a net flow from the dilute side to the concentrated side until concentration on both sides of the membrane are equal. This process will also take place if the pressures on both sides are different, as long as the pressure difference Δp between the concentrated and dilute side is not larger than a certain value which depends on the difference of the respective concentrations and is called the osmotic pressure difference $\Delta\Pi$. If Δp is greater than $\Delta\Pi$, the direction of flow is reversed and water flows from the concentrated side to the dilute side. This process is called RO. In RO, a pressure greater than the osmotic pressure is applied on the salt water to force fresh water through a semi-permeable membrane so as to overcome the concentration difference (Fig. 2).

The pressure applied depends on the total dissolved solids (TDS) of feedwater. The pressure is generated by pumps, thus TDS of feedwater influences the energy use and the corresponding cost of product water. The pressure ranges from 10 to 28 bar (145 to 400 psi) for brackish water and 54–83 bar (800–1,200 psi) for seawater [22].

4.3.2. RO membranes

Membranes can be made using polymeric materials like cellulose, actetate or non-polymeric materials like ceramic. Synthetic membranes are mainly used in the desalination industry and their use is growing at a rate of 5–10% annually [23]. The first commercial RO membranes used were cellulose—acetate.

Cellulose acetate. These are produced by phase inversion. A film of dissolved polymer (cellulose acetate [CA] and acetone) is immersed into a precipitant (water). Acetone is replaced by water and the polymer-rich phase starts to precipitate. The rate of precipitation is an important factor—a slow rate of precipitation results in symmetrical pores that are relatively large while a fast rate of precipitation tends to produce small and asymmetric pores [24]. CA membranes deteriorate by hydrolysis. This reaction is highly dependent on pH. Ideally, the pH should be in the range of 4–6. Hence pH needs to be adjusted and controlled to prolong membrane life. CA membranes, under high pressure, tend to compact and this affects the overall performance and system integrity.

Thin film composite membranes (TFC). These are the most common membranes used in desalination and water treatment today. TFC membranes are made with a porous, highly permeable support such as

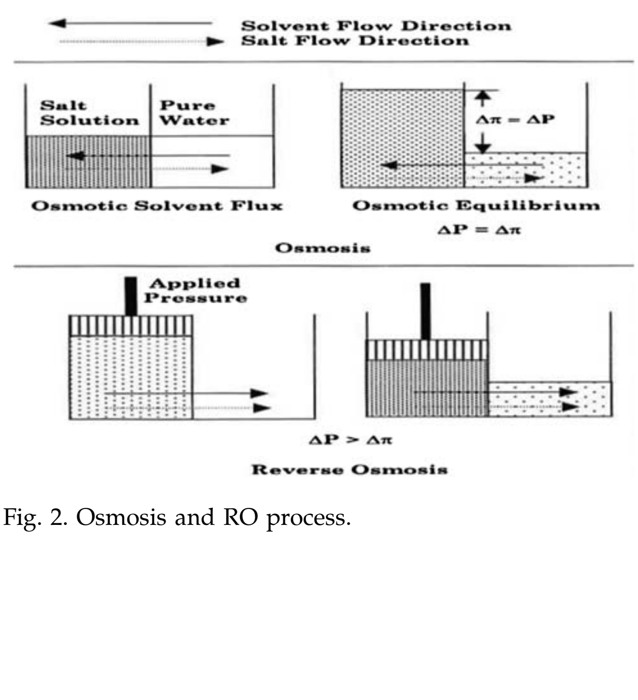


Fig. 2. Osmosis and RO process.

polysulfone coated with a cross-linked polyamide thin film [25]. The porous support is made by the phase inversion technique, while the thin layer is made by interfacial polymerisation [26]. TFC membranes are more stable. They do not hydrolyse and can work in a wider pH range of 3–11. They offer better flux and salt rejection as compared to CA membranes. However, TFC membranes are highly susceptible to attack by free chlorine and other oxidants [27].

4.3.3. RO membrane modules and configurations

RO membrane packaging plays an important role in the efficiency of the process. Ideally, the membrane module should be such that it:

- Offers mechanical support to the fragile RO membrane even at high operating pressures.
- Minimises pressure drop across the module as well as reduces fouling.
- Is relatively inexpensive and easy to replace [28].

The commercially available membrane modules include plate and frame, tubular, spiral wound and hollow fibre.

Plate-and-frame modules consist of flat sheet membranes placed on supports; each membrane and support is separated by spacers. This module has a fairly high resistance to fouling; however, it is expensive as it has a low packing density and its use is limited in areas with space restrictions. Tubular membrane elements consist of membrane tubes supported within perforated steel tubes. These, too, have low packing density. Spiral wound elements consist of a flat sheet membrane wrapped around a perforated permeate collection tube. The feed is channelled through these rolled membrane sheets and permeates throughout the membrane and is collected in the centre tube. This module has a high packing density, moderate fouling resistance and lower operating costs. Hollow fibre modules consist of large number of fine hollow fibre membranes placed in a pressure vessel. The feed water flows outside the fibre and permeates through the membrane. The hollow fibre modules have high packing density and permeate production rates, but are prone to fouling (Fig. 3).

4.3.4. Challenges

(1) The major challenge in RO is the fouling of membranes.

Fouling is the deposition of material, referred to as foulant, on the membrane surface or in its pores, leading to a change in membrane behaviour or even complete plugging of the membrane. There are four types of fouling observed: biofouling, scaling, organic and colloidal.

Biofouling. Raw water contains micro-organisms like viruses, bacteria, algae, etc. which are attached to the membrane surface. They then grow and multiply at the expense of feedwater nutrients, forming a biofilm, which increases the resistance to water permeation through the membrane. Biofouling is influenced by factors like temperature, nutrient load and depth and intake of feedwater. Chlorine is used to control biofouling, however, experiments have shown that use of sodium metabisulphite to remove chlorine supply nutrients to the surviving bacteria results in aftergrowth and deposition of slime on the membrane surface [30].

Scaling. Scaling occurs due to deposition of sparingly soluble salts [31]. Dissolved inorganics such as Ca^{2+}, Mg^{2+}, CO_3^{2-}, SO_4^{2-}, silica and iron are most likely to precipitate as insoluble salts (or scales) on the membrane surface if the solubility limits are exceeded.

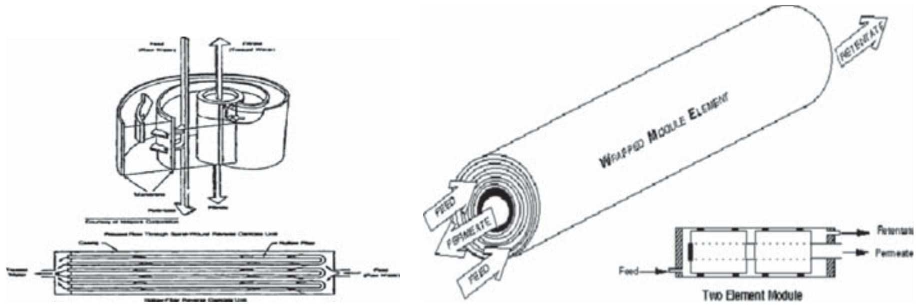
Organic fouling. This is one of the most prevalent problems in water treatment. Natural water contains humic substances in concentrations between 0.5 and 20 mg/L in brackish water and up to 100 mg/L in seawater. Humic substances form chelates with metal ions, especially iron; a gel like layer is formed by complexation with multivalent ions. The adsorption of these on membrane surface results in permeability decline.

Colloidal fouling. Colloidal particles are major foulants in all kinds of membrane processes. Examples include clay minerals, colloidal silica and silicon [32].

(2) The rejected brine has a TDS value of around 70,000 ppm. The chemicals used in the sea water reverse osmosis (SWRO) process and the by-products are discharged into the sea, and contaminate the marine environment. The density differences between seawater and brine discharged affect the ecology beneath the sea [33].

(3) Coagulants like ferric salts are added to the feedwater. The backwash water containing the suspended particles and the coagulants are discharged into the ocean water, which can cause an intense colouration of the reject stream (red brines). This increases turbidity and reduces light penetration [34].

(4) RO process is highly influenced by the quality of raw water intake. Elevation of silt density index (SDI), algal and planktonic blooms and jelly fish swarms have affected the functioning of the plants.



Spiral – wound module

Hollow Fibre Module

Fig. 3. Membrane types [29].

Also, the intake zone needs to be segregated from the discharge zone to prevent contamination of feedwater by discharge brine to prevent recirculation of the effluent-mixed layer [35].

(5) The energy cost in a RO plant can approach up to 45% of the permeate production cost due to the high feed pressure that the process requires. Adopted energy reducing techniques such as use of low-energy membrane elements and advanced energy recovery devices have been a significant success [36].

Pre-treatment also contributes significantly to the cost. Conventional pre-treatment involves less capital expenditure, but the membrane pre-treatment is becoming more popular, because it is found to substantially reduce RO maintenance and operation costs, and is more effective in open water intake plants [37].

4.4. Electrodialysis (ED)

4.4.1. Process description

This process is suitable for the desalination of brackish water with a salinity of up to 12,000 mg/L. Brackish water is passed through a series of stacked cationic and anionic membranes, and an electric potential is applied. Most salts dissolved in water being ionic, migrate towards the electrode with the opposite electric charge. The cationic and anionic membranes are arranged alternately and a spacer sheet is placed between each pair of membranes. As the electrodes are charged, the anions in the water are attracted towards the positive electrode. They pass through the anion-selective membrane but are blocked by the cation-selective membrane. Similarly, cations move through the cation-selective membrane to the concentrated channel on the other side, where they are trapped because the next membrane is anion selective. By this arrangement, concentrated and dilute solutions are created in the spaces between the alternating membranes. These spaces, bounded by the two types of membranes are called cells. A basic ED unit is made of several hundred cell pairs bound together with electrodes on the outside and is referred to as a membrane stack.

A recent development to this method is the ED Reversal technique. EDR process involves a reversal of water flow to break up and flush out scales, slime and other foulants deposited in the cells. This flushing also enables the ED unit to work with fewer pre-treatment chemicals, thus minimising costs (Fig. 4).

4.4.2. Challenges

Scale formation, which fouls the membrane surfaces and blocks the passages in the stack,

Leaks in membrane stacks and

Bacteria and non-ionic substances remain in the water obtained and further treatment is required before water quality standards are met.

5. Pre-treatment of seawater

5.1. Pre-treatment for MSF

Pre-treatment for MSF includes use of antiscalants like Belgard-2030, Sokolan PM-39 and POC-3000. Antifoaming agents like Antispumin DS are commonly used to reduce foam when water boils. Acids are sometimes used to cause depletion of carbonates in seawater [38].

5.2. Pre-treatment for RO

5.2.1. Conventional pre-treatment

The conventional pre-treatment includes physical and chemical pre-treatment without the use of membrane technologies. The pre-treatment used in RO is:

- Screens for coarse filtration.
- *Chlorination*: to prevent biological growth and disinfect water. Chlorine is added as NaOCl or chlorine gas. Chlorine or NaOCl hydrolyses in water to

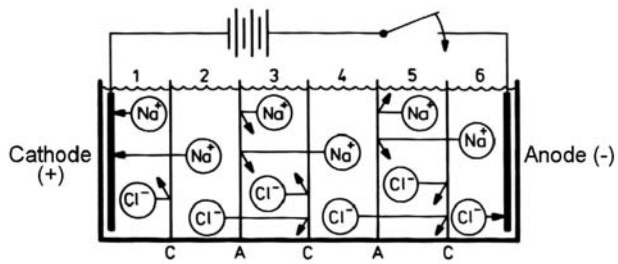


Fig. 4. Electrodialysis [22].

form hypochlorous acid, HOCl. HOCl then dissociates to form H^+ and OCl^- ions. A concentration of 0.5–1 ppm is maintained to prevent biofouling.

- *Addition of coagulants and flocculants*: coagulation and flocculation agents are added to cause dissolved matter to adsorb on hydroxides formed and colloidal matter to agglomerate.
- *Sand filtration*: to remove agglomerates from seawater.
- Addition of antiscalants, sulphuric acid to prevent scaling due to calcium carbonate.
- *Addition of sodium metabisulphite*: sodium metabisulphite is used as a dechlorinating agent as chlorine has to be removed before the RO stage. In water, it reacts to give sodium bisulphite, which then reduces hypochlorous acid.

$$Na_2S_2O_5 + H_2O \rightarrow 2NaHSO_3$$
$$2NaHSO_3 + 2HOCl \rightarrow H_2SO_4 + 2HCl + Na_2SO_4$$

- Cartridge filtration (5–10 μm mesh size) (Fig. 5).

Conventional pre-treatment is not effective when the feedwater quality is poor. It is unable to remove smaller particles (smaller than 10 to 15 μm); use of coagulant affects membrane performance and the process leaves behind a large footprint, is labour intensive and space consuming [40].

Conventional pre-treatment consisting of pressure sand filters is an age-old, cumbersome, unstable SDI/FI. It depends on the source water and is predominantly site specific. Limitations to this process exist to date.

5.2.2. Membrane pretreatment

Ultrafiltration/microfiltration (UF/MF). Ultrafiltration/microfiltration (UF/MF) are being increasingly used as pre-treatment to RO process and is particularly effective in the desalination of high-fouling water such as open seawater intake. There are two types of UF/MF membranes—dead end and cross flow. Cross-flow membranes consist of three streams—feed flow, concentrate flow and filtrate flow. These membranes are generally used for feedwaters with high-suspended solids. The dead-end flow mode of operation consists of only feed flow and filtrate flow and is used in feed streams with low-suspended solids [41]. The MF membranes have a pore size of 0.1–0.35 μm and UF membranes have a pore size of 0.01–0.05 μm. The feedwater is passed through strainers and occasionally, coagulants like ferrous salts are used prior to passing it through MF/UF membranes.

MF membranes are effective for the removal of total coliform bacteria (TCB) [42]. Moderate removal of suspended solids is achieved using this pre-treatment and SDI values are found to be less than three [43]. These membranes are cleaned by using an air backwash stream.

UF membranes reject particles of size up to 0.01–0.02 μm and can perform even during unfavourable

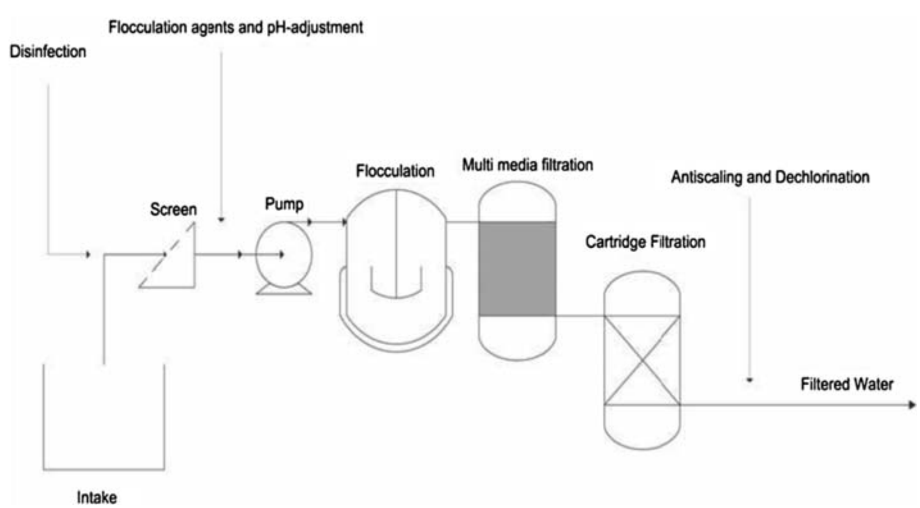


Fig. 5. Conventional pre-treatment [39].

conditions such as algal blooms. SDI values less than 2.5 can be obtained using this process [44].

Advantages of UF/MF pre-treatment:

- higher RO flux and recovery;
- longer life of RO membranes;
- lower consumption of chemicals;
- decreased manpower due to complete automation;
- smaller footprint; and
- reduced cleaning frequency leading to reduced downtime.

The capital costs of implementing UF/MF could be about 25% higher, while the life cycle cost is comparable to the conventional methods [45].

5.2.3. Nanofiltration

Commercial NF membranes are made from poly piperazineamide, sulfonated polysulfone and CA [46]. Molecular weight cut-off is between 300 and 1,000. Energy consumption is comparatively low and it effectively removes pollutants [47]. NF membranes have properties between RO and UF and provide a higher water flux at lower operating pressure [48]. They offer a very high rejection of divalent ions, while rejection of monovalent ions is limited. Sulphate rejection is around 99% while rejection of Ca, Mg is 98 and 92%, respectively [49]. In addition, NF is used in softening, disinfection and removal of organic materials and metals. Due to its capability of effectively removing dissolved organic compounds and bivalent ions, NF membranes are of considerable interest from the standpoint of meeting the water quality standards [50].

Adoption of integrated membrane systems (IMS) like UF/RO, MF/RO or NF/RO helps to improve desalination operations and meets the increasing demand for pure water.

6. Hybrid desalination systems and ongoing research

In recent years, several cogeneration schemes have been implemented wherein power generation and thermal desalination as well as thermal and membrane desalination processes have been integrated. Integration of power generation with MSF is one of the main technological options prevalent in the UAE. Since MSF is an energy-intensive process, recovering waste heat from large-scale power plants helps to reduce the cost involved in thermal desalination. RO processes have also been integrated with MSF/power cogeneration systems. When RO and MSF are in parallel operation, capital savings result from the use of common intake–outfall facilities [51]. Such a plant is operational at Fujairah, UAE. It has a production capacity of 500 MW of electricity and 454,200 m^3/d of water, and is one of the largest desalination plants in the world. Water (62.5%) is produced from five MSF units coupled with the power plants and 37.5% from RO [52].

A solar–MED plant built in Umm Al Nar, Abu Dhabi has a desalination capacity of 120 m^3/d. The thermal energy required for MED is provided by solar thermal collectors.

The Layyah plant in Sharjah integrates RO with MSF and MED thermal systems [53].

Nuclear heat reactors can also be integrated with MSF or RO plants. Electricity generated in the nuclear power plants can be used to drive the high-pressure pumps in the RO process or for heating the brine in the MSF process. The environmental impact too would be minimum compared to other methods [54]. Using nuclear power for desalination is a challenging option to reduce the cost of desalinated water for GCC countries, especially when faced with the prospect of fossil fuel depletion [55]. In the Middle East region, wind or solar energy could be used to power the desalination plants. However, these are subject to variable intensities while desalination processes are designed for continuous operation. Research work is in progress on a dihybrid plant coupling NF pre-treatment with MED, which can facilitate an operational TBT of 120° as compared to the maximum TBT of 65°C currently used [56].

To reduce the impact of desalination on the environment, there is ongoing research to integrate membrane processes like RO, NF with crystallisation methods to achieve zero liquid discharge. The desalination industry continues to advance technologies that reduce energy requirements, enhance sustainability and address environmental responsibility.

7. Current projects

- AbuDhabi Water and Electricity Authority have signed a memorandum with Sembcorp Utilities to develop a new SWRO with production capacity of around 136,000 m^3/d. This will be located on the same site as the Fujairah I Independent water and power plant and will be operational in 2013 [57].
- A hybrid desalination plant, Ras Assour, is being built at Saudi Arabia. It will have a capacity of 1,036,500 m^3/d and is supposed to be the largest desalination plant in the world. This project is scheduled to be completed by 2014 [58].
- Oman is planning four new desalination plants—the Qurayat project will have a capacity of 182,000 m^3/d

while the Suwaiq project will have a capacity of 227,000 m^3/d [59].

- A 136,400 m^3/d seawater RO plant is being built at Kuwait. The facility will include 1,300 membrane pressure vessels with each pressure vessel holding a total of eight membranes, working pressure being 83 bar [60].
- A SWRO facility is being built at Ghalilah, Ras al Khaimah by Aquatech. This plant would have a capacity of 68,000 m^3/d and is expected to be operational in late 2013 [61].

Total capacity of new plants contracted 2010–2011 [62]:

Country	Capacity (m^3/d)
UAE	138,286
Bahrain	44,500
Kuwait	140,800
Oman	19,350
Qatar	54,922
Saudi Arabia	262,756

References

[1] K.V. Reddy, N. Ghaffour, Overview of the cost of desalinated water costing methodologies, Desalination 205 (2007) 340–353.
[2] Bart Van der Bruggen, Carlo Vandecasteele, Distillation vs. membrane filtration: Overview of process evolutions in seawater desalination, Desalination 143 (2002) 207–218.
[3] The current state of desalination, International Desalination Association and Global Water Intelligence Desal Data service V03. 2010.
[4] M.A. Dawoud, Water import and transfer vs desalination in arid regions: GCC countries case study, Desalin. Water Treat. 28 (2011) 153–163.
[5] A Raouf, Mohamed, Water issues in the Gulf: Time for action, 22 (January 2009), The Middle East Institute Policy Brief, Washington, DC.
[6] Sherif Mohsen, Kacimov Anvar, Modeling groundwater flow and seawater intrusion in the coastal aquifer of Wadi Ham, UAE, Water Resour. Manage. 26 (2012) 751–774.
[7] Mike Brook, Mohamed A. Dawoud, Coastal water Resource Management in the UAE, Integrated Coastal zone management in the UAE, Abudhabi, 2005.
[8] Ettouney Hisham, Wilf Mark (Eds.), Commercial desalination technologies, Seawater Desalination, Green Energy Technologies, Springer, Berlin, 2009, pp. 77–107.
[9] O.K. Buros, ABCs of desalting, International Desalination Association (2009) 7–8.
[10] Tom Pankratz, Advances in desalination technology, Int. J. Nucl. Desalin. 1(4) (2005) 450–455.
[11] Rouzbeh Shafaghat, Hoda Shafaghat, Fatemeh Ghanbari, Pouya Sirous Rezaei, Rohollah Espanani, Design of a MSF desalination plants to be supplied by new specific 42MW power plant located in Iran, World Academy Sci. Eng. Technol. 62 (2012) 515–521.
[12] A.M. Shams El Din, R.A. Mohammed, Brine and scale chemistry in MSF distillers, Desalination 99(1) (1994) 73–111.
[13] M. Shams El Din, R.A. Mohammed, M.E. El-Dahshan, Scale formation in flash chambers of high temperature MSF distillers, Desalination 177 (2005) 241–258.
[14] Anees U. Malik, P.C. Mayan Kutty, Ismail N. Andijani, Saleh A. Al-Fozan, Materials performance and failure evaluation in SWCC MSF plants, Desalination 97 (1994) 171–187.
[15] Shams El Din, El Dahshan, M.E. Haggag, Carbon induced corrosion of MSF condenser tubes in Arabian Gulf waters, Desalination 172 (2005) 215–226.
[16] Roberto Borsani, Silvio Rebagliati, Fundamentals and costing of MSF desalination plants and comparison with other technologies, Desalination 182 (2005) 29–37.
[17] Mohamed Eltawil, Zhao Zengming, A review of renewable energy technologies integrated with desalination systems, Renew. Sustain. Energy Rev. 13 (2009) 2245–2262.
[18] M. Al-Shammiri, M. Safar, Multi-effect distillation plants: State of the art, Desalination 126 (1999) 45–59.
[19] T. Michels, Recent achievements of low temperature multiple effect desalination in the western areas of Abu Dhabi, UAE, Desalination 93 (1993) 111–118.
[20] K.V Reddy, N. Ghaffour, Overview of the cost of desalinated water and costing methodologies, Desalination 205 (2007) 340–353.
[21] C. Sommariva, V.S.N Syambabu, Increase in water production in the UAE, Desalination 138 (2001) 173–179.
[22] Tamim Younos, Kimberly E. Tulou, Overview of desalination techniques, J. Contemporary Water Res. Edu. (132) (2005) 3–10.
[23] John Krukowski, Opening the black box: Regulations and recycling drive use of membrane technologies, Pollut. Eng. 33 (2001) 20–25.
[24] H. Strathmann, A.S. Michaels, Polymer—Water interaction and its relation to reverse osmosis desalination efficiency, Desalination 21(2) (1977) 195–202.
[25] Richard W. Baker, Membrane Technology and Applications, John Wiley and Sons, Chichester, second ed., 2004, pp. 191–212.
[26] Marcel Mulder, Basic principles of membrane technology, Kluwer, The Netherlands, 81–87 1996.
[27] H.D. Raval, J.J. Trivedi, C.V. Devmurari, Flux enhancement of thin film composite RO membrane by controlled chlorine treatment, Desalination 250(3) (2010) 945–949.
[28] D. Bhattacharya, M.E. Williams, Membrane Handbook, Van Nostrand Reinhold, New York, NY, 1992.
[29] Nelson da Franca Ribeiro Dos Anjos, Source book of alternate technologies for fresh water augmentation in Latin America and the Carribean, Water Res. Dev. 14(3) (1998) 365–398.
[30] Mohammed Saeed, A.T. Jamaludeen, A. Tisam, Biofouling in a seawater reverse osmosis plant on Red Sea Coast, Saudi Arabia, Desalination 128 (2000) 177–190.
[31] R. Sheikholeslami, Assessment of the scaling potential for sparingly soluble salts in RO and NF units, Desalination 167 (2004) 247–256.
[32] Xiaohua Zhu, Menachem Elimelech, Colloidal fouling of reverse osmosis membranes: Measurements and fouling mechanisms, Environ. Sci. Technol. 31 (1997) 3654–3662.
[33] Young M. Kim, Seung J. Kim, Overview of systems engineering approaches for a large scale desalination plant with a RO network, Desalination 238 (2009) 312–332.
[34] Sabine Lattemann, Thomas Hopner, Environmental impact and impact assessment of Seawater desalination, Desalination 220 (2008) 1–15.
[35] P.K. Abdul Azis, Ibrahim Al-Tisan, Mohammad Al-Daili, Effect of environment on source water for desalination plants on the eastern coast of Saudi Arabia, Desalination 132 (2000) 29–40.
[36] M. Wilf, Design consequences of recent improvements in membrane performance, Desalination 113 (1997) 157–163.
[37] F. Greenlee Lauren, Desmond F. Lawler., Reverse osmosis: Water sources, technology and today's challenges, Water Res. 43 (2009) 2317–2348.
[38] Noura S. Al. Deffeeri, Heat transfer measurement as a criterion for performance evaluation of scale inhibition in MSF plants in Kuwait, Desalination 204(1–3) (2007) 423–436.

[39] C. Fritzmann, J. Löwenberg, T. Wintgens, T. Melin, State-of-the-art of reverse osmosis desalination, Desalination 216 (2007) 1–76.
[40] S. van Hoof, J.G. Minnery, B. Mack, Dead end ultrafiltration as an alternative pretreatment to RO in seawater desalination, Desalination 139 (2010) 161–168.
[41] Wayne Bates, Capillary UF as RO pre-treatment, International Water Conference, Pittsburgh, PA, US, October 1999.
[42] S. Ebrahim, M. Abdel Jawad, S. Bou-Hamad, M. Safar, Pretreatment technologies for RO systems, Desalination 135 (2001) 141–153.
[43] C.K. Teng, M.N.A Hawlader, A. Malek, An experiment with different pretreatment methods, Desalination 156 (2003) 51–58.
[44] H. Peter, Steve Siverns Wolf, Sandro Monti, UF membranes for RO desalination pretreatment, Desalination 182 (2005) 293–300.
[45] C.V. Vedavyasan, Pretreatment trends—An overview, Desalination 203(1–3) (2007) 296–299.
[46] R. Petersen, Composite reverse osmosis and nanofiltration membranes, J. Membr. Sci. 83 (1993) 81–150.
[47] Peter Eriksson, NF extends range of membrane filtration, Environ. Prog. 7(1) (1988) 58–62.
[48] L.P. Raman, M. Cheryan, N. Rajagopalan, Nanofiltration for membrane separations, Chem. Eng. Prog. 90 (1994) 68–74.
[49] Peter Eriksson, Markus Kyburz, Wil Pergande, NF membrane characteristics and evaluation for seawater processing applications, Desalination 184(1–3) (2005) 281–294.
[50] Enrico Drioli, Alessandra Criscuoli, Efrem Curcio, Integrated membrane operations for seawater desalination, Desalination 147(1–3) (2002) 77–81.
[51] E. Cardona, A. Piacentino, Optimal design of cogeneration plants for seawater desalination, Desalination 167 (2004) 411–426.
[52] M.A. Sanza, V. Bonnelyea, G. Cremerb, Fujairah RO plant: 2 Years of operation, Desalination 203(1–3) (2007) 91–99.
[53] Asam Almulla, Ahmad Hamad, Integrating hybrid systems with existing thermal desalination plants, Desalination 174 (2005) 171–192.
[54] S. Ibrahim, Al Mutaz, Potential of nuclear desalination in Arabian Gulf countries, Desalination 135(1–3) (2001) 187–194.
[55] M.A. Dawoud, The role of desalination in augmentation of water supplies in GCC countries, Desalination 186(1–3) (2005) 187–198.
[56] Osman A. Hamed, Overview of hybrid desalination systems, Desalination 186(1–3) (2005) 207–214.
[57] The International Desalination and water Reuse Quarterly industry website, Sembcorp to develop SWRO plant in Abu Dhabi, June 2010.
[58] The International Desalination and water Reuse Quarterly industry website, Doosan wins giant Ras Azzour desalination plant contract, September 2010.
[59] The International Desalination and water Reuse Quarterly industry website, OPWP chief sets out Oman's desalination plans, October 2011.
[60] The International Desalination and water Reuse Quarterly industry website, BEL lands Kuwait desalination supply contract, March 2012.
[61] The International Desalination and water Reuse Quarterly industry website, ERI lands contract for Ghalilah desalination project, June 2011.
[62] New plants contracted 2010–2011, IDA Desalination yearbook 2011–2012.