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Chapter 2

SWRO desalination plants

2.1 OVERALL PROCESS

Recent seawater reverse osmosis (SWRO) desalination plants are standardized high-efficiency plants. Typical processes of an SWRO desalination plant are illustrated in Figure 2.1. However, specific designs can vary depending on the feed quality, required product quality, and recovery. An SWRO desalination plant is composed of three parts: pre-treatment, RO process, and post-treatment.

Pre-treatment units were employed to remove large particles and solids before the SWRO process. In seawater, various ions/particles/solids/organic matter are dissolved or suspended. Undissolved solids frequently cause fouling (except scaling) on the surface of RO membranes or damage RO membranes. Thus, it is crucial to remove the foulants before the RO process to maintain and secure the RO performance. The pre-treatment process removes undissolved solids in the feed and supplies foulant-free feed to the RO system. The process is composed of intake, dissolved air flotation (DAF) (optional), dual-media filtration (DMF) or MF/UF (microfiltration/ultrafiltration), and cartridge filter (CF).

The RO system can remove dissolved ions from the pre-treated feed and produce freshwater. Chemical species and ions are dissolved in seawater (i.e., total dissolved solids (TDS)), and the concentration of TDS generally ranges between 30 000 and 40 000 mg/L [58]. However, the TDS range can be 45 000 to 48 000 mg/L in the Arabian Gulf. TDS should be rejected through the membrane to obtain fresh water from seawater, and this can be achieved using semi-permeable RO membranes. However, the feed has an osmotic pressure of 20–30 bar due to high TDS, and the osmotic pressure should be overcome to separate water and salts across the SWRO membranes. Thus, the pre-treated feed is pressurized by a high-pressure pump (HPP) and fed to the SWRO membranes.

The chapter is from the book *Seawater Reverse Osmosis (SWRO) Desalination: Energy consumption in plants, advanced low-energy technologies, and future developments for improving energy efficiency*, Seungkwan Hong, Kiho Park, Jungbin Kim, Abayomi Babatunde Alayande and Youngjin Kim (Authors).

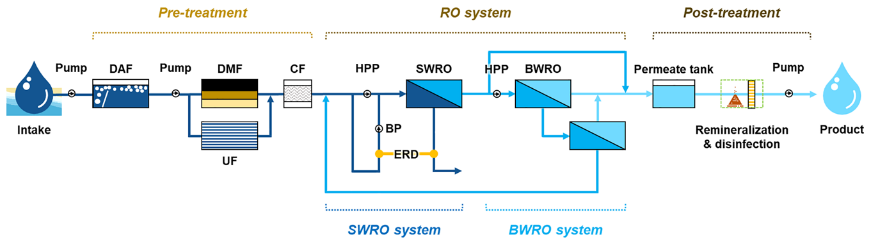

Figure 2.1 Scheme of SWRO desalination process. A feed is pre-treated by several processes, including DAF (optional), DMF/UF, and CF. The pre-treated feed is sent to an RO system composed of an SWRO system and a BWRO system (optional). The permeate is processed by remineralization and disinfection, and the product is distributed.

When the hydraulic pressure of the feed is higher than the osmotic pressure, water is produced on the permeate side, and the rejected feed is sent to the outlet. Multiple SWRO membrane modules (e.g., six–eight modules) are installed in a pressure vessel (PV) and recover 40–50% of feed as permeate. The rejected feed is called concentrate/brine, and an energy recovery device (ERD) recovers hydraulic energy and delivers it to the part of the feed associated with a booster pump (BP). The SWRO permeate can be used directly, but further desalination can also be performed using brackish water reverse osmosis (BWRO) membranes.

Post-treatment is necessary to stabilize and disinfect water. As divalent ions (e.g., Ca^{2+} and Mg^{2+}) are highly rejected through SWRO membranes, desalinated water has low hardness. In addition, both the pH and alkalinity are low. Thus, desalinated water is remineralized with useful minerals to secure the water distribution system from corrosion and maintain water quality. Furthermore, disinfection using chlorine of ultraviolet (UV) irradiation is required to prevent biological activity and contamination.

Because each compartment is associated with one another, the application of new desalination technologies to the current system would be a challenge. In addition, engineers in the industry prefer to use conventional technologies rather than unproven technologies. However, the design of SWRO desalination plants has advanced further with decades of experience.

2.2 SWRO INTAKE

The intake system of the SWRO plant is a critical and significant aspect of the process. The intake unit may occupy more than 20% of the capital cost while still occupying a significant portion of the operating expenses [59]. A good intake system would not only meet the water quality required for the SWRO plant but would have less impact on the ecosystem. The types of SWRO intake include open water intake and subsurface intake. The selection of intake type is based on a thorough assessment of sea conditions and environmental concerns.

2.2.1 Open water intakes

Open water intake is the most widely used intake type because of its high intake volumes, suitable for large SWRO plants, providing an opportunity for co-location with power plants. They can be easily installed at any location without serious consideration. Open intake is classified as surface open intake or submerged open intake.

Surface open intake incorporates active screen systems to eliminate debris, aquatic life, and trash from reaching the SWRO line. Traveling water screens are furnished with both revolving and wire mesh panels, with panel mesh sizes varying from 9.5 to 13 mm. The spinning of wire mesh panels allows high-pressure water to remove accumulated debris from the screens. Smaller mesh sizes can be used seasonally or regionally to remove eggs and larvae, but this could cause operational difficulties as debris and marine life increase significantly.

The feed is collected by a submerged open intake 2–6 m above the seabed. Passive displays are mounted in the submerged open intake (fine: 0.5–10 mm, coarse: 50–300 mm). There is no movement or velocity limit, which is a behavioral barrier that keeps aquatic life and sediment out of intake pipes. The intake head can be fitted with a coarse velocity cap. The carriage pipe is then used to store water offshore. Open intake can easily be scaled up or down to meet capacity requirements. However, impingement/entrainment and heavy organic load make it vulnerable. Because the RO membrane is sensitive to various types of foulants, SWRO plants with open water intake systems normally have more complex pretreatment processes. As a result, pretreatment units that can manage any water quality must be built to remove silts, organics, and microbes that cause clogging and fouling of plant equipment and membranes. Pretreatment failure may affect the quality of the permeate.

2.2.2 Subsurface intakes

Subsurface intake collects seawater through sea wells (e.g., vertical, horizontal, slant, or radial), infiltration galleries, or other locations below the seabed. Subsurface intake is more suitable when geological conditions are below the seabed owing to their natural filtration ability. Natural filtration in subsurface intake is similar to sand filtration during physical and biological removal. Subsurface intake can remove microorganisms such as bacteria, algae, and biopolymers (proteins and polysaccharides) from the intake water. Thus, the intake system can reduce clogging and fouling of SWRO pretreatment units/membranes. The feed is relatively clean and thus requires less chemical treatment, such as antiscalants and coagulants. Furthermore, subsurface intakes pose less risk to environmental and marine life because the productivity of the ocean is believed to decrease with increasing depth [60]. Therefore, environmental problems such as impingement and entrainment encountered in open water intakes are mitigated by subsurface intakes.

However, subsurface intakes are not without challenges. For example, subsurface intakes require extremely favorable hydrogeological conditions, which are usually challenging to find in the vicinity of SWRO plants. It is commonly used for small SWRO plants. Debris is retained on the ocean floor in the well area, and beach erosion could hinder the performance of the subsurface pretreatment due to the corrosion of the filtration layer over time. Subsurface waters are lower in dissolved oxygen (DO) (between 0 and 1.5 mg/L) and high in hydrogen sulfide, which are not rejected by the RO membrane [61, 62]; hence, additional cost would be required to reaerate produced water. The release of low DO brine would cause oxygen depletion, causing harm to marine life around the brine discharged area, and significant maintenance efforts are required for periodic dredging or replacement of the upper portion of the intake filtration media.

2.3 PRE-TREATMENT

2.3.1 Dissolved air flotation

In the SWRO process, dissolved air flotation (DAF) is used as a clarification technique to remove solid particles before passing the effluent to either DMF or UF units. The principle of DAF involves the attachment of air bubbles to particles or flocs and then moves them to the surface of the water. The DAF system is usually divided into two compartments, the contact and separation compartments (Figure 2.2). It is paramount to allow collision of solid particles and bubbles in the contact compartment. The attachment of air bubbles to solid particles is called floc–bubble aggregation. Floc–bubble aggregates, and the remaining free bubbles are transferred to the separating compartment where free bubbles and floc–bubble aggregates float to the surface of the water. As the concentration of floc–bubble aggregates increases on the surface of the water, sludge is formed, collected, and removed. Clarified water at the bottom of the DAF unit (sometimes called a subnatant) was collected and transferred to DMF or UF for further pretreatment.

Bubbles (10–100 μm) are generated by saturating pressurized recycle flow with air. The rapid release of pressure via nozzles or special valves at the

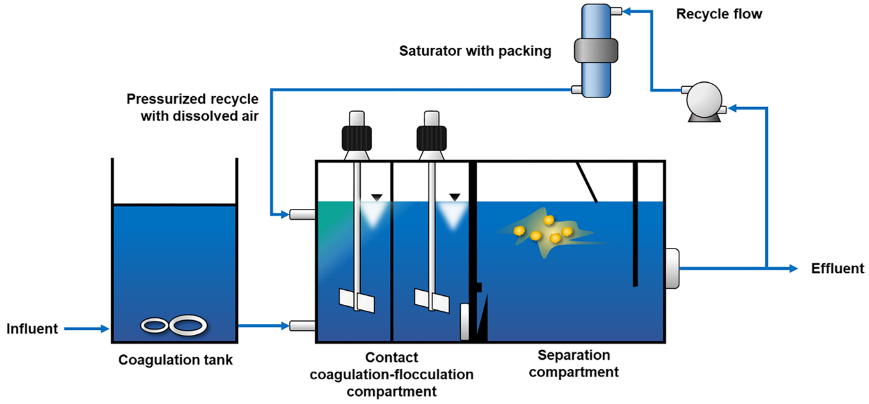

Figure 2.2 Dissolved air flotation unit.

bottom of the influent entrance spontaneously produces bubble nuclei due to the difference in pressure between the nozzles/valves and supersaturated water. The steady-state size of a bubble depends on the saturator pressure or air injection flow rate. High injection pressure results in small bubbles; however, a pressure point is reached where the increase in injection pressure does not correspond to a reduction in bubble size [63]. Bubbles are formed in the DAF unit via nucleation (homogeneous and heterogeneous) and growth. Homogeneous nucleation is a process of bubble formation within water when the difference between the surrounding pressure and dissolved air pressure is more than 100 bar [64]. The critical bubble diameter (d_{cb}) in homogeneous nucleation is projected using Equation (2.1):

$$d_{\mathrm{cd}} = \frac{4\sigma}{\Delta P} \tag{2.1}$$

where σ represents the surface tension of water and ΔP represents the pressure difference across the nozzle or injection valve. However, homogeneous nucleation is not expected in a DAF unit. On the contrary, heterogeneous nucleation is the process of bubble formation within pre-formed air gas pockets in the vicinity of surface cracks and imperfect solid particles. Heterogeneous nucleation occurs during the supersaturation of water [65]. Consequently, the bubbles grow by (1) uptake of air from water, (2) hydrostatic pressure decrease due to the upward movement of bubbles, and (3) merging or coalescence of bubbles.

Floc–bubble aggregates are formed by the entrapment of bubbles in a large floc, the growth of bubble nuclei on or with the floc, and collision and merging with the floc. The electrical charge interactions and attractions with van der Waals forces must be reduced for particles to attach to bubbles effectively. This is because most of the suspended particles are negatively charged, and bubbles are also thought to be negatively charged because of the ability of anions in water to attach more easily to the air bubble. For the particles to float, the charge of the particles must be neutralized, and the hydrophobicity must be increased [66]. Prior physical/chemical pretreatment of DAF influent by the addition of cationic surfactants or polyelectrolytes enhances floc–bubble aggregation [67–69].

The fundamental mechanism of solid particle removal in DAF is flotation. Unlike the sedimentation tank, DAF is more effective at removing low-density particles that cannot be removed from the sedimentation tank. Thus, DAF is more appropriate as a pretreatment for the SWRO process for algal-laden seawater rich in organic matter. Moreover, DAF does not necessarily require the formation of large flocs to achieve optimal performance. Therefore, a lower coagulation dose and shorter flocculation time compared to the sedimentation process are required. Nevertheless, coagulation is an important pretreatment step in DAF. Coagulation helps to transform the negative charge of particles to enable bubble attachment. Examples of seawater coagulants used for pretreatment are ferric chloride, aluminum sulfate, and polyaluminum chloride. Similarly, design parameters such as the hydraulic loading rate, solids loading rate, and air-to-solids ratio are essential for the optimum performance of the DAF system. This predicts the quantity of water and air that should be supplied to the DAF system simultaneously for efficient treatment and operation. The hydraulic loading rate is expressed in terms of the relationship between the DAF surface area and the total flow rate (influent and recycling). On the contrary, the solid loading rate is expressed with respect to the relationship between the DAF effective surface area and the total amount of solids entering the DAF unit. DAF can be operated efficiently at higher surface loading rates (SLRs). As in the sedimentation overflow rate, hydraulic loadings were used to represent the rate and size of the DAF unit. A conventional DAF unit is designed with hydraulic loading between 5 and 25 m/h, while newly designed units have hydraulic loadings between 15 and 30 m/h or more.

Owing to the flotation mechanism in DAF, it is very effective for removing low-density solid particles. In the SWRO process, DAF is applied because of its suitability for removal in algae-laden water [70, 71]. The occurrence of harmful algal blooms (HABs) in the Gulf of Oman and the Arabian Gulf in 2008–2009 resulted in the closure of numerous SWRO plants. This intensified the necessity for DAF as a pretreatment unit in the SWRO process for the removal of algae and algal-related organic matter. The use of DAF technology has increased dramatically since 2009, with almost all newly installed plants equipped with DAF units. In a report by Veolia, the use of DAF in the Fujairah II SWRO plant enabled the successful operation of the plant, even under severe HAB occurrences [72]. Gallou *et al.* reported 99% removal of algae by coagulation-AquaDAF™ followed by DMF in Al-Dur, Bahrain [73].

Appropriate pretreatments prior to DAF treatment would increase its effectiveness in handling algae, turbidity, organic matter, and color. The optimal coagulation dose and pH adjustment can affect the particle charge, and thus, the bubble can quickly attach to them. It is important that the coagulants used for pretreatment do not increase the hydrophilicity of the particles. Flocculation in DAF is quite different from flocculation during sedimentation. In sedimentation pretreatment in the SWRO process, the goal is to have a large floc that can easily settle to the bottom of the sedimentation tank. On the contrary, the floc in DAF is expected to be smaller for quick flotation. The preferable floc sizes were within 25–50 μm. Overall, DAF had superior solid particles and turbidity removal over sedimentation.

The DAF requires high energy and maintenance costs. Saturated pressurized recycle flow and aeration significantly contribute to the power cost of the unit. The average energy consumption was reported to be 0.05–0.075 kWh/m^3 of water treated [74]. Another recent work presented estimated SEC under varying recycling rate and aeration saturation pressure conditions, with a value ranging from 0.01 to 0.06 kWh/m^3 [75]. Although certain levels of algal cell concentration and turbidity are present in seawater year-round, occurrences that can be classified as HABs are seasonal events during the spring and fall seasons. Extreme cases such as those of the Gulf of Oman and the Arabian Gulf in 2008–2009 are infrequent. This affects the overall efficiency of DAF as higher efficiency is obtained in heavy-laden algae water compared to low-algae-level waters. Hence, research attention is needed to increase the efficiency of DAF regardless of algae concentration and to reduce the energy required for bubble formation.

2.3.2 Dual media filtration

A wide area of the filtration bed is used in the depth filtration process. The efficiency of the depth filtration is determined by the size and density of the medium. Backwashing is an efficient way to improve the performance of depth filtration owing to the density of the medium. Therefore, depth filtration is a better option for seawater desalination than surface filtration pretreatment. The principle is to implement DMF with different densities to boost the efficiency of depth filtration (e.g., filtration speeds, operational runs, and minimal backwash water usage). This concept is called DMF (Figure 2.3).

For high suspended solids and turbidity reduction, various SWRO plants use DMF as a primary pretreatment for seawater/brackish water feed. DMF is a mechanical process that removes turbidity, organic matter, color, and odor by straining, sedimentation, impaction, interception, adhesion, adsorption, flocculation, and sometimes biological growth. Sand, calcites, anthracite, and activated carbon are some of the media used in DMF units. Calcite medium is widely used because it is abundant in nature, inexpensive, and helps to improve pH levels by neutralizing water. Because it is lighter than sand and has a high carbon content, anthracite is commonly used in DMF systems to remove suspended solids and turbidity while resisting chemical attack. Activated carbon media can eliminate large amounts of organic matter, ammonia, and

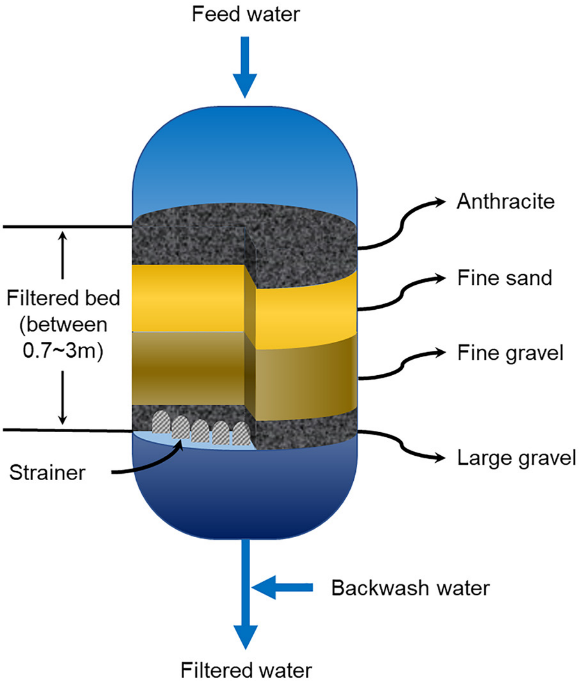

Figure 2.3 Layout of DMF.

disinfectants. Because of the high cost of anthracite, it is usually mixed with a sand bed. Anthracite ranging in size from 1.5 to 2 mm, with an average size of 0.5 Â mm, is placed on top of the sand bed.

DMF incorporates both depth and surface filtration techniques. DMF is more efficient than surface filtration alone. This is because the entire depth is used, provides better quality performance, and has a high flow rate. DMF is more cost-effective because it can be used with chemical coagulation, lowering the overall process cost of the system. Additionally, in the presence of high organic matter concentrations or turbidity spikes, coagulants are needed to reduce the footprint and ensure adequate permeate consistency (SDI 5). In the DMF unit, either inline or full-scale coagulation was carried out. Coagulants, such as ferric chloride, are widely used in SWRO plants.

Media properties, such as size distribution, shape, density, and porosity, are crucial in determining the filtration performance of DMF. The amount of head loss that accumulates during a filtration run is affected by the size of the media. The smaller the media, the smaller the pore opening, allowing water to permeate and aids foulant removal. The efficiency of the DMF unit improves if the pore opening is minimal. Small pore openings increase head loss through the media. The size of the medium was specified as the effective size. The effective size is defined as the size of the openings that allow 10% of the medium by weight to pass. The uniformity of the media is represented by the uniformity coefficient. The uniformity coefficient is measured as the size opening that allows 60% of the medium to pass through, divided by the size opening that allows 10% of the medium to pass through. The uniformity coefficient describes the spectrum of media sizes, whereas the effective size describes the average media size. The ideal uniformity coefficient of DMF is less than 1.7. Media shape is also important because it affects the fixed-bed porosity, filtrate head loss, filtration efficiency, and ease of filtration. The DMF backwash efficiency is dependent on the shape, density, and porosity of the media.

Backwashing of DMF removes the suspended materials that accumulate on the filter media during filtration. The ease with which DMF can be washed by backwashing contributes to the cost-effectiveness of the process. However, unlike the single filtration method, which is cleaned easily by backwashing, cleaning the DMF by backwashing can be more difficult at times. This is because the top layer of DMF is normally fine and can be identical in size to the attached materials. The fine topmost layers could be washed with suspended materials without caution. Increased head loss through the media up to the available lower-level limit, degradation of filtered water quality, and exceeding the maximum time limit are all indicators of backwashing in DMF. DMF is usually backwashed with water or water aided by air scouring after 24–36 h in SWRO pretreatment measures. Supplied air may be applied before water backwashing, or both air and water may be applied concurrently in air-scouring supported backwashing.

Although the DMF method uses fewer resources, it has a low level of organic and biofouling mitigation. If the organic load and turbidity of the SWRO intake water are high and not removed prior to the DMF unit, the DMF unit will become clogged, resulting in short filter runs and a filtrate with a high risk of fouling the SWRO membrane. Unfortunately, in an environment with a high organic and microbial load, DMF pretreatment is insufficient to produce water of adequate quality to minimize fouling on SWRO membranes [76]. The filtration rates should be shortened to ensure the adequate use of DMF with high organic and microbial loads. A shorter rate would result in less clogging of the media (this is still subject to the physical properties of feedwater) [77]. Nevertheless, the shortening of the filtration rate requires a corresponding increase in the active surface area of the media. This could lead to an increase in the footprint and construction costs of the SWRO pretreatment system. Plant operators have attempted to improve the performance of DMF by improving the coagulation strategies.

Several studies have examined the efficiency of DMF under various conditions in the literature [78–82]. Overall, the use of coagulation prior to DMF showed improved performance in terms of turbidity and organic removal compared to DMF alone, validating the need for some pretreatment steps for DMF unit stability.

2.3.3 Membrane-based pretreatment

The SWRO process has seen improvements in all aspects of the process, including the RO membrane, module design, process optimization, and pretreatment. Pretreatment is an essential component of the SWRO process. This is because, regardless of how far other areas of the SWRO process have progressed, their performance is still heavily reliant on feed quality due to potential issues, including membrane fouling caused by poor feed quality. Fouling in the SWRO process can be avoided by using an effective pretreatment process. Furthermore, with a given hydraulic pressure, a high-quality feed will sustain the permeate flux. Therefore, the need for implementing appropriate pretreatment processes is a viable way to increase the energy efficiency of SWRO desalination. Traditional pretreatment technologies, such as coagulation/flocculation, disinfection, DAF, and DMF, have been previously used in SWRO plants to pretreat seawater feed. However, these methods have not been able to overcome the difficulties of membrane fouling. This has led to the recent implementation of advanced pretreatment technologies, such as MF, UF, and nanofiltration (NF).

2.3.3.1 Microfiltration

MF pretreatment using membranes with pore sizes in the range 0.1–0.35 μm [83] was introduced as a pretreatment unit in the SWRO process as a submerged MF process usually installed in the SWRO process owing to its fouling resistance and ability to withstand different seawater feed conditions. The MF process can effectively remove particulate matter and microbes from the feedwater, thus preventing fouling on the RO membrane. Unfortunately, during MF pretreatment, a large amount of foam is formed because of the protein content of marine microbes [84] and the MF membrane is easily fouled. Therefore, for the efficient and effective operation of the MF system, an adequate pretreatment step such as coagulation/chlorination is necessary for better removal of organic and inorganic materials to mitigate fouling on the MF membrane [85, 86]. Significant efforts have been made to improve MF membranes to enhance flux, rejection, and reduce fouling and cost. These efforts are centered on improving MF membrane hydrophilicity, incorporating into the membrane matrix, or using inorganic materials [87].

2.3.3.2 Ultrafiltration

The UF process has gained more applicability in the SWRO process than the MF process. This is due to its higher operational flexibility and considerable balance between water transport and foulant rejection in difficult water conditions. The UF membrane pore size is smaller than that of the MF membrane, with pore sizes ranging from 0.01 to 0.05 μm [83]. UF can eliminate a wide range of pollutants present in seawater feed, such as algae, bacteria, fungi, silt, and some organic matter. The fouling potential of the RO membrane by permeate from the UF system is lower than that of the MF system. However, as in the MF system, the efficiency of the UF system is improved by coupling the UF system with conventional pretreatments such as coagulation, DMF, or DAF. A consistent UF permeate of <3 SDI can be achieved by coupling UF with the appropriate coagulant during HAB [88]. A lower SDI of 0.5 was reported when the UF system was coupled with coagulation [89]. Inappropriate pretreatment is detrimental to the UF membrane because foulants can accumulate on the membrane surface and within its pores. The impact of foulants on the UF membrane can be minimized by developing new UF membrane materials or modifying the UF membrane surface.

2.3.3.3 Nanofiltration

Even though significant improvements in feedwater quality have been achieved using MF and UF systems, RO membrane fouling is still a significant problem in the SWRO process, especially with difficult feedwater. In addition, MF and UF have poor ionic species rejection. Hence, the permeate of these processes has numerous low-molecular-weight organics and scaling fouling potentials. Thus, the NF unit was introduced. An appropriate NF membrane has a molecular weight cut-off (MWCO) below 1000 Da and can effectively reject both charged and uncharged ions [90]. Today, the research trend is to use NF pretreatment instead of MF and UF. Although NF requires higher pressure due to the tightness of the NF membrane pores, NF, however, produces a lower saline permeate. Lower feed salinity passed on to the RO membrane would, in turn, reduce the pressure required to transport water across the RO membrane. Therefore, utilizing NF for SWRO pretreatment reduces the RO pressure requirement due to low salinity and organic foulants and increases RO recovery and water flux [91, 92]. However, effective and consistent operation of the NF process can only be achieved by adequate pretreatment of raw feedwater; similar to the RO unit, the NF system is susceptible to fouling. Therefore, to ensure proper pretreatment, the NF system is coupled with other membrane processes, such as MF or conventional pretreatment processes, to improve the quality of NF feedwater conditions. Similarly, recent developments in membrane materials (inorganic, ceramics, etc.) have been shown to be alternative membrane materials for the NF process. This is because these new membrane materials can tolerate harsh feedwater conditions, and have self-cleaning properties (stimuli-responsive materials).

2.3.3.4 Inline coagulation using advanced coagulation process

Owing to the propensity of membrane-based pretreatment for fouling, adequate pretreatment is required. A common practice is to combine a membrane-based pretreatment unit with a conventional coagulation process. However, conventional coagulation is often followed by flocculation and sedimentation tanks to remove flocs and sludge before the membrane unit. This increases the footprint of the SWRO process. Therefore, the introduction of inline coagulation eliminates the need for a sedimentation process, thus reducing the SWRO footprint. Recently, an advanced coagulation process has been introduced in the SWRO process. Inline advanced coagulation technology using liquid ferrate at low concentrations is an excellent technology because of the combined oxidation, disinfection, and coagulation properties. This inline technology saves both capital and operating costs that would otherwise be spent on energy and chemicals. The addition of oxidation aids in removing organic components from the feedwater without the need for physical separation. As organic and biological components can be mineralized, the effluent from this phase would have limited environmental effects. Superior microbial and organic removal was documented when an advanced coagulation pretreatment process was combined with a membrane process [93, 94].

2.3.4 Cartridge filter

Cartridge filters (CFs) are pressure filtration devices used for the removal of suspended solids and chemicals for which total concentrations are less than 100 mg/L. Filtration by CFs is mostly outside-in; therefore, filters need to be mechanically strong to accommodate changes in pressure during filtration operation. Hence, the CFs are enclosed within a housing/casing to withstand such pressure changes. In the SWRO process, CFs are often used as a pretreatment step before the RO system. These filters are available in various lengths and diameters, and materials (e.g., pleated membranes, woven, and non-woven).

CFs are categorized into two types: surface and depth cartridge filters. Surface CFs remove contaminants, mainly by size exclusion. Here, contaminants larger than the pore size of CF are restricted from entering the filter media. Depth CFs, on the other hand, remove contaminants by Brownian transport. Here, the multiple layers and thickness of the filter provide a tortuous path for the contaminants, and eventually, they are trapped within the filter. With depth CF, contaminants are often smaller than the pore size of the filter. Regardless of the CF type, contaminants are either collected on the filter surface or within the pores until the filter clogs. Filters are sometimes designed to possess cleaning cycles; however, in the case of heavy fouling, the filters can be chemically cleaned (if recommended by the manufacturer) or replaced.

2.4 RO SYSTEM EQUIPMENT

The feed after the pre-treatment unit is fed into the RO system to produce freshwater. A schematic of the RO system is shown in Figure 2.4. Because water permeation in the RO system is conducted by pressurization, the main body of the RO system consists of a HPP for pressurization and a PV for membrane housing. It is desirable to recover the remaining pressure energy in the concentrate stream to maximize the energy efficiency of the RO system. Thus, an ERD should be installed between the outlet stream of the concentrate and the inlet stream of the feed to transfer the remaining pressure energy from the concentrate to the feed; then, the concentrate stream is discharged from the RO system after the ERD. Owing to the imperfect recovery of the remaining pressure and the pressure drop during the RO system, the feed stream after the ERD is insufficient to operate the RO system continuously. The insufficient pressure on the feed stream is compensated for by a high-pressure pump, usually called a BP. This is the basic structure of an RO system. Hence, the energy consumption of the RO system is determined by a HPP and BP. To run the RO system effectively, it is imperative to use a HPP and an ERD with high energy efficiency.

2.4.1 High-pressure pump

A positive displacement pump can achieve an energy efficiency of over 90%; hence it can be utilized as a high-pressure pump in seawater desalination systems requiring high energy efficiency. In some cases, the positive displacement pump can even show a very high pump efficiency of approximately 97% [36]. Many small desalination plants have taken advantage of the high efficiency of positive displacement pumps [36]. Although a positive displacement pump has some disadvantages, such as complex structure and difficulty in operation, its high energy efficiency provides substantial merit for minimizing the energy consumption of desalination plants. Thus, the use of positive displacement pumps was recommended for many new desalination plants in the Canary Islands [95, 96], as well as technologies such as batch RO [97, 98] and CCD [99]. However, a positive displacement pump cannot be easily used in large-scale

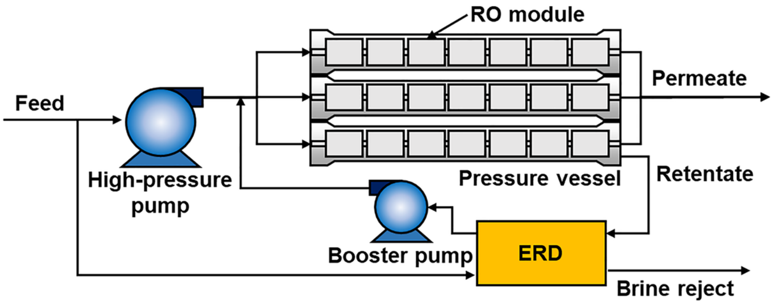

Figure 2.4 Schematic of RO system.

desalination systems of over 1000 m^3/day. The main reason for this is that a large positive displacement pump is costly, increasing the water production cost immensely.

On the contrary, centrifugal pump is widely utilized in many large-scale desalination plants such as the Sydney Water, Perth I and II, Adelaide SWRO desalination plants in Australia, and many desalination plants in Spain and the Middle East [36]. Centrifugal pumps can be easily and cheaply manufactured for a large volume of feed supply compared to a positive displacement pump, which is the main reason for its wide utilization in large-scale desalination plants. Although centrifugal pumps have lower pump efficiency than positive displacement pumps [100], the advantage of using a centrifugal pump is quite beneficial for the economics of operating desalination plants. In addition, the energy efficiency of a centrifugal pump can be improved by expanding its size because a multistage centrifugal pump design in the large-size desalination plants could be operated more effectively than the single-stage pump. The practical limitation of a centrifugal pump is its efficiency of approximately 90% [36]. In many recently constructed large-size desalination plants with over 100 000 m^3/day capacities, high-efficiency, large-size centrifugal pumps are used, and the efficiency of the pumps is higher than 85% [36].

2.4.2 Energy-recovery device

Many of the SWRO plants are operated under 40–50% recovery because of the limitation of the maximum sustainable pressure on the SWRO membrane (<83 bar) [101]. Thus, a high amount of concentrate is discharged at high hydraulic pressure. Such hydraulic pressure in the concentrate is recovered by the ERD application and can reduce the energy consumption of the RO system. The development of ERDs has been one of the main contributors to energy reduction in SWRO plants in recent decades [11].

Different types of ERD can be applied depending on the design of the SWRO plants. ERDs are classified into two groups: turbine (or centrifugal) and isobaric ERD. Turbine ERD includes a Francis turbine (FT), Pelton turbine (PT), turbocharger (TC), and isobaric ERD, which includes dual work exchanger energy recovery (DWEER) and pressure exchanger (PX). However, most SWRO plants employ ERD in PT, DWEER, or PX.

PT recovers the hydraulic pressure of the concentrate by rotating the shaft connected between the wheel and the HPP (Figure 2.5a). PT is relatively easy to operate at a relatively low cost, and its size is more compact than isobaric ERDs [102]. However, as the hydraulic energy of the concentrate is converted into mechanical energy and again to hydraulic energy, the energy efficiency of PT is lower than that of isobaric ERDs. As a result, the use of PT was the mainstream ERD application in the early 2000s, but its application dramatically decreased with the development of isobaric ERDs.

DWEER directly delivers the hydraulic pressure of the concentrate to the feed by operating the pistons (Figure 2.5b). At the two sides of the device, one is filled with the feed with low pressure, and the other is filled with the concentrate with high pressure. The hydraulic pressure is exchanged when

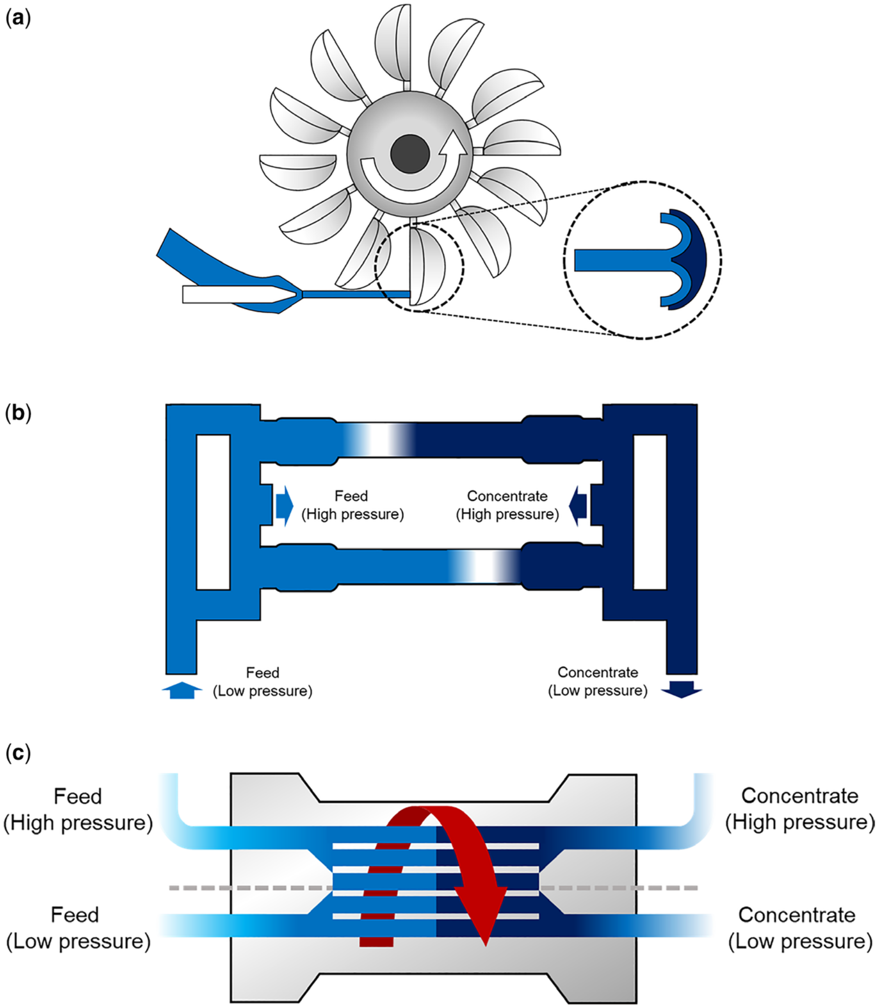

Figure 2.5 Types of ERD: (a) PT, (b) DWEER, and (c) PX.

the pistons move back and forth. The direct exchange of hydraulic pressure improves the energy efficiency of the DWEER over turbine ERDs. However, moving parts in DWEER would require intensive maintenance, which is not favorable for operators.

The PX is equipped with a rotor to deliver the hydraulic pressure of the concentrate to the feed directly (Figure 2.5c). The rotor rotates when it is filled with low-pressure feed, and the low-pressure feed in the rotor is exposed to the high-pressure concentrate. The feed is then pressurized by the concentrate and sent to the feed line of the RO system. The unpressurized concentrate is pushed by low-pressure feed and discharged. It has been reported that PX exhibits superior energy efficiency compared to other commercial ERDs, leading to low-energy SWRO desalination. Despite having the highest energy efficiency, high-salinity concentrates can be mixed with low-salinity feed. The increase in feed salinity slightly increases the SEC and lowers the permeate quality.

Different types of ERD have been employed in SWRO desalination plants. In particular, high-energy-efficient ERDs are adopted, as they are fundamental in reducing the SEC of RO systems. Currently, as PX is highly energy-efficient, low-cost, and stable, it has been widely applied to SWRO desalination plants. However, PX might be substituted by a new type of ERD if several improvements are launched moving forward.

2.5 RO MEMBRANES

RO membranes are the main equipment used in SWRO desalination. This allows water molecules to permeate but rejects salts toward the permeate side. As a result, the performance of RO membranes determines the performance of the RO system (e.g., water quantity and quality). Different RO configurations can be adopted based on the characteristics of the membranes. Thus, the selection of RO membranes is critical, depending on the target design.

The performance of RO membranes is indicated using water permeability (*A*) and salt permeability (*B*). Because membrane manufacturers provide the performance of membranes under test conditions, water and salt permeability should be calculated using several mathematical equations by utilizing Equations (2.2) and (2.3):

$$J_\mathrm{w} = A\left[\left(P_\mathrm{f} - P_\mathrm{p}\right) - \left(CPF \times \pi_\mathrm{f} - \pi_\mathrm{p}\right)\right] \tag{2.2}$$

$$J_\mathrm{s} = B\left(CPF \times C_\mathrm{f} - C_\mathrm{p}\right) \tag{2.3}$$

where J_w and J_s are the water and salt fluxes, P_f and P_p are the hydraulic pressures for the feed and permeate, respectively; π_f and π_p are the osmotic pressures for the feed and permeate, respectively; C_f and C_p are the concentration for the feed and permeate, respectively; and *CPF* is the concentration polarization factor. Thus, several SWRO and BWRO membranes were calculated and are listed in Table 2.1. The water permeability values for the SWRO membranes were approximately 1–2 L/m^2 h bar, and those for BWRO membranes are 3–6 L/m^2 h bar (Figure 2.6).

RO membranes can be classified as depending on water and salt permeability. High-rejection membranes are those with low salt permeability values. It rejects salts with high efficiency, but the water permeability is relatively low. In contrast, high-flux membranes exhibit high water permeability, but their salt permeability is low. Although high water permeability and low salt permeability are preferred to improve the efficiency of desalination, it is difficult to achieve both objectives.

Table 2.1 *A* and *B* values for commercial SWRO and BWRO membranes.

Type of RO membrane	Manufacturer	Model	Water permeability, A (L/m^2 h bar)	B (L/m^2 h)
SWRO	LG Chem	SW400GR	1.25	4.36×10^{-2}
		SW400R	1.52	5.20×10^{-2}
		SW400ES	2.36	1.04×10^{-1}
	DuPont Water Solutions	SW30XHR−400i	0.99	4.22×10^{-2}
		SW30HRLE−400i	1.25	5.82×10^{-2}
		SW30XLE−400i	1.52	6.94×10^{-2}
	Toray	TM820K−400	0.98	3.11×10^{-2}
		TM820C−400	1.10	6.22×10^{-2}
		TM820M−400	1.19	5.34×10^{-2}
		TM820E−400	1.28	7.11×10^{-2}
		TM820V−400	1.56	6.79×10^{-2}
	CSM	RE8040-SHN 400	1.08	6.34×10^{-2}
		RE8040-SHA 400	1.25	7.28×10^{-2}
		RE8040-SHF 400	1.63	1.12×10^{-1}
BWRO	LG Chem	BW400R	3.30	1.48×10^{-1}
		BW400ES	5.36	1.48×10^{-1}
	DuPont Water Solutions	BW30−400	3.29	1.92×10^{-1}
		LE−400	5.86	1.25×10^{-1}
		ECO−400i	5.89	1.21×10^{-1}

Basic performances for SWRO membranes were obtained in the condition of 32 000 ppm NaCl and 5 ppm boron at 25°C (77°F), 800 psi (55 bar), pH 8, and 8% recovery. Those for BWRO membranes were evaluated with 2000 ppm NaCl at 25°C (77°F), 225 psi (15.5 bar), pH 7, and 15% recovery.

Several RO modules are equipped with thicker spacers to reduce the fouling propensity. Fouling can be easily formed when the feed channel (i.e., space between membrane leaves) is narrow. Generally, 28 mil (0.71 mm) spacers are employed in membrane modules, but 34 mil (0.86 mm) spacers can be used to mitigate fouling formation. RO modules with 34 mil spacers can be employed in the region where the feed sources contain high foulants, such as organic matter.

Because the key of SWRO technologies is RO membranes, advanced RO membranes should be developed to satisfy the low SEC requirement and high water quality. In addition, high-pressure resistant membranes should be developed to meet the needs of membrane brine concentrators.

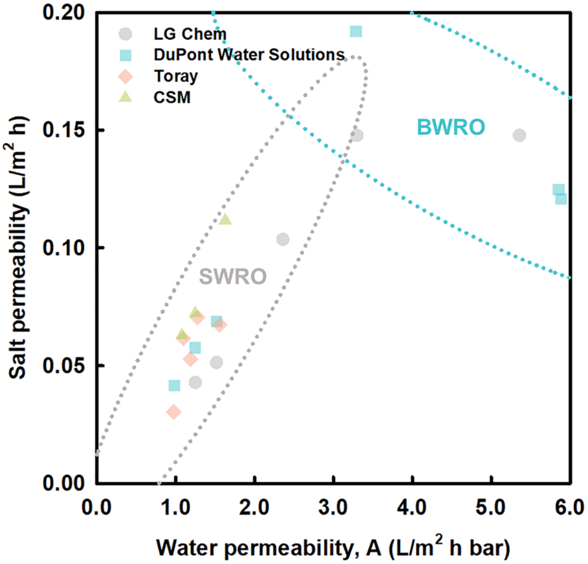

Figure 2.6 Water and salt permeability of SWRO and BWRO membranes.

2.6 RO CONFIGURATIONS

RO configurations determine the major performance of SWRO desalination plants. In this regard, RO configurations should be designed based on the targeting performance of SWRO desalination plants. Although various RO configurations have been adopted for different plants, the classifications of the RO process are not clearly summarized. In particular, the concept of pass and stage design has often been misunderstood in numerous studies. In addition, the overall RO system is explained only by a part of the RO configuration. Thus, RO configurations should be classified systemically.

The RO pass design should first be defined to present the overall RO configuration. When the RO system is composed of SWRO membranes, the RO system is classified as a single-pass RO system. The desalination process was performed using SWRO membranes only, and the permeate underwent post-treatment as a product. Furthermore, if the RO system is composed of both SWRO and BWRO membranes, the RO system is considered a two-pass RO. After the permeate is produced from the SWRO membranes, the BWRO membranes further desalinate the SWRO permeate. Depending on the features of the streamlines, a two-pass RO can be classified further.

After the RO pass design is defined, specific designs for the SWRO and BWRO systems can be classified (Figure 2.7). Most SWRO systems are composed of single-stage systems, but two-stage systems can be adopted for several plants. Further designs can be implemented to improve the performance of SWRO systems, such as pressure-center design and internally staged design. In contrast,

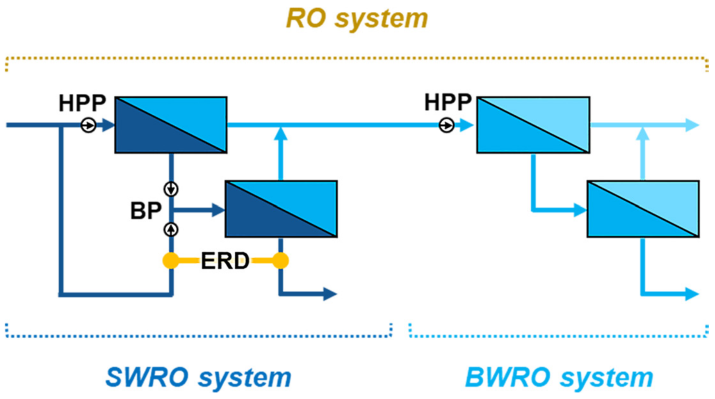

Figure 2.7 Composition of RO system. The SWRO system is a necessary part of the RO system, while the BWRO system is an optional process for improving water quality.

BWRO systems in SWRO desalination plants are generally configured as two-stage, and variations of two-stage BWRO, such as cascade, are widely adopted.

Owing to the application of multiple designs in a single SWRO desalination plant, it is necessary to define the type of RO system as (1) RO pass, (2) SWRO, and (3) BWRO configurations. However, the RO configuration is often referred to as the RO pass configuration. For example, single-pass RO refers to an RO system composed of single-stage SWRO, and two-pass RO refers to an RO system composed of single-stage and two-stage BWRO (Table 2.2).

2.6.1 RO pass configuration

The majority of RO pass designs are single- or two-pass RO for SWRO desalination plants. Single-pass and two-pass RO systems are also referred to as one- and double-pass RO systems, respectively. However, single- and two-pass RO systems are more general terminations for configurations. Various types of single- and two-pass RO systems have been developed and applied to satisfy water quality and energy efficiency.

Table 2.2 Summary of general termination for RO configurations.

Feed	Overall RO configuration	SWRO configuration	BWRO configuration
Seawater	Single pass	Single stage	N/A
	Two stage	Two stage	N/A
	Full two pass	Single stage	Two stage (or cascade)
	Partial second pass	Single stage	Two stage (or cascade)
	Split partial second pass	Single stage	Two stage (or cascade)

For overall RO configuration, it is preferred to name the overall pass configuration first (if the number of pass is multiple) and then specify stage configuration.

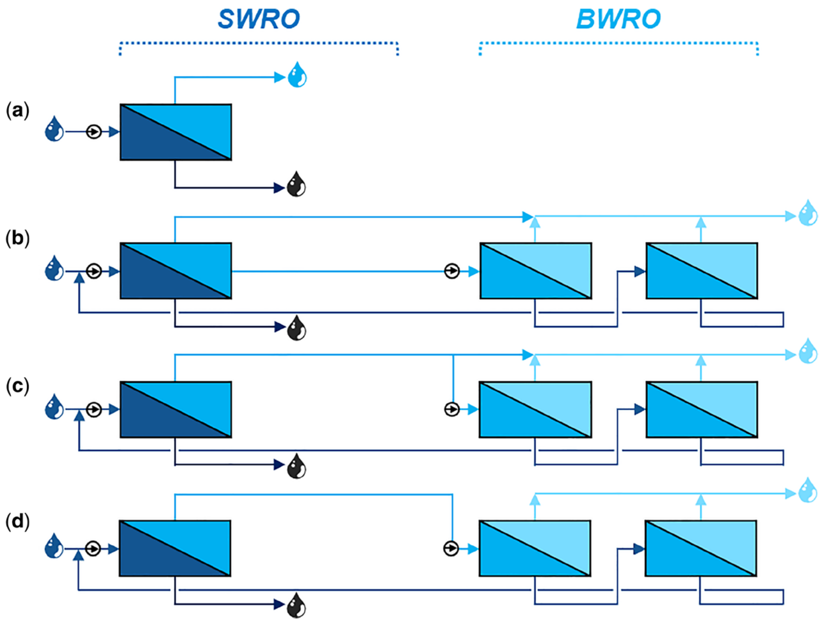

Figure 2.8 Scheme of RO pass configurations: (a) single-pass, (b) split partial second-pass, (c) partial second-pass, and (d) full two-pass RO.

2.6.1.1 Single-pass RO

Single-pass RO is only composed of an SWRO system without a BWRO system (Figure 2.8a). In single-pass RO systems, permeate is directly produced from seawater across SWRO membranes, and thus its TDS is relatively higher (e.g., 300–500 mg/L) than two-pass RO systems. Furthermore, the recovery of single-pass RO systems is higher than that of two-pass RO systems. This is because the SWRO permeate was not lost by the BWRO system. Owing to its simple configuration, single-pass RO can be widely used to produce freshwater for living in the environment and drinking. However, the TDS of the permeate would be higher in the region where high-salinity seawater is the source of feed (e.g., the Arabian Gulf). Thus, the application of a single-pass configuration is limited in terms of permeate quality.

2.6.1.2 Split partial second-pass RO (or split partial two-pass RO)

Split partial second-pass RO utilizes the front, and rear SWRO permeates separately to improve permeate quality with energy efficiency. When SWRO membranes are located in a PV system, the water flux and feed salinity are distributed differently. The feed salinity is relatively low, and the water flux is high in the front elements of the SWRO process. In contrast, the feed salinity is high, and the water flux is low at the rear elements. As a result, the permeate TDS is low for the front elements and high for the rear elements [17]. In this regard, it is thermodynamically energy-efficient to improve the final water quality by desalinating high-salinity permeate only and mixing it with low-salinity permeate. This concept is applied to the configuration of split partial second-pass (SPSP) RO. The SWRO front permeate (i.e., low salinity) is sent to a product tank directly, while the rear permeate (i.e., high salinity) is sent to the BWRO system for purer permeate production (Figure 2.8b).

2.6.1.3 Partial second-pass RO (or partial two-pass RO)

Partial second-pass RO treats a part of the SWRO permeate through the BWRO system to improve permeate quality (Figure 2.8c) [17]. The SWRO permeate is divided into two streams: one is sent to the product tank, and the other passes the BWRO system. Product quality can vary depending on the ratio of the partial streams. If the ratio of the stream sent to the BWRO system is higher, the TDS of the product is lower. Thus, the ratio is often higher during the summer to meet the permeate quality, as the TDS of the SWRO permeate is higher with an increase in temperature. However, as a part of the SWRO permeate is taken without splitting, the energy efficiency of partial second-pass RO is lower than that of split partial second-pass RO.

2.6.1.4 Full two-pass RO

Full two-pass RO wholly supplies the SWRO permeate to the BWRO without splitting the stream. Thus, the TDS of the SWRO permeate is significantly lowered by the BWRO system, and the TDS of the final product is low. In this regard, a full two-pass RO is employed when the permeate is highly pure (Figure 2.8d). Owing to its low TDS level, the product of full two-pass RO would not be adequate for drinking water production. Thus, the low-salinity product must serve as drinking water with remineralization or be utilized as industrial water demanding pure water. Though rarely, the permeate of full two-pass RO can be treated further by BWRO (i.e., full triple-pass RO) when extremely high-purity water is produced for industrial use [11].

2.6.2 SWRO system configuration

2.6.2.1 Single-stage SWRO

SWRO is generally composed of a single-stage configuration (Figure 2.9a). Multiple PVs are installed in an SWRO train, and the concentrate from the train is disposed of after its hydraulic energy is recovered. Because SWRO equipment and devices are standardized for single-stage SWRO operations, the configuration is a basic choice for SWRO design. However, the SWRO system configuration can be modified to overcome the limitations of the single-stage operation.

2.6.2.2 Two-stage SWRO

Two-stage SWRO can increase the recovery of the SWRO system by producing additional permeate from the second stage (Figure 2.9b). At the rear SWRO elements, the osmotic pressure of the feed almost reaches the hydraulic pressure of the feed. Because the net driving pressure (NDP) is low, a low amount of permeate is produced from the element. Thus, SWRO as a single stage is limited for high-recovery operations. However, when additional hydraulic pressure is

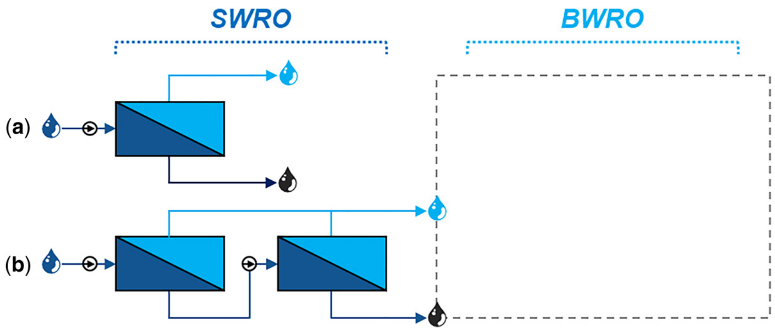

Figure 2.9 Scheme of SWRO system configurations: (a) single-stage and (b) two-stage SWRO.

applied to the feed, the permeate can be produced from the SWRO element because of the higher NDP. By elevating the hydraulic pressure through the inner boost pump between the first- and second-stage SWRO, the second-stage SWRO produces additional permeate. The ratio of permeate for the first and second stages is 2:1 as a rule of thumb [103, 104]. However, high-pressure-resistant SWRO membranes and equipment should be employed to overcome hydraulic pressures higher than 80 bar. As commercial SWRO membranes are designed to overcome a hydraulic pressure of 80 bar, a higher capital cost is required for the SWRO design. A two-stage SWRO design is often employed for retrofitting old plants to increase plant capacity.

2.6.2.3 Pressure center design

The energy efficiency of HPPs significantly affects the overall energy consumption of SWRO, as it is the dominant energy-consuming unit. To achieve low-energy consumption in RO systems, high-efficiency HPPs should be employed in the systems. Notably, the mechanical efficiency of the pump is highly associated with its capacity, and the efficiency is improved when the capacity of the HPP is increased. Thus, a pressure-center (or three-center) design is developed to lower the energy consumption of the RO system by increasing the capacity of HPPs and BPs. In particular, the pressure-center design combines several SWRO trains to the main feed line to supply pressurized feed simultaneously using larger-sized HPPs (Figure 2.10). In addition, the design allows the SWRO system to produce varying amounts of permeate more effectively by integrating multiple SWRO trains. This leads to a more flexible operation of the RO system in accordance with the water demand. In contrast, the combination of multiple SWRO trains was not beneficial in terms of the maintenance of the RO system. While each SWRO train can be repaired separately in a conventional system, all SWRO trains must be stopped to repair a single SWRO train. Despite its advantages in SEC reduction and disadvantages in maintenance, several SWRO desalination plants have adopted the design of SWRO systems to reduce SEC. Because the design was developed by an Israeli company, IDE Technologies, the design has been mainly applied to Israeli plants [11, 105–107].

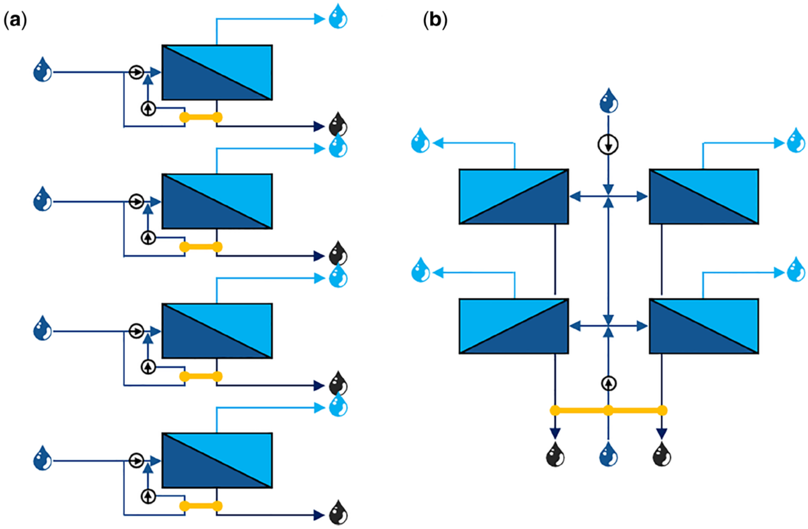

Figure 2.10 Scheme of pressure-center design: (a) typical RO trains and (b) RO trains with pressure-center design.

2.6.2.4 Internally staged design

Internally staged design (ISD) utilizes different RO membranes in a PV to acquire performance benefits (Figure 2.11) [17, 108]. When RO membranes are placed in a PV, high-rejection membranes and high-flux membranes are in the front and rear, respectively. The arrangement exhibits several operational benefits compared to RO systems employing single-type membranes.

ISD can reduce the fouling propensity by decreasing the water flux at the front elements. Front RO elements are easily fouled with organic and colloidal particles owing to high-flux operation. However, when the front RO membranes are high-rejection membranes (i.e., low water permeability), the membranes are operated at lower fluxes. In other words, fouling is mitigated by ISD.

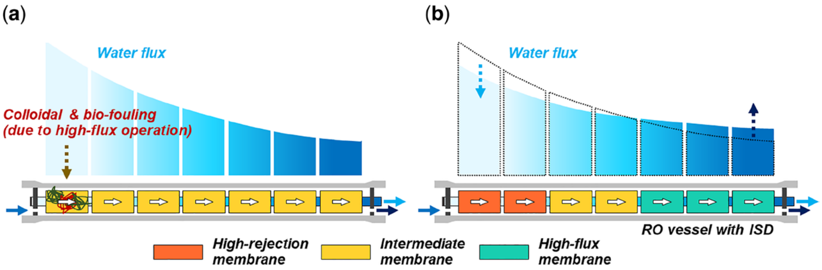

Figure 2.11 Scheme of internally staged design (ISD) in RO process: (a) normal design and (b) ISD.

More diverse RO performance can be obtained by utilizing different types of membranes. Achievable RO performance is limited when single-type membranes are used. In addition, RO systems equipped with different membranes can exhibit wider RO performance. The use of an optimized membrane arrangement allows the RO system to operate with higher energy efficiency under the control of operating conditions.

With the operational benefits, it has been reported that Las Palmas III, Mazarrón, and El Coloso SWRO plants adopted ISD to SWRO systems [109]. However, the complexity of maintenance still needs to be addressed to utilize ISD [108].

2.6.3 BWRO system configuration

2.6.3.1 Single-stage BWRO

Brackish water has a TDS of 500–15 000 mg/L. However, BWRO plants typically treat feeds of 500–10 000 mg/L [102]. Because there are various sources of brackish water, it can be classified with more detailed criteria: water with a TDS of 500–2500 mg/L is classified as low saline and that with a TDS of 2500–10 000 mg/L as high saline. Notably, the osmotic pressure of brackish water is not as high as that of seawater and is still lower than that of seawater even when it is concentrated up to 90% in low-salinity brackish water. Because of the low osmotic pressure, BWRO systems can be operated at a low hydraulic pressure, and the system recovery can be increased substantially. When the feed is low-salinity brackish water, a single-stage (or -pass) system can be adopted (Figure 2.12a) [102]. However, high recovery cannot be achieved through single-stage/pass BWRO systems, even though brackish feed has low osmotic pressure.

2.6.3.2 Two-stage BWRO

Two/multistage systems are common in BWRO applications to achieve high recovery. The target recovery is 70–90% with a water flux of 20–40 L/m^2 h, depending on feed salinity and characteristics [17], and the value is still higher than that of single-stage (-or pass) operation. The staged system generally follows a 2:1 array for a two-stage configuration (where the ratio of the PV number for the first and second stages is 2:1) and 3:2:1 for the three-stage configuration [102].

However, BWRO systems differ depending on the salinity of brackish water. For low-salinity brackish water, two/multistage BWRO systems are commonly used as well as single-stage BWRO systems, and no BPs are installed between the first and second stages (Figure 2.12b). This is because the hydraulic pressure is sufficiently high to overcome the osmotic pressure of the feed. In contrast, when the feed is high-salinity brackish water, two-stage BWRO equipped with BPs between the stages is applied to further produce permeate from the second stage (Figure 2.12c).

Two/multistage BWRO systems can also be implemented in SWRO desalination plants to improve the water quality. In two-pass SWRO systems, the first pass comprises SWRO membranes and the second pass of BWRO membranes [11, 17]. As the feed for the second pass is a low-salinity brackish, it is usually configured as a two-stage BWRO system without inner BPs.

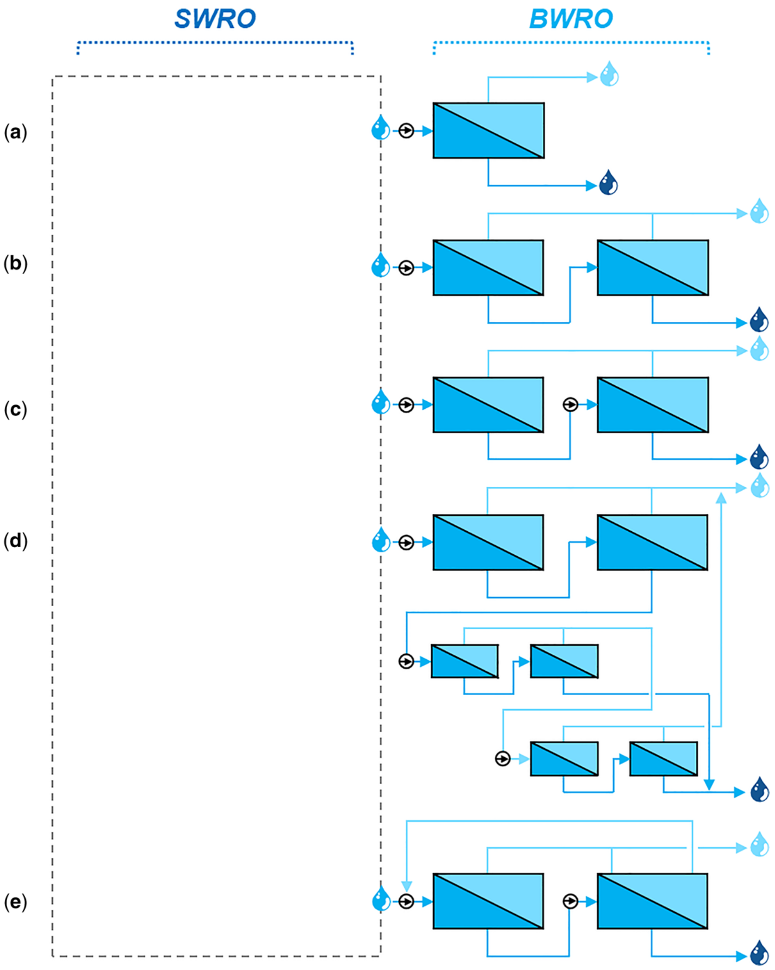

Figure 2.12 Scheme of BWRO configurations: (a) single-stage, (b) two-stage (low-salinity water), (c) two-stage (high-salinity water), (d) multistage/cascade (low-salinity water), and (e) permeate circulation process (PCP).

2.6.3.3 Cascade BWRO

To achieve higher water quantity and quality, several SWRO desalination plants use a cascade BWRO system similar to multistage systems (Figure 2.12d). The cascade system can be varied, but it is usually a set of BWRO systems where the first-pass permeate is treated by a BWRO multistage system (2–4 stages) to increase water recovery. Furthermore, the permeate produced from the rear BWRO stages is further treated by another set of BWRO stages to reduce TDS.

2.6.3.4 Permeate circulation BWRO

In contrast, a permeate circulation process (PCP) has been applied to BWRO systems (i.e., second pass) of Shuqaiq II SWRO desalination plants where the BWRO rear permeate is circulated back to the feed to improve water quality (Figure 2.12e) [11, 110]. Likewise, BWRO integrated with SWRO has been extensively adopted, even in SWRO desalination plants.

BWRO systems can be utilized for both treating brackish water and improving the water quality of SWRO systems. In other words, the role of BWRO will increase in the future desalination market, regardless of feed salinity. Because the main benefit of BWRO is a high-recovery operation, BWRO systems should be developed further to maximize their recovery while ensuring permeate quality.

2.7 POST-TREATMENT

The permeate of SWRO membranes is usually depleted in minerals and thus has a high corrosion potential. This makes SWRO permeate aggressive to the components of water distribution systems such as pipes, pumps, and tanks (when tankers distribute water). The aggressiveness of the SWRO permeate is controlled by increasing its hardness and alkalinity. However, in some cases where the intake is from the subsurface, there might be a need to remove carbon dioxide and hydrogen sulfide because subsurface intake water is high in carbon dioxide and hydrogen sulfide, which are not removed during the SWRO process.

In some SWRO plants producing potable water for industrial and domestic purposes, a portion of the pre-treated feed is blended with the SWRO permeate for many reasons, such as water stability, corrosion control, capital operating expenditure, and footprint reduction. The blending proportion is dependent on both the treated water quality and pretreated water quality. Blending can also be done with water from other sources, such as groundwater and potable water. Overall, blending improves the stability and taste/dietary components of SWRO-treated water. Blending seems to be an easy post-treatment strategy to overcome most of the challenges posed by SWRO permeates; however, there are concerns regarding the potential addition of anions such as bromide and iodide, which could cause disinfection byproducts in the treated water. Therefore, proper assessment of both the pretreated and post-treated water is essential to determine the ratio of blending for water quality control. The pretreated water to be blended with SWRO permeate must also be evaluated for microbial and chemical contaminants and duly removed before blending with SWRO permeate as they have the potential to compromise the safety of the treated water [111]. Blending should not allow the introduction of pathogenic microorganisms into the treated water. In the case where potable water from other sources is used to blend SWRO permeate, caution should be exercised in selecting piping materials to eliminate the possible leaching of contaminants from pipe materials [112]. Generally, blending is not sufficient for SWRO permeate stability; thus, the alkalinity and hardness of the water need to be increased. Nevertheless, appropriate blending reduces the quantity of chemicals required for corrosion control and stability.

SWRO plants have diverse post-treatment strategies depending on the use of the permeate as regulated by the authorities. However, conventional post-treatment steps in the SWRO process include stabilization and corrosion control, disinfection, and air stripping and degasification (especially of CO_2 and H_2S gases).

2.7.1 Stabilization and corrosion control

Permeate stabilization is believed to be one of the most essential aspects of the SWRO desalination process. Corrosion prevention would significantly reduce the frequency of pipes, pumps, and other distribution unit replacements and, in turn, reduce the operating costs of the process. However, stabilizing SWRO permeate could be demanding, as the chemical and dosage requirements differ from plant to plant. Therefore, each plant needs to be evaluated to assess its control needs when designing a permeate stabilization strategy. Over the years, SWRO plant operators have used three parameters to improve the stability of the SWRO permeate. These parameters included pH, alkalinity, and calcium carbonate adjustment. Each parameter has its own characteristics that can help improve the stability of the permeate within the process and during distribution.

2.7.2 pH adjustment

The pH of the SWRO permeate is mostly a factor of bicarbonate alkalinity and other elements such as calcium, sulfate, chloride, DO, total dissolved solids, and boron content. The pH of the permeate can be adjusted using sodium hydroxide, potassium hydroxide, carbon dioxide, lime, or soda ash. The pH of the permeate affects the metal ion dissolution potential and the precipitation of insoluble compounds. This means that metal material pipes can be prevented from corrosion by lowering their dissolution. The precipitation of insoluble carbonate on the surface of the pipes could serve as a coating agent to prevent corrosion. Insoluble carbonate was precipitated at an elevated pH (>8.4). The possibility of biofilm formation in the distribution pipes is lower if the permeate pH is adjusted to ≥ 9.0. pH adjustment may not be suitable for permeates with high hardness (>150 mg/L $CaCO_3$). Inappropriate pH could cause problems such as copper pitting, trihalomethane production ($pH > 8.1$), disinfection byproducts ($pH > 7.8$), $CaCO_3$ sealing ($pH > 7.9$), and growth of ammonia-oxidizing bacteria ($pH < 8$).

2.7.3 Alkalinity adjustment

The buffering capacity of the SWRO permeate is measured by its alkalinity. The corrosion tendency and susceptibility to pH changes by SWRO permeate are reduced at elevated alkalinity. Therefore, the alkalinity of the water is adjusted so that it can induce the precipitation of insoluble compounds on the surface of the water distribution units. The coating of distribution surfaces could help prevent corrosion and subsequently increase the lifespan of such distribution components. The alkalinity of the permeate is directly linked to the pH of water, bicarbonate, carbonate, and hydroxide ions. Alkaline water can easily produce H^+ and OH^- ions to neutralize the effect of pH change, thus stabilizing the water. Although alkalinity adjustment improves the buffering capacity of the permeate, there are still some challenges of operation and maintenance costs and high carbonate scaling on pipelines.

2.7.4 Hardness ($CaCO_3$) adjustment

Hardness (CaCO3) adjustment is often done to control the corrosion ability of the permeate. The goal of this approach is to develop a $CaCO_3$ film on the surface of the distribution unit. Usually, pH and alkalinity adjustment create an environment suitable for the precipitation of Ca and CO_3. The precipitation of these compounds is achieved by introducing CO_2, $CaCO_3$, soda ash, and lime into the water. The major challenge of this approach is that $CaCO_3$ films are not formed on the pipes alone but also in all the distribution units, such as pipes, pumps, and boilers. Similarly, this post-treatment strategy could also lead to sulfate precipitation.

2.7.5 Disinfection

The SWRO-treated water is temporarily stored before distribution. The treated water experiences microbial contamination. Therefore, disinfection is conducted to deactivate residual microbes in the treated water and protect it from subsequent microbial contamination during storage and distribution. The selection of disinfection chemicals depends on costs, safety, and availability [113]. Post-treatment disinfection is achieved with liquid or gas chlorine, production of hypochlorite on-site, calcium hypochlorite, and bulk hypochlorite. Chlorine disinfection is mostly used in SWRO processes. If the SWRO permeate is not contaminated with organic matter during remineralization, disinfection byproducts are not generated during the disinfection process. However, if the treated water is contaminated with disinfection byproduct precursors such as dissolved organics, chlorination would result in the generation of disinfection byproducts. Similarly, chlorine disinfection could also help in the removal of H_2S because of the ability of chlorine to react selectively with sulfides. Chlorine dosages between 5 and 10 mg/L is sufficient to preserve the water from microbial attack.

2.7.6 Aeration and degasification

When SWRO intake is from the subsurface or well, it is characterized by low DO and high H_2S. DO and H_2S are not eliminated during the desalination process, thus making their way to the permeate. Therefore, in this case, the permeate must be aerated and degassed before distribution. Aeration is performed to increase the DO content of the permeate, remove volatile organic compound contaminants, degas H_2S, and remove CO_2, consequently reducing the corrosion ability and increasing pH. The SWRO permeate is aerated either by allowing the permeate to fall through air or by injecting air into the permeate.

2.8 DISCHARGE

All SWRO plants, irrespective of their size, need to discharge their waste/concentrate. The discharge from the SWRO plant is usually from different sections of the SWRO process. These sections include waste from pretreatment units such as sludge (from sedimentation tank and DAF), backwash water, concentrate from membrane units (UF, NF, and RO), metals from corrosion and waste from processes, and membrane cleaning [114]. This discharge is characterized by physical properties (salinity, 65 000–85 000 ppm, temperature, 5–10°C of ambient seawater temperature, suspended solids and coagulants, antiscalants, metals, and cleaning chemicals [61, 115].

2.8.1 Conventional discharge strategy

The aim of conventional discharge is to release SWRO brine through an open pipe directly into the ocean deep without any detrimental impact on marine life. Because the density of seawater is a function of its salinity, SWRO brine tends to sink and dilute slowly on the seabed. Therefore, discharge pipes are often placed in locations where the discharge can be easily and quickly mixed with the receiving seawater. Sometimes, the pipes are equipped with diffusers (nozzles used to increase the mixing of the concentrate to prevent stagnation on the ocean floor). Alternatively, the effluent from the SWRO plant is mixed with the treated discharge from the sewage plant to dilute the brine. However, owing to the environmental impact of direct discharge into the ocean, SWRO effluents are generally treated before discharge to meet the discharge regulations of the region.

When designing or deciding the proper discharge site in the open ocean discharge, it is important that the concentrate is not discharged in locations with stressed and endangered marine ecosystems. It is equally important to discharge concentrate in locations where there is a strong underwater current for the accelerated mixing of the concentrate.

2.8.2 Discharge to injection wells

Injection well systems are considered environmentally benign discharge methods, and an injection zone is available that can accept the discharge without any significant perturbation to marine life. Injection wells are of two types: shallow and deep wells. The deep-well system is usually hundreds of meters below the land surface, and the discharge is expected to remain underground permanently. Generally, the injection well discharge method is characterized by injecting SWRO waste into an underground aquifer isolated from other water aquifers. It is important that the aquifer has the capacity to collect such waste through the life of the SWRO plant (usually 25–30 years) [116].

2.8.3 Discharge to offshore galleries and trenches

The SWRO concentrate and waste are discharged into the infiltration trenches. Infiltration trenches are mostly perforated pipes buried parallel to the beach. This discharge method is used in small-scale desalination plants. One advantage of infiltration trenches is their ability to slowly diffuse SWRO brine offshore without any significant impact on marine life. Large-scale SWRO desalination plants can use the beach gallery method because the brine can be discharged via the top of the gallery, unlike in infiltration trenches, where pipes are run horizontally along shallow sediments.

2.8.4 Zero liquid discharge (ZLD)

Owing to increasing concerns of indiscriminate discharge and its impact on the environment, regulatory bodies are implementing stricter discharge requirements that are often difficult to meet by conventional discharge methods [117]. Therefore, it is a matter of urgency to use discharge strategies that will satisfy the requirement for discharge and, perhaps during the process, improve the performance and the efficiency of the entire process. ZLD is considered one of the safest discharge methods, without any significant adverse effects on the environment. This method is beneficial for SWRO plants located in inland regions. ZLD can be achieved using evaporation ponds, crystallizers, and spray dryers.

In the evaporation pond discharge method, the SWRO effluent collected in an impervious lined shallow earthen basin can slowly evaporate by utilizing energy from the sun. The impervious lining is essential to prevent waste from contaminating underground aquifers. After the water is completely evaporated, the remaining solid waste is collected and disposed of. The major drawback of this approach is the requirement for a large expense of land, which could significantly increase the plant's capital costs. This method is also limited to dry and semi-arid regions.

Crystallizers are cylindrical vessels that can be heated by either a steam source or a vapor compressor to produce a crystal/precipitate. Crystallizers can be used to achieve ZLD in SWRO discharge without the need for frequent cleaning and excessive scale development.

Spray dryers are an alternative to crystallizers for producing salt crystals from SWRO brine. The advantage of spray dryers over crystallizers is that in spray dryers, the product shape, size distribution, and density can be controlled [118].

2.8.5 Dilution of concentrate using forward osmosis process

The forward osmosis (FO) process is a promising SWRO concentrate diluting technology owing to its ability to use an osmotic pressure gradient to draw water. In the FO process, a high saline SWRO concentrate is used to draw water from the domestic wastewater and in so doing, the SWRO concentrate is diluted by the automatically treated wastewater. Although this approach has not yet been commercialized for discharge, it is a promising discharge method suitable for meeting the discharge requirements.