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Needed seawater reverse osmosis pilot plant in Qatar

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ABSTRACT

Seawater reverse osmosis (SWRO) is the most cost-effective, practical, and widely used desalting system. Its energy consumption, for Arabian Gulf seawater conditions is in the range of 5–6 kWh/m^3. These are less than 1/3 of the equivalent mechanical energy of the thermal desalination systems presently used in Qatar. Besides, these thermal systems consume 2–4 kWh/m^3 for pumping. Therefore, using SWRO system in Qatar can save up to 75% of the desalination energy cost. For Qatar, current desalting water production using thermal methods is 480 Mm^3/year at $0.1–1.2/kWh energy price; the energy cost is at least one Billion US dollars per annum. A SWRO pilot plant is to be built in Qatar prior to building a full size desalting plant (DP) in order to determine site-specific treatment guidelines and to provide a full range of performance information to be used in the design of a full-scale plant. The pilot plant will be tested when the feedwater quality is good, and when there are major storm events or algae blooms exist. Red tide events in 2008–2009 forced many DPs in Gulf Co-operation Countries area to shut down. This paper reviews the SWRO pretreatment process, which depends on local conditions and is the main factor affecting the SWRO reliability. These include the extensively used conventional pretreatment of coagulation–flocculation and granular media filtration (GMF). This is almost necessary for open sea intake. Sever red tide blooms, when occur, cause clogging of GMF, resulted in biological and organic foulants on SWRO membranes, and even DP shut down. So, low-pressure membranes such as ultrafiltration (UF) or microfiltration (MF) can replace or integrated with GMF. Since flotation is more robust than sedimentation (used in GMF) in dealing with high concentration of suspended matter, dissolved air flotation is started to be used as pretreatment. Since it is a new method that met success in several plants, it thoroughly reviewed in this paper when integrated with GMF or membrane treatment. Additionally, the expensive pretreatment with UF and MF is discussed with given examples. Preliminary experimentation with SWRO pretreatment in Qatar was presented. Moreover, energy recovery devices to be used with the pilot SWRO are discussed. Membranes configuration and the equipment to be included are also outlined.

Keywords: Seawater reverse osmosis; Energy consumption for desalination; SWRO pilot plant; Energy recovery system; SWRO pre-treatment; Algae blooms

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1. Introduction

Qatar desalted seawater (DW) production, increased from 178 Mm^3/year in 2004 to 373 Mm^3/year in 2010, at annual average increasing rate of 18%. The DW production may reach 489 Mm^3/year in 2014 if the annual increase rate is reduced to only 7% from 2010 to 2014. DW is presently produced in Qatar by multi-stage flash (MSF) and multi-effect thermal vapor compression (ME-TVC) desalting systems. The MSF system consumes about 270 MJ/m^3 thermal energy (per m^3 of DW) in the form of steam, at an average temperature of 120˚C, besides specific pumping energy about 4 kWh/m^3. The MSF specific consumed equivalent energy (SEC), in terms of mechanical (or electrical), including thermal and pumping is about 20 kWh/m^3. The ME-TVC has almost the same SEC as the MSF system. The ME-TVC consumed thermal energy is similar to that of MSF system but using steam of relatively higher pressure than that used in the MSF system; and specific pumping energy is about 2 kWh/m^3. So, the energy consumed by desalting units in 2014 can be estimated as 9,779 GWh at a cost of $M 1,173, if the cost of one kWh is $0.12/kWh. If the 2014 DW production (489 Mm^3/year), was produced by seawater reverse osmosis (SWRO) desalting system consuming only 5 kWh/m^3 of DW, the energy cost would be $M 293, or annual saving of $M 880/year (or 75%). This is enough reason to adopt the use of SWRO in place of MSF or ME-TVC system. The use of SWRO is the common practice worldwide, except in the Gulf Cooperation Countries, where the fuel cost is underestimated, and the SWRO is considered unreliable because the complexity of SWRO feedwater pretreatment. Proper pretreatment of the feed SW is essential to ensure reliable performance of any SWRO plant.

Prior to building full-size SWRO desalting plant (DP) in a particular site, a SWRO pilot plant has to be installed and tested in order to determine the required specific pretreatment for this site and to provide a full range of performance information that can be used in the design of the full-scale plant. Testing in the pilot plant should be conducted when seawater quality is normally good and when there is major storm events or algae blooms (i.e. red tides); and this should be applied for Qatar.

Therefore, the main objectives of building SWRO pilot plant in Qatar are to enable the designer of the full plant to choose:

(1) The most suitable pretreatment for seawater (SW) feed before its inlet to the SWRO membranes.
(2) Best brine energy recovery devices (ERD) in terms of efficiency, reliability, and ease of operation.
(3) Best configuration of SWRO membrane modules for the least consumed energy.
(4) Effective method to prevent (or reduce) fouling in order to have reliable and easy operation.

This paper reviews the membrane fouling and the equipment needed to be included in this pilot plant. The suggested capacity of the pilot plant is 400 m^3/d and consists of two trains of 200 m^3/d permeate capacity each for possible testing of the following pretreatment methods, namely:

(1) Dissolved air floatation (DAF) plus ultrafiltration (UF).
(2) DAF + granular media filtration (GMF) and cartridge microfilters.
(3) Multimedia filtration.

Several spiral wound membrane types should be tested, e.g. Toray, Dow, and others. The plant is to be equipped with turbo charger (assembled high-pressure (HP) feedwater pump with centrifugal turbine operated by the brine using the same shaft). Future considerations of using:

(1) Separate HP pump and Pelton wheel turbine.
(2) Separate HP pump and pressure exchanger (PX).

Table 1 gives the SW analysis in Ras Abu Fontas (RAF-B) in the East and Dukhan in the West of Qatar. The table shows very high salinity of SW in Dukhan. The turbidity in both locations is good (<3). However, the good water quality conditions do not prevail all the year. SW temperature and salinity variations are shown in Fig. 1, as given in [1].

2. SWRO pretreatment technologies

The selected pretreatment procedures and the process engineering that determines the SWRO facility design are entirely dependent upon the quality of the SW source and its variations, especially, if it is coming from an open SW intake. Although the reverse osmosis (RO) membranes are the heart of the SWRO desalination process, selection and proper operation of the pretreatment system is essential for successful and reliable operation of the downstream desalination process.

Table 1
SW analysis in RAF and Dukhan [1]

Parameter	Location		Units
	RAF-B	DUKHAN	
pH	8.15	8.17	
Conductivity	62,500	77,000	μs/cm
TDS	44,276	57,507	ppm
Total hardness	7,900	10,690	ppm as $CaCO_3$
Calcium hardness	1,160	1,380	ppm as $CaCO_3$
Magnesium hardness	6,740	9,310	ppm as $CaCO_3$
Total alkalinity	119	128	ppm as $CaCO_3$
Bicarbonate	145	156	ppm
Calcium	464	552	ppm as Ca
Magnesium	1,618	2,234	ppm as Mg
Sulfate	3,100	4,150	ppm as SO_4
Sodium	11,800	13,200	ppm as Na
Chloride	24,530	31,866	ppm as Cl
Bromide	74	78	ppm as Br
Copper	0.06	0.08	ppm
Iron	0.22	0.03	ppm
Silica	0.8	0.9	ppm as SiO_2
Ammonia	0.4	0.45	ppm
Free chlorine	0.32	0.02	ppm
Suspended solids	5.4	5.8	ppm
Turbidity	2	2.2	NTU

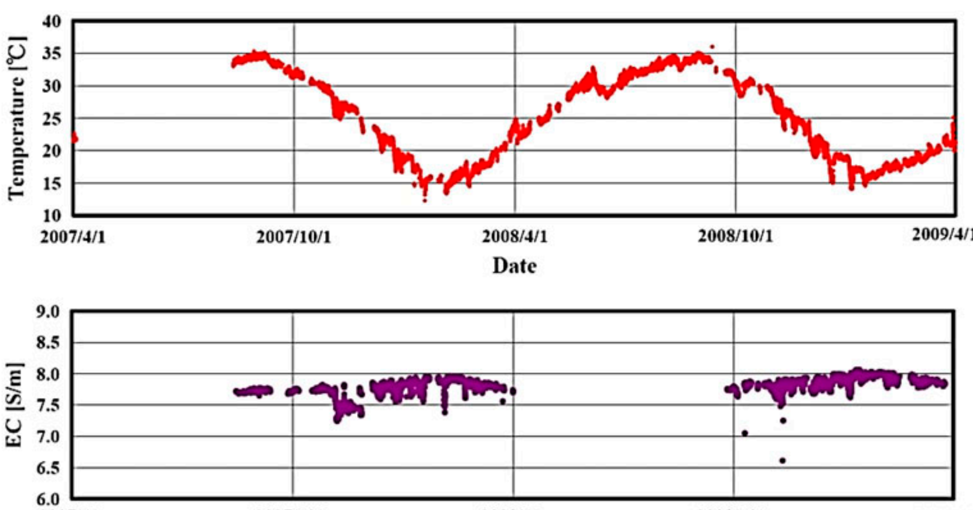

Fig. 1. Temperature and electric conductivity of SW [1].

The pretreatment in general, consists of the intake and screening systems, removal of particulate matter, control of biological growth, and chemical conditioning of the SW feed to the membranes. Open surface SW has higher membranes fouling tendency and requires extensive pretreatment compared with the beach well waters. Use of beach well water feed is limited to low capacity SWRO systems. Maintaining constant high feed quality SW is the main factor for successful SWRO operation, as most failures are actually due to pretreatment failures. The feed SW quality is usually expressed by turbidity, silt density index

(SDI), total organic carbon (TOC), critical flux (the maximum membrane flux above which colloidal fouling will occur for a particular pretreated water), red tide algal bloom events, and colloidal destabilization caused by chemical dosing such as chlorine. Although these parameters provide useful data for the design and operation of pretreatment system, no model currently exists that can predict with certainty the fouling rate in the SWRO plants. For this reason, careful monitoring is essential for operation and maintenance of the SWRO system [2].

There is evidence that algae can be a major cause of operational problems in SWRO plants, when intakes are from raw water where algal blooms frequently occur. An algal bloom is a "population explosion" of naturally occurring microscopic algae, triggered mainly by seasonal changes in temperature, abundance of sunlight, and/or high nutrient concentration in the water. Some algal blooms are considered harmful because the causative algal species produce toxic organic compounds which can cause illness/mortalities to humans and/or aquatic organisms. However, some harmful algal blooms do not produce toxic compounds but the algal biomass and algal organic matter (AOM) can accumulate in dense concentrations near the water surface. Bacterial degradation of this organic material can lead to a sudden drop in dissolved oxygen concentration in the water and eventually cause mortalities of aquatic flora and fauna. Recently, the desalination industry realized the negative effects of algal blooms, which started to gain more attention during the severe "red tide" bloom in the Gulf of Oman between 2008 and 2009. That algal bloom forced several SWRO plants in the region to reduce or shutdown operations due to clogging of pretreatment systems components (i.e. granular media filters) and/or due to unacceptable RO feedwater quality (i.e. SDI > 5) which triggers concerns of irreversible fouling problems in the RO membranes [2–6].

Advancements in pretreatment techniques can be adequately piloted or demonstrated for any given feed SW due to the unpredictable nature of SW. Performance of SWRO is site specific, and each site should be investigated for proper choice of the SWRO pretreatment. There is tendency to use UF/microfiltration (MF) instead of the conventional treatment to provide SDI values well below two, which thus enables an SWRO plant to perform at its original design capacity with reduced downtime. The use of larger pore size membranes such as UF and MF has gradually gained acceptance in recent years as the preferred pretreatment for SWRO, see Fig. 2. Pilot and/or full-scale plants have been operated in many parts of the world

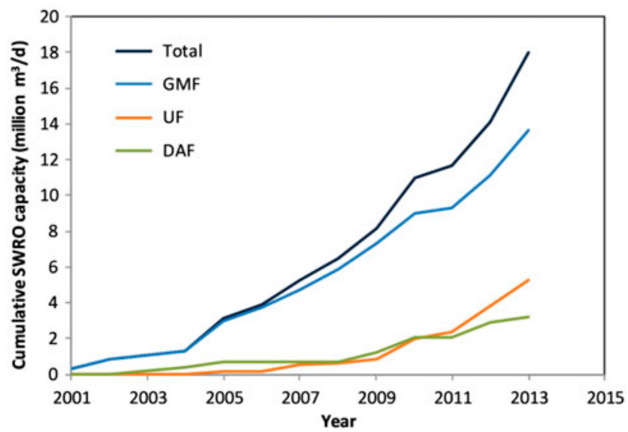

Fig. 2. Comparison of production capacity of 49 largest SWRO plants installed between 2001 and 2013 in terms of pretreatment technologies: GMF, UF, and DAF. DAF pretreatment system is always installed in combination with GMF and/or UF pretreatments [3].

to examine the capacity and reliability of UF/MF pretreatment systems in preparing compatible feedwater for the SWRO membrane.

2.1. Conventional pretreatment

Conventional pretreatment, typically, consists of coagulation–flocculation and media filtration using various filtration media, Fig. 3. In coagulation step, a coagulant is added to SW before sand or multi-media filters to enhance removal of suspended particles. Single and/or two-stage filters can be utilized. GMF is a proven technology that has lower operation and maintenance costs compared with membrane filtration. It has large footprint, effluent water quality is highly dependent on feedwater quality, and is extensively used for SWRO plants.

2.1.1. Granular media filtration

The most common pretreatment for open SW is the granular media filters. It is possible to use a single-stage filtration if the feedwater is constantly of high quality (Fig. 3). There are two principle types of GMF: rapid filters and slow sand filters. Slow sand filters are very efficient in removing micro-organisms from water. Rapid filters are used primarily to remove turbidity after coagulation and flocculation (Fig. 4). The GMF can use dual layers of sand and anthracite (garnet is sometimes used), and typically applied in gravity or pressurized configuration. Sand and anthracite (0.8–1.2 mm/2–3 mm) filter beds are superior to single media filtration as they provide higher filtration rates, longer runs, and require less backwash water [3].

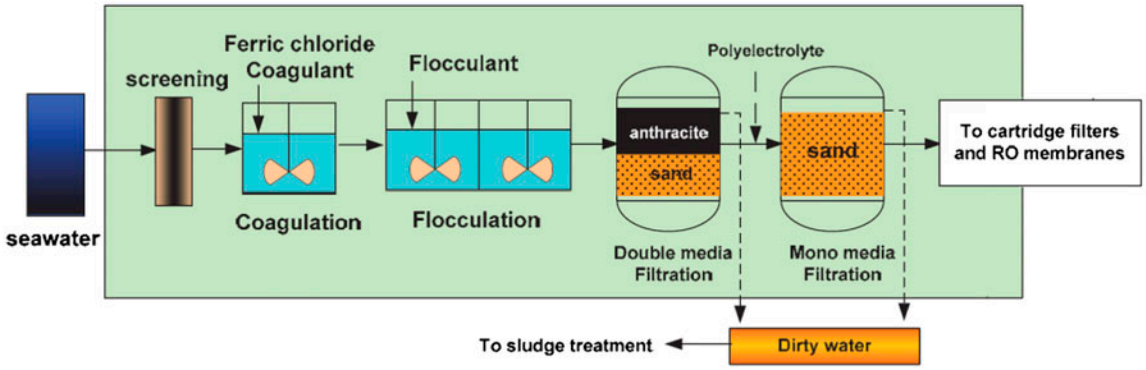

Fig. 3. Principle of coagulation–flocculation with double stage filtration system [7].

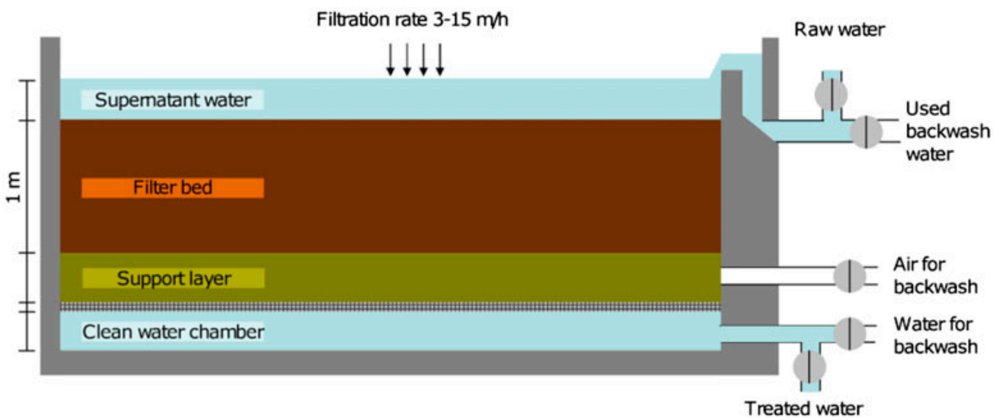

Fig. 4. Open-top gravity rapid filter with air scour backwash system [8].

Anthracite/sand/garnet beds have operated at normal rates of approximately 12 m/h and peak rates as high as 20 m/h without loss of effluent quality. The primary function of GMF in SWRO pretreatment is to reduce high loads of particulate and colloidal matter (i.e. turbidity). GMF relies on depth filtration to enhance the feedwater quality. High organic matter concentrations or turbidity loads may necessitate the use of coagulation to ensure RO feedwater of acceptable quality; (SDI < 5). Coagulation is applied either in full scale or inline mode in these systems. The commonly applied coagulant in SWRO pretreatment is ferric salts (i.e. ferric chloride or ferric sulfate).

Poor removal of algae can lead to clogging of GMF and short filter runs. While diatoms are well-known filter clogging algae, other algae types can clog filters including green algae, flagellates, and cyanobacteria [9].

In case of open SW intake, the use of coagulants and sedimentation or flotation equipment may be necessary, followed by GMF. The GMF needs to be carefully designed and diligently operated. Its use has not been able to adequately pretreat the feed raw SW in several instances. Challenging raw SW supplies, as in the Arabian Gulf, can result in large amounts of particulate and organic foulants on SWRO membranes. Some of the SWRO DPs using open SW intake and employ conventional pretreatment with chemical coagulation, clarification, and GMF experienced severe fouling: biological, organic, particulate, or scaling. In many cases, shutdowns and cleanings every 1–6 months and membrane replacement every 3–6 years were needed. Some plants in the Arabian Gulf were shutdown during red tide events accompanied with increased rates of fouling in 2008–2009. Biological fouling is of particular concern as it increases the power required for desalination and is often difficult to remove without harsh cleaning solutions that increase membrane replacement frequency to achieve water quality objectives.

Alternatively, GMF can be replaced by low pressure (LP) membrane systems such as UF or MF. So, GMF is to be integrated with other processes, although it can be the main process. Filtration is an essential mechanical operation with the goal to trap particles larger than 10 μm (100,000 Å). In GMF, interception, gravitational sedimentation, and Brownian diffusion are the key mechanisms of colloidal particle transport from the pore fluid to the surface of a filter grain [10].

During the severe red tide bloom event in the Gulf of Oman and Persian Gulf in 2008–09, conventional pretreatment systems were not able to maintain production capacity and resulted in treated water quality at high algal cell concentrations of approximately 27,000 cells/mL, [5]. Operation of GMF was characterized by rapid clogging rates and deteriorating quality of pretreated water. As a result, frequent backwashing was required with increased downtime and required pretreatment capacity could not be maintained. At the Fujairah plant in UAE, filter runs were reduced from 24 to 2 h. Moreover, deteriorating quality of the pretreated water, i.e. SDI > 5, led to the increased dosage of coagulant to enhance treated water quality. Increasing coagulant dose can lead to higher clogging rates of media filters. Coagulation enlarges particulate and colloidal matter in SW and can therefore shift filtration mechanism from standard blocking (depth filtration) to surface blocking (cake filtration). As filtration rates are relatively high (5–10 m/h) in media filters, cake filtration can result in exponential head loss in the filters.

Reducing filtration rates of the media filters during such extreme events can enhance operation. Reducing the rate of filtration by 50% will result in much lower clogging rates, e.g. by a factor 2–4 depending on the size and characteristics of the foulants (e.g. algae). However, reducing filtration rates will require increased surface area of the media filters. This implies significant investment costs and larger foot print of the treatment plant. Another way to enhance operation of GMF during such extreme events is to provide a clarification step, e.g. sedimentation or flotation, after coagulation–flocculation to reduce the load of particulate-colloidal matter (including coagulated flocs) on the media filters.

Flotation is more robust process than sedimentation as it can handle large concentrations of suspended matter (e.g. algae). Currently, flotation preceding media filtration is proposed as the solution for algal blooms. Flotation can reduce the algal concentration to a large extent, protecting media filters from rapid clogging, reduced capacity, and breakthrough. However, a coagulant dose of 1–2 mg Fe^{3+}/L or higher is usually required to render the process effective. Furthermore, coagulant might be required upstream of the media filters to ensure an acceptable SDI in the effluent.

Installing flotation units in front of media filtration might be cheaper than sedimentation units, as the surface loading rates in high-rate DAF systems can reach 30 m/h [9]. Consequently, flotation may require much lower footprint than sedimentation. However, the process scheme will require flocculation basins, air saturation, and sludge treatment facilities.

2.2. Dissolved air flotation

Application of DAF in SWRO plants pretreatment is new, and some review on that process is given here. The DAF process can clarify feed SW by removing suspended matter such as oil or solids. The removal is achieved by dissolving air in the water under pressure and then releasing the air at an atmospheric pressure into a flotation tank or basin. The released air forms tiny bubbles which adhere to the suspended matter causing the suspended matter to float to the surface of the water where it may then be removed by a skimming device.

The feedwater to the DAF float tank is often (but not always) dosed with a coagulant (such as ferric chloride or aluminum sulfate) to flocculate the suspended matter, see Figs. 5(a–c), 6 and 7. A portion of the clarified effluent water leaving the DAF tank is pumped into a small pressure vessel (called the air drum) into which compressed air is also introduced. The resulted saturated pressurized effluent water with air is recycled to the front of the float tank and flows through a pressure reduction valve just as it enters the float tank. The released air, in the form of tiny bubbles, has rising velocity higher than the water velocity and the air bubbles will thus collide with the flocs in water. The density of the aggregates decreases to values below the water density. As they rise to the surface, the buoyant flocs form a stable sludge layer over the water surface. Mechanical scrapers skim the solids from the surface into a collecting bin. When surface scrapers are used, sludge with dry solids content in excess of 2–3% may be produced. The bubbles size greatly affects the efficiency of the flotation process, with bubbles (30–100) μm considered the most effective. Air bubbles of 20–50 μm are considered the best for the recovery of fats. The air to solids ratio has a major effect on the performance of a DAF unit. Clarified water is drawn off the bottom of the tank by a series of lateral draw-off pipes. Conventional DAF systems operate at nominal hydraulic loading rates of 5–15 m/h. More recent DAF units are developed for loadings of 15–30 m/h and greater. As a result, DAF

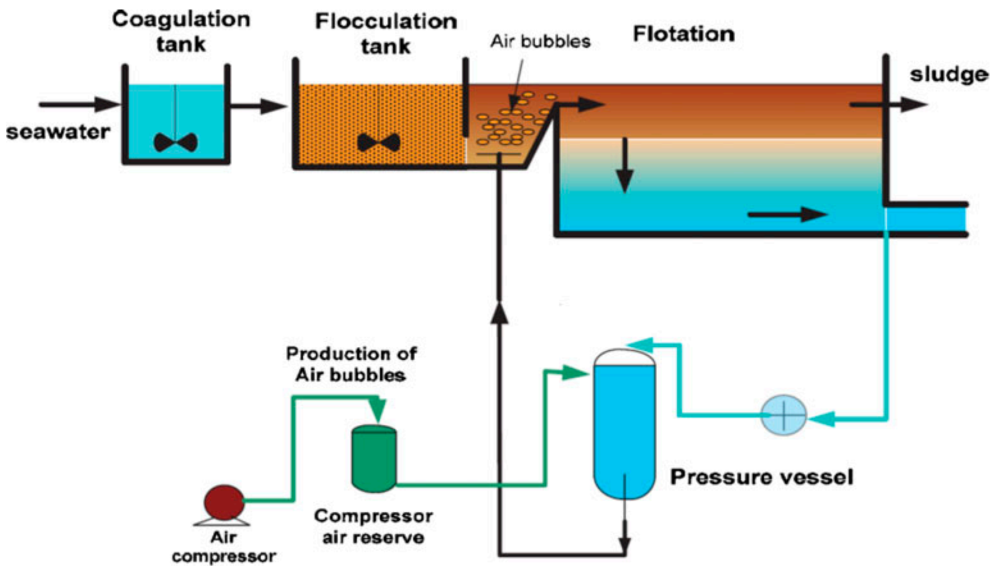

Fig. 5(a). A sketch of a typical DAF unit.

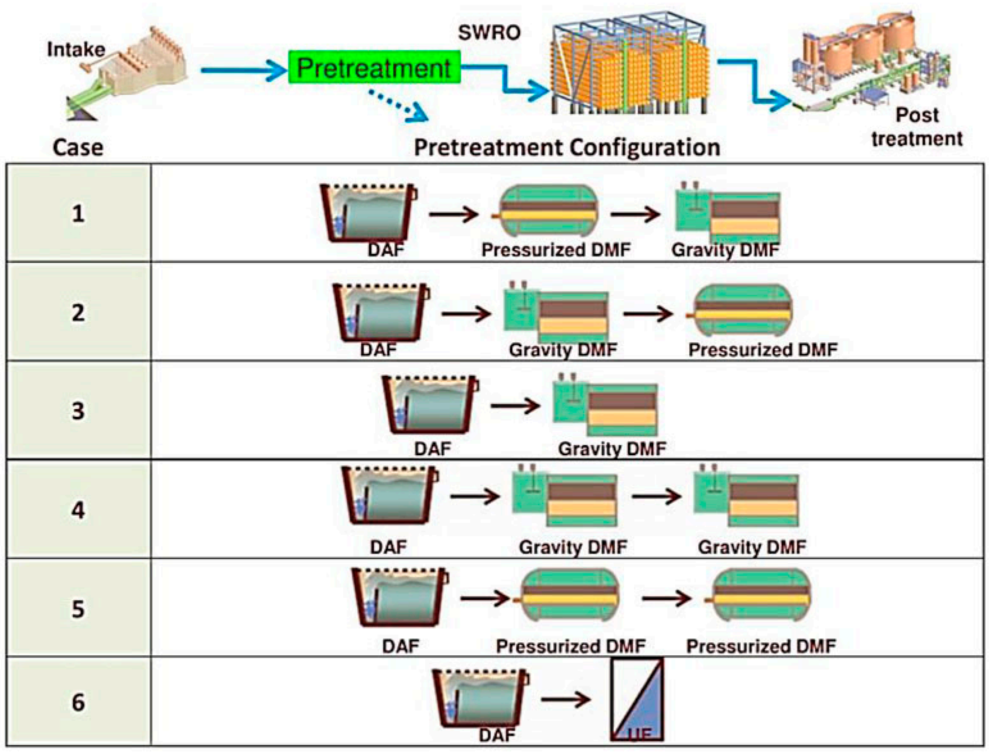

Fig. 5(b). A sketch of typical DAF followed by other filtration processes [11].

requires a smaller footprint than sedimentation. Depending on the raw water quality and the efficiency of mixing of the recycle stream with the flocculated water, the amount of recycle required typically lies somewhere between 8 and 12% of the influent flow. Typical DAF is usually preceded with coagulation and flocculation as shown in Fig. 5(a), and followed by GMF or UF as shown in Figs. 5(b) and (c).

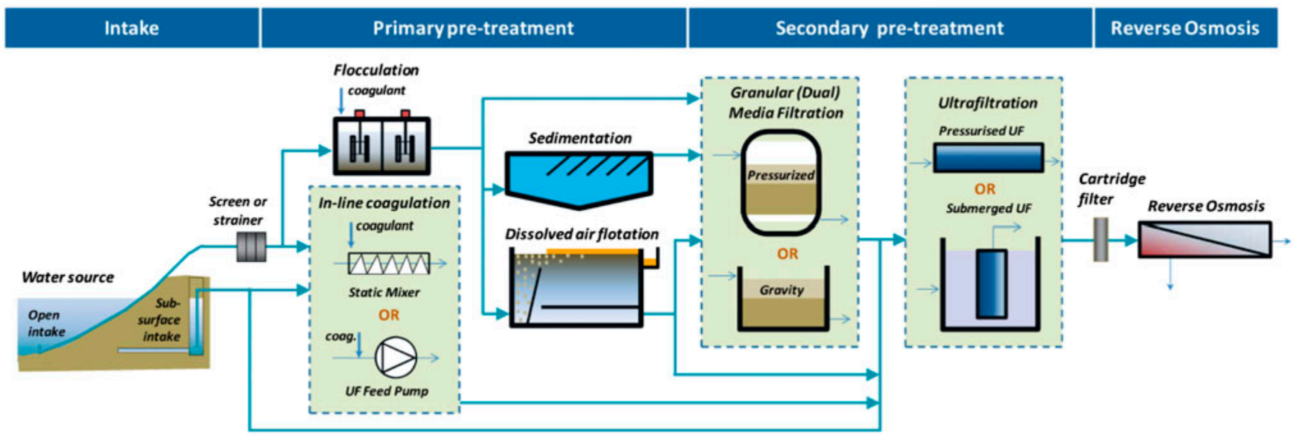

Fig. 5(c). Process diagram of typical DAF pretreatment system proceeded by coagulation and followed by UF or submerged UF [3].

Fig. 5(c) shows many schemes that can be used with the DAF pretreatment and include in-line coagulation (before the DAF tank), gravity of pressurized GMF, UF, and MF [3].

DAF is believed to be one of the best-suited processes to remove oil from SW. If oil was to get through the flocculation zones onto the flotation zone as free oil it will most likely be trapped by the microbubbles and be floated off into the sludge blanket for removal along with the flocs. The percent removal is around 90%. The filtration stage will not remove oil content; it is why the DAF has to be well designed to ensure the system operates against oil presence.

One of the main applications of DAF is the removal of algae [7]. Algae are difficult to remove by conventional treatment such as sedimentation, as they are naturally less dense than water, and do not settle well. Poor removal of algae (diatoms, green algae, flagellates, and blue green algae) can lead to clogging of granular media filters and short filter runs. The 99–99.9% removal of algae that can be obtained with DAF is more effective compared with sedimentation of 60–90% removal [7]. Algal species typically are characterized by a negative surface charge in natural water environments. Algal destabilization by charge neutralization was achieved through chemical coagulation and flocculation. Maximum filterability of suspended algae was observed when algal cells were destabilized in aggregate form. Poor removal of algae (diatoms, green algae, flagellates, and blue green algae) can lead to clogging of granular media filters and short filter runs.

Gaid [7], stated that if the chemistry is right, the chances of achieving the treated water quality is much better with DAF followed by Filtration than with any other process and that could possibly include membrane filtration. The reason for this is: the very small particles that make up the material collected on the filter paper when measuring SDI is the very small material that for some reason is not captured in the floc or did break away from the floc and has a density equal to or even a little lighter than water [12].

DAF systems can have the circular shape (more efficient), shown in Fig. 6, or rectangular shape (more residence time), shown in Fig. 7. The former type requires just 3 min. The rectangular type requires 20–30 min.

Bonnélye et al. [13] and Huehmer and Henthorne [15] presented literature review on the DAF application in SWRO. Cleveland et al. [16] studied the use of DAF as UF pretreatment for algal-laden surface water. They found that the UF flux could be increased 70% following DAF pretreatment, resulting in substantial reductions in capital costs. The results of research performed by Braghetta et al. [17] similarly, showed enhanced UF membrane performance following DAF. Recently, DAF has been extensively piloted in SW applications. Extensive piloting conducted in El Coloso, Chile indicated that three-stage flocculation, DAF, and two-stage filtration were able to produce RO feedwater with SDI less than four (typically less than three) over a wide range of operating parameters when treating SW possessing high concentrations of algae and zooplankton with maximum turbidity of 2 NTU [18]. DAF was suggested to enhance the robustness of the SWRO pretreatment scheme in case of oil spills or algal bloom events, and in case high coagulant concentrations were required during turbidity spikes. Algal cell concentrations were reportedly below 100 cells/mL during this period, which is far

Fig. 6. Conventional DAF on open SW intake in Tarragona, Spain, [13].

below concentrations observed during severe bloom conditions. Sanz et al. [18] demonstrated the effectiveness of DAF coupled with coagulation prior to dual stage GMF in producing RO feedwater with SDI < 4 (typically less than 3) when treating SW containing various algae, including red tide species [18].

Rovel [19] reported successful use of DAF in pilot testing for the Taweelah SWRO plant in Abu Dhabi, conducted in 2002–2003. In this application, DAF was placed upstream of each of three filtration processes: two-stage dual media GMF, submerged UF, and pressurized UF. The DAF was shown to achieve on average a 20–35% removal of organics as measured by UV absorbance. DAF was also expected to be useful during rough sea conditions to reduce turbidity, during oil spills to remove micronic oil droplets, and during algae and planktonic blooms. The Al-Taweelah SWRO full-scale plant uses DAF before two-stage media filters. When coupled with optimized coagulation chemistry and media filtration, DAF was capable of producing SW feed having SDI less than four, with values of less than three frequently achieved.

Fig. 7. Horizontal dissolved air flotation system, (DAF) [14].

Le Gallou et al. [20], reported higher than 99% removal of algal cells during pilot testing of coagulation AquaDAF™ prior to GMF in Al-Dur, Bahrain. However, real bloom conditions were not encountered during the pilot phase with algal cell counts reaching only 200 cells/mL. The Al-Shuwaikh desalination plant in Kuwait was equipped with DAF/UF as pretreatment, and consistently provides SDI < 2.5 for good quality feedwater and SDI < 3.5 for deteriorated conditions during a red tide event [6].

Full-scale facilities using DAF as pretreatment for SW DP exist in El Coloso, Chile; Tarragona, Spain; Atacama, Chile; Mejillones, Chile and Tuas, in Singapore [18]. The largest constructed to date, the Tuas desalination Plant in Singapore utilizes DAF and single-stage filtration (F) process, and thus called DAFF as pretreatment to SWRO [21]. This system has met with good success during piloting prior to plant construction but has been less successful in the full-scale facility. The Tuas DAF is designed with filter loading of 8 m^3/m^2 using 1,100 mm of medium sand with a recycle rate of up to 15% and utilizing preflocculation.

DAF is also being demonstrated preceding two-stage filtration at the Layyah site in Sharjah, UAE for the 1,000 m^3/d GrahamTek RO Demonstration Plant, and will also be used in the 23,000 m^3/d SWRO facility presently under construction at this site using conventional SWRO desalination. Early results from this demonstration indicate the pretreatment system consistently provides SDI values less than three.

Several full-scale applications appeared early in Europe (Spain) and in South America [22] and [23]. The first DAF built at the end of 1980 as pretreatment for RO desalination was the pretreatment upgrading of the Almaraz nuclear power Plant in Spain, supplied by brackish water. The initial pretreatment included decarbonation followed by sand filters and RO before the demineralization resin. Due to feedwater degradation (organics, algae, ... etc.), the upgrading consisted of the construction of a pre-ozonation followed by a conventional DAF unit. De-carbonation was also improved by the use or an external recirculation of sludge before cartridge filters, SDI was below 0.5. Those plants, generally are small units, use ferric chloride as coagulant, a flocculation aid, and are followed by a one-stage filtration unit.

DAF is more effective than sedimentation in removing low-density particles from water and is therefore a suitable treatment process for algal bloom-impacted waters. Gregory and Edzwald [24] reported 90–99% removal by DAF of algal cells of different types compared with 60–90% by sedimentation. A review paper on separation of algae by Henderson et al. [25] reported DAF removals of 96–99.9% of algae when pretreatment and DAF are optimized. Advancements in pretreatment techniques can be adequately piloted or demonstrated for any given feedwater due to the unpredictable nature of SW. Performance of SWRO is site specific, and each site should be investigated for proper choice of the SWRO pretreatment. There is tendency to use UF/MF instead of the conventional treatment to provide SDI values well below two, which thus enables an SWRO plant to perform at its original design capacity with reduced downtime. The use of larger pore size membranes such as UF and MF has gradually gained acceptance in recent years as the preferred pretreatment for SWRO. Pilot and/or full-scale plants have been operated in many parts of the world to examine the capacity and reliability of UF/MF pretreatment systems in preparing compatible feedwater for the SWRO membrane.

2.3. Ultrafiltration

The application of LP membranes, MF, UF, and nanofiltration (NF) as pretreatment for SWRO is new and provides better pretreatment for SWRO DP; but at high capital and operating costs. Fig. 8, Table 2, and Fig. 9 illustrate the spectrum of each type of the mostly used membrane filtration.

MF removes particles in the range of approximately 0.1–1 µm, see Fig. 8. In general, suspended particles and large colloids are rejected while macromolecules and dissolved solids pass through the MF membrane. Applications of MF include removal of bacteria, flocculated materials, or total suspended solids. Transmembrane pressures are typically 10 psi (0.7 bar).

UF provides macromolecular separation for particles in the 20–1,000 Å range (up to 0.1 µm). All dissolved salts and smaller molecules pass through the membrane. Items rejected by the membrane includes colloids, proteins, microbiological contaminants, and large organic molecules. Most UF membranes have molecular weight cut-off values between 1,000 and 100,000. Trans-membrane pressures are typically 15–100 psi (1–7 bar).

NF refers to a special membrane process which rejects particles in the approximate size range of 1 nm (10 Å); hence, the term NF operates in the realm between UF and RO. Organic molecules with molecular weights greater than 200–400 are rejected. Moreover, dissolved salts are rejected in the range of 20–98%. Salts which have monovalent anions (e.g. sodium chloride or calcium chloride) have rejections of 20–80%, whereas salts with divalent anions (e.g. magnesium sulfate) have higher rejections of 90–98%. Typical applications include removal of color and TOC from surface water, removal of hardness or radium from well water, overall reduction of total dissolved solids (TDS), and the separation of organic from inorganic matter in specialty food and wastewater applications. Trans-membrane pressures are typically 50–225 psi (3.5–16 bar). The application of NF is usually used to increase the recovery ratio of the RO system, and not for removing particulates. Therefore, MF/UF is the most used technology as pretreatment

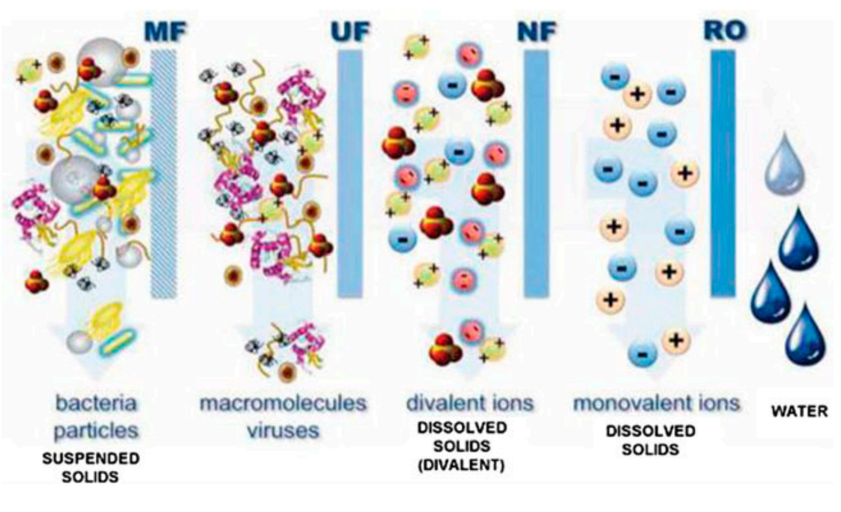

Fig. 8. Contaminants which can be removed by membrane filtration processes [3].

Table 2
Characteristics of different membrane filtration processes [3]

Process and abbreviations	Pore size (nm)	MWCO[a] (kDa)	Pressure (bar)	Materials typically retained
Microfiltration (MF)	50–5,000	>500	0.1–2	Particles + large colloids + large bacteria
Ultrafiltration (UF)	5–50	2–500	1–5	As above + small colloids + small bacteria + viruses + organic macromolecules
Nanofiltration (NF)	<10	0.2–2	2.5–20	As above + multi-valent ions
Reverse osmosis (RO)	<<1	<0.2	10–100	As above + mono-valent ions

[a]Molecular weight cut-off = molecular weight of solutes with similar weight of which 90% were rejected by the membrane.

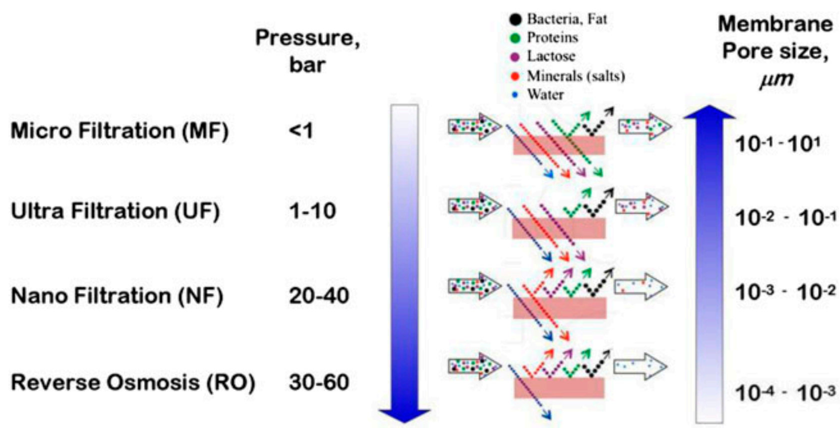

Fig. 9. Membrane filtration principles [26].

to SWRO and provides very low SDI water, compared with conventional filtration.

The membrane pretreatment for SWRO plant includes: (1) Coarse and fine screens similar to these used for plants with conventional pretreatment; (2) Microscreens to remove fine particulates and sharp objects from the SW which could damage the membranes; and (3) UF or MF membrane system [27], see Fig. 10. The use of cartridge filters between the pretreatment and SWRO membranes is not needed, since the membrane filtration media size is an order-of-magnitude smaller than the size of the cartridge filters. However, some conservative designs incorporate cartridge filters to provide protection against the particulates that may be released into the filter effluent due to MF or UF fiber breakage. UF is an alternative (and more reliable) to conventional GMF (with and without coagulation) for feed SW pretreatment in SWRO systems. UF membranes were tested and applied at pilot and commercial scale in SWRO plant as pretreatment. When compared with conventional pretreatment systems, UF has lower footprint, constant high permeate quality (in terms of SDI), higher retention of large molecular weight organics, lower overall chemical consumption, etc. [28].

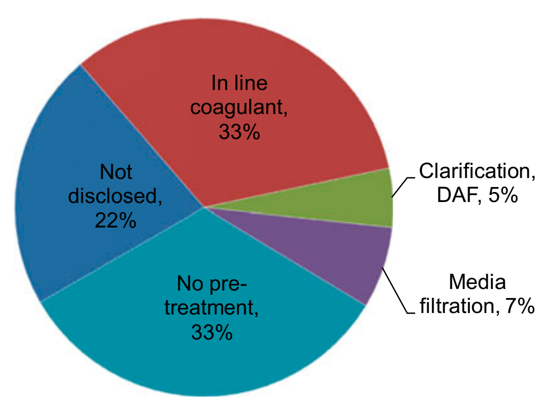

Fig. 10. Pretreatment used before MF/UF as pretreatment to SWRO [27].

MF and UF membrane systems have been shown to be very efficient in removing turbidity and nonsoluble and colloidal organics contained in the source SW. Turbidity can be lowered consistently below 0.1 NTU (usually down to 0.03–0.05 NTU) and filter effluent SDI levels are usually below 3 over 90% of the time.

Both MF and UF systems can remove four or more logs of pathogens such as Giardia and Cryptosporidium. In contrast to MF, UF membranes can also effectively remove viruses. The use of MF/UF gives more simplicity of operation and maintenance, and has gained acceptance in recent years as the preferred pretreatment for SWRO (Fig. 2). List of large SWRO plants using MF/UF membranes pretreatment is given in Table 3.

Comparison of conventional and UF membrane pretreatments was presented by Villacorte [3] and Kim et al. [30]. Their findings are given in Tables 4 and 5.

Some details of membranes pretreatment are presented here. Prihasto et al. [31] gave two examples of pretreatment plants. The first is Addur SWRO Desalination Plant, Bahrain. SW in this area has high salinity and bioactivity. Industrial and residential waste disposals caused additional organic content. Temperature range is 16–36˚C and SDI range is 15–19. In the full-scale plant, the pretreatment system includes prechlorination, sand filtration, and UF spiral wound membranes. In addition to the full-scale plant, there was a pilot plant consisting of prechlorination, screening, and UF (Multibore membranes). The UF Multibore membranes (Inge AG, Germany) have a pore diameter of 20 nm, average flux of 70 L/(m^2 h), with filtration time between 17 and 20 min, and chemical enhanced backwash with addition of NaOCl (50 ppm as free Cl_2, 20 min soaking) every 2–3 h. The experience shows that prechlorination demonstrated negative effects on the existing full-scale plant, while has positive effect on the pilot plant. The laboratory tests indicated that coagulation ($FeCl_3$) has a positive effect on performance and cleaning of the membranes. The dose of 0.25 ppm $FeCl_3$ seems to be the optimum dose for the UF membranes. The result of dosing the $FeCl_3$ coagulant is the forming of filtration cake on the membrane surface that acts as an additional pre-filter that protects the membrane from irreversible fouling by dissolved organic compounds and improves the filtrate quality. It was found out that the chlorine dose at the intake must be raised to 2 ppm in summer to avoid bioactivity, whereas 1 ppm was sufficient during winter. Also, stable operation at a flux of 70 L/(m^2 h) was achieved during the summer months. The multibore membranes allow substantial reduction of consumed chemical and saving energy compared with existing spiral wound UF modules.

The second plant given by Prihasto et al. [31] was Doha Research Plant, Kuwait. In Doha Research Plant, a conventional system was implemented to pretreat the surface SW required to feed the RO lines [31]. These are three RO lines had their own additional pretreatment system, in addition to the conventional pretreatment. The surface SW in Doha was characterized by TDS of 47,000 mg/L and SDI equal 15 (more

Table 4
Operational parameters for UF and media filtration typically applied in SWRO pretreatment [3]

	UF	GMF
Pores (μm)	0.02	150
Filtration rate (L/m^2 h)	50–100	5,000–10,000
Run length (h)	1	24
Backwash rate:filtration rate	2.5	2.5–5
Backwash time (min)	1	30
Filtered volume/m^2 per cycle (L)	50–100	120,000–240,000
Pressure loss (bar)	0.2–2	0.2–2

Table 3
Examples of desalination plants using MF/UF membranes pretreatment [29]

Desalination plant location and capacity	Pretreatment system type and configuration	Notes
Adelaide, Australia (300,000 m/d)	Submersible UF membranes	Offshore open intake
Fukuoka, Japan (96,000 m/d)	Pressure UF membranes	Infiltration gallery
Kindasa, Saudi Arabia (90,000 m/d)	Dual media granular pressure filtration followed by pressure UF membranes	Near-shore open intake in industrial port
Palm Jumeirah, UAE (64,000 m/d)	Pressure UF system	Offshore open intake
Yu-Huan, China (34,500 m/d)	Submersible UF membranes	Offshore open intake
Colakoglu Steel Mill SWRO Plant, Turkey (6,700 m/d)	Pressure UF system	Offshore open intake

Table 5
Comparison of conventional and UF membrane pretreatments [30]

	Conventional pretreatment	UF membrane pretreatment
Treated water quality	Unstable and fluctuating water quality depending on raw seawater (Silt density index, SDI < 4.0)	Stable and constant water quality (SDI < 2.0)
Average RO flux	100%	20% higher
RO membrane fouling rate	High fouling potential	Lower fouling potential
RO membrane cleaning frequency	1–2 times per year	4–12 times per year
Typical life time filters	Filters: 20–30 years Cartridges: 2–8 weeks	UF/NF membranes: 5–10 years Cartridges: often not needed
RO membrane replacement rate	100%	33% lower
Capital cost 100% 0–25% higher	100%	0–25% higher
Footprint	100%	30–60% smaller
Energy consumption	Lower than UF	Higher than conventional
Chemical dosing rate	High	Lower
Intake line	Long	Shorter
Operation/management costs	High	Low
Miscellaneous	–	Better boron control

than 6.5 on average). The removal of suspended and colloidal particles from the untreated SW was carried out by flocculation and filtration. The flocculants, FeC-lSO_4 (ferric chloride sulfate), was added to the untreated SW at the inlet to the destabilization tank. The pH value was adjusted for destabilization and flocculation by adding H_2SO_4. The media filter consisted of a supporting layer (with various grain size and height of 0.3 m), silica sand (0.7–1.2 mm, 1 m), and hydro anthracite (1.4–2.5 mm, 0.7 m). Before entering the storage tank, chlorine gas was added, in condition when the chlorine content was less than the minimum level. The filtrate in the storage tank was then fed to the RO lines. Each of the RO lines had its own pretreatment system to achieve the specified quality of feedwater according to each specific RO membrane manufacturer. They consisted of:

(1) *RO Line 1*: Sodium hydrogen sulfite dosing to remove residual chlorine, activated carbon filters to ensure the complete removal of residual chlorine, antiscalant to prevent sulfate scaling, acid dosing system to prevent carbonate scaling, and cartridge filters (micron filters) to filter out particles larger than 5 μm.
(2) *RO Line 2*: Acid dosing system to prevent carbonate scaling, Polyelectrolyte dosing system and three in-line coagulation filters to further reduce the SDI of the feed to less than 3.0, sodium hydrogen sulfite dosing to remove residual chlorine, and three cartridge filters to remove particles larger than 5 μm.
(3) *RO Line 3*: Acid dosing system to prevent carbonate scaling, antiscalant dosing system to prevent sulfate scaling, sodium hydrogen dosing system to remove residual chloride, and two cartridge filters to filter out particles larger than 25 μm.

During the operation period, the system was successfully controlled to give the desired quantity of filtrate with an SDI value of 3.6. However, during certain conditions the system failed to produce acceptable quality and quantity of filtrate to the RO lines. The failures reasons were mainly attributed to clogging of the dual media filters, effect of pH, dosing rate of $FeClSO_4$, dosing rate of polyelectrolyte, energy input, and climatic conditions (such as temperature, dust storm, and wind).

The effect of algal blooms on the operational performance of UF membranes was investigated by [32–34]. Large macromolecules (e.g. polysaccharides and proteins) produced by these algae are the main causes of membrane fouling, and more than the algal cell themselves. High concentrations of sticky AOM substances e.g. transparent exopolymer particles present during an algal bloom can impair UF operation by attaching to the membrane surface and pores resulting in permeability decline.

2.4. SWRO for Qatar SW and previous pretreatment trials conditions

Very limited published data on the SWRO pretreatment in Qatar as a result of only one found (in the literature) pilot plant study conducted in the Dukhan area, West of Qatar, and were reported by Hirai et al. [35] and Hirai et al. [1].

Hirai et al. [35], reported the study's results of the first phase of this pilot plant. The experimental setup is shown in Fig. 11(a). In this work, SW was taken from a line SW intake line that was used for the cooling of a thermal power plant. Pressure-type single media filter (called RF) using anthracite was installed to treat SW of high turbidity. The RF filter size was 1.2 m in diameter and anthracite layer of 500 mm with design filtration velocity of 15 m/h. The SW was then fed to microfilters (MF) with through a by-pass line to be used during backwashing. MF equipment was installed to clarify the pressurized feed treated SW to meet the RO feedwater required conditions. The MF modules were made by Asahi Kasei Chemicals that have 50 m^2 filtration area per module and 10 modules were used. Toray's RO membrane elements for high-pressure operation were adopted for the desalination of the high salinity feed SW. Energy recovery PX was used to recover the effluent brine energy. This experiment used conventional pretreatment.

Some results of the above-mentioned Qatar's experimental work as reported by Hirai et al. [1,35] are:

(1) SW of Duhkan showed poor coagulation property. The TDS was about 58,000 ppm and the turbidity was usually less than 1 NTU, but increased rapidly to 10 NTU in bad weather.

(2) Media filter was clogged soon in its coagulation operations. Coagulant injection at the inlet of the media filter was impossible because of rapid clogging.

(3) Clogging of MF membrane was very rapid. The pressure drop of the MF membranes increased rapidly; the maximum increase rate was 30 kPa/h. A newly developed washing procedure enabled continuous operation. It was easily clogged and the cleaning with 150–200 mg/L chlorine combined with the sulfuric acid was necessary.

(4) The recovery ratio of SWRO desalination was set at 32.5% under HP due to high salinity of the feed SW.

(5) SW temperature in summer increased up to 37.5˚C, which was considered very high. Considering these severe conditions, the average membrane flux should be set at lower level.

(6) During continuous operation, serious biofouling was observed, which might be due to the serious SW conditions. Bio-fouling of SWRO was caused by the presence of sulfur oxidation bacteria.

(7) Post treatment for boron rejection was necessary to reduce boron level in product water from 3 mg/L to less than 0.5 mg/L. Permeate cycling process for boron removal was very effective.

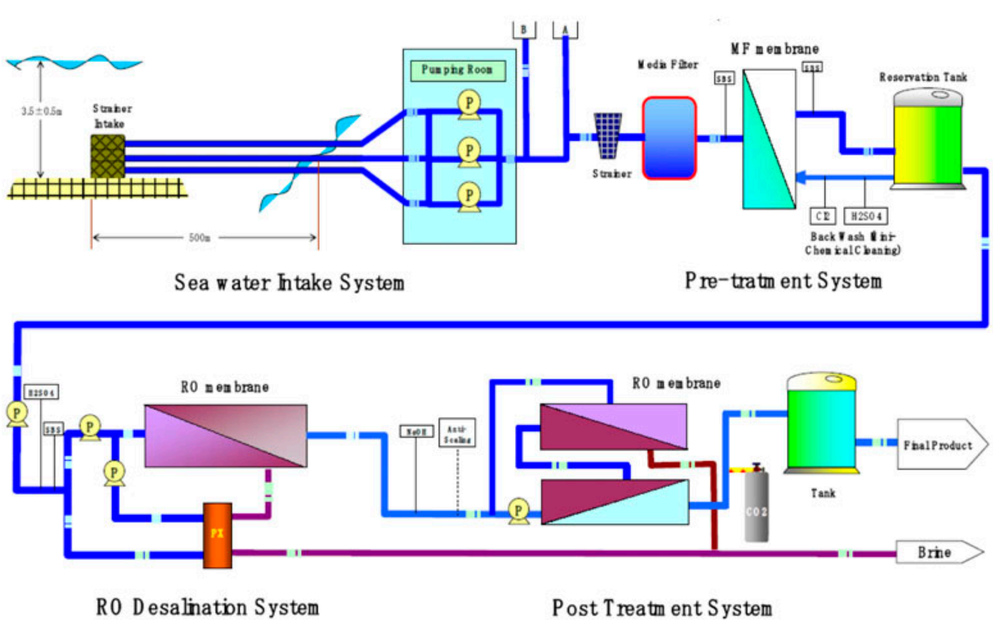

Fig. 11(a). Schematic flow diagram of demonstration plant in Dukhan [35].

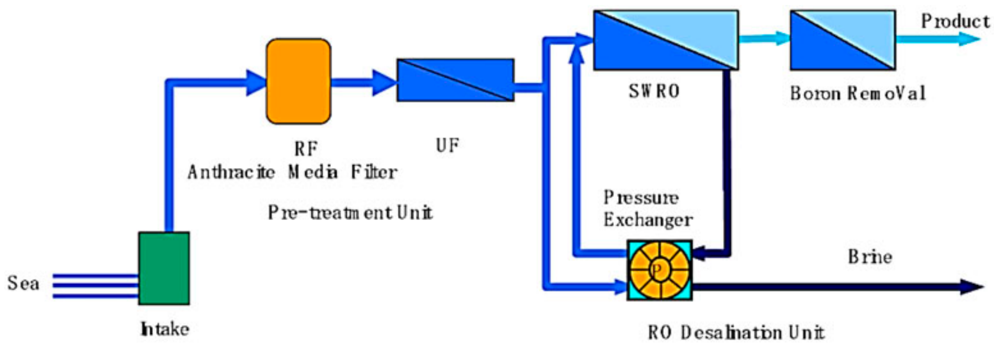

Fig. 11(b). Schematic flow diagram of demonstration plant in Dukhan [1].

Hirai et al. [1] reported the extension of the first-phase study. During 2008, some modifications were introduced as shown in Fig. 11(b), and concerning the pretreatment and the SWRO process, and can be summarized as, [1]:

(1) Replacement of MF membrane by UF membrane (Toray HFU-2020 8 modules on September 2008).
(2) Replacement of the HP pump (August 2007) due to damage, and the former all SWRO membranes were replaced by a new one because of damage or performance degradation due to chlorine solution for MF washing flew into the RO modules by mistake, the new modules were Toray TM820H-400, 8 vessels × 3 elements.
(3) The presence of sulfur oxidation bacteria could be prevented by managing injection of sulfite salt (Sodium Hyposulfite (SBS). They concluded that the best pretreatment was changing the process from MF to UF and using industrial water for decomposing chlorine.
(4) The pretreatment equipment consists of two stages of a single-media filter packed with anthracite followed by the UF membranes. At the beginning, coagulant injection was planned at the RF, but it caused furious clogging followed by rapid increase of differential pressure, and consequently, chemical dilution for the backwash process, resulted in stable operations were impossible.

2.5. Comparison between conventional and membrane pretreatment

Combination of DAF and pressurized UF pretreatment was applied in Shuwaikh, Kuwait's SWRO desalination plant. It was proved to be an efficient pretreatment for the SWRO system for the SW feed that has high turbidity, and even can be operated reliably during red tides. The UF permeate capacity was 350 million liters per d (MLD) and RO output is 94.7 MLD. The SW in that location is highly saline, rich in organic components, and known for occasional red tides, which can last for 10 d. The DAF and UF efficiently remove high concentrations of suspended solids and small-sized colloidal particulates. The produced RO feed SW has consistently SDI of less than 3.0 at all times. Combined DAF and UF pretreatment proved successful in removing the increased number of particles caused by the abnormal algae growth with turbidity levels of up to 31 NTU. This prevents reduced production or plant shutdown and helps ensure continuous supply of potable water to the city of Kuwait. Only small operational adjustments were needed to be taken to guarantee optimum pretreatment for the RO system.

The published work on the DAF pretreatment in SWRO is limited, as indicated by Huehmer and Henthorne [15] who present excellent review on the subject. The use of DAF as pretreatment of SW feed is more advantageous over conventional coagulation–flocculation–sedimentation–filtration by preferentially reducing proteins associated (in fresh water applications) with membrane fouling.

The difficult problem of oil contamination can be solved by removing the oil when DAF is used during membrane pretreatment, besides removing other pollutants such as: colloids, fine and ultra-fine particles, precipitates, ions, micro-organisms, and proteins. Compared with typical sedimentation process, DAF allows light particles that settle slowly to be removed more effectively and in a shorter time; it also usually produces a low generation of sludge from the system.

3. Suggested SWRO pilot plant system

The above review indicates that extensive pretreatment is needed for the feed SW to the RO membranes. The choice of these methods is a site dependent, and what suit a certain location may not be applied to others. Most large SWRO projects should be started by building a pilot plant on the same site to choose the most suitable pretreatment processes. This is certainly applied to Qatar. Several schemes are suggested for the SWRO pilot plant in Qatar. All schemes for large capacity SWRP plants are using open intakes, fine screening, precoagulation, prechlorination, and cartridge filters before the RO membranes. Two trains can be built with components shown in Fig. 12.

The first train is using conventional pretreatment and uses coagulation-flocculation-sedimentation. DAF is to be built and operated in parallel with the sedimentation process for comparison. The sedimentation (or DAF) is followed by GMF and cartridge filtration before the RO inlet. The GMF can be of single or double stages and with several media.

The second train uses a nonconventional pretreatment process; with the same arrangement of the first train, but with MF and UF following the GMF, as well as cartridge filter (as safety) before the RO membranes. Arrangements to bypass some of conventional pretreatment process are to be included.

In an optional case for SW coming from subsurface intake (beach well), inline coagulation and UF followed by cartridge filtration can be used before the RO membranes. Inline coagulation can be bypassed for good quality water.

When the DAF filtration system is used, the clarification and filtration processes are combined as one unit and the pretreatment system becomes a compact one. It is capable of removing color, and suspended and colloidal solids through the process train comprising coagulation–flocculation, DAF clarification, and sand filtration.

The widespread of the SWRO desalination process is primarily due to its lower consumed energy in comparison with thermal desalination processes and rapidly increasing energy costs. The reported specific energy consumption (SEC) of SWRO in the Gulf area is in the range of 4–6 kWh/m^3 when ERD are used, compared with equivalent mechanical specific energy of 20–22 kWh/m^3 for MSF and ME-TVC desalting systems. The SWRO consumed energy is influenced by several parameters, such as SW salinity, recovery ratio, number of used RO stages (single or double) necessary to achieve the required product quality, SW temperature, RO train configuration, selected ERD, and efficiencies of the used pumps and ERD. In planning large SWRO system, optimization of the consumed energy is important.

The SEC (total) of the desalination plant is the summation of the consumed power by individual SWRO processes. The SEC is itemized in the next equation for the SW extraction, screening and pumping systems, pretreatment system, RO system (for one or two passes and cleaning), post treatment, and auxiliaries such as air conditioning (A/C), lighting, communication systems, etc.

SEC (total) = SEC (SW extraction, screening, and pumping) + SEC (pretreatment) + SEC (RO system for one or two passes and cleaning) + SEC (post treatment) + SEC (auxiliaries)

3.1. Pretreatment systems energy consumption

The pretreatment system contributes (but not much) to the whole plant consumed energy. Table 6

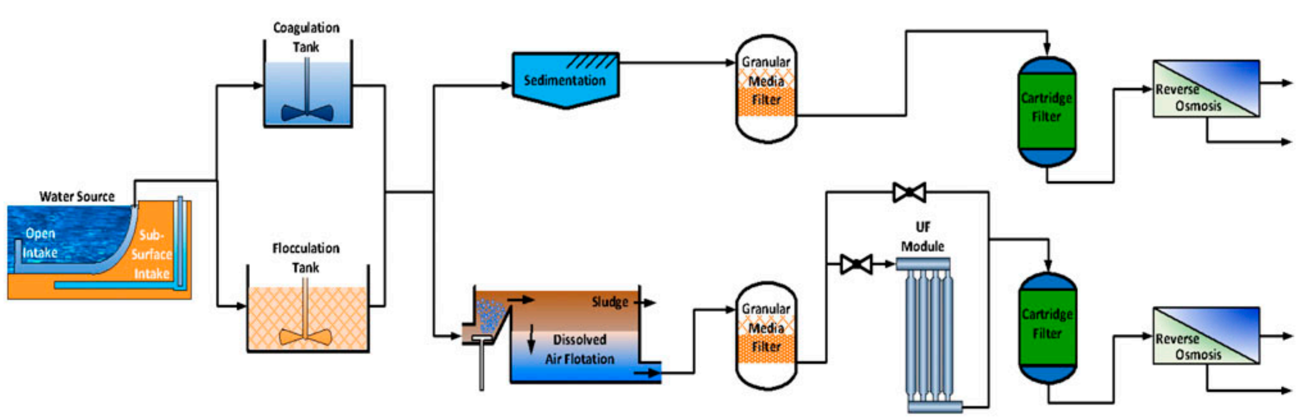

Fig. 12. Suggested components of the SWRO pilot plant pre-treatment system SWRO system energy consumption and ERD.

Table 6
The specific energy consumption of several applied pretreatment processes chosen based on the SW characteristics [36]

No.	Type of pretreatment process	Abbreviation	SEC (kWh/m^3)
1	Filtration gravity + static mixer	1 FF + SM-1F	0.02 (one stage GMF)
		2 FF + SM-2F	0.03 (two stage GMF)
2	Filtration gravity + basins	1 FF + FB-1F	0.1 (one stage GMF)
		2 FF + FB-2F	0.12 (two stage GMF)
3	Filtration pressure + static mixer	1 FFP + SM-1F	0.2 (one stage GMF)
4	Sedimentation + filtration	1 S + F-1F	0.14 (one stage GMF)
5	Flotation + filtration	1 DAF + F-1F	0.15 (one stage GMF)
6	Membrane filtration	MF	0.1–0.2
7	Flotation + membrane filtration	DAF + MF	0.24

shows the SEC of several applied pretreatment processes chosen based on the SW [36].

Filtration with the use of a static mixer is clearly the most less energy pretreatment process for both single and two-stage filtration. Membrane filtration SEC range is above filtration with basins and pressure filter filtration, then followed by more extensive conventional pretreatment processes.

The share of pretreatment in the overall energy demand of the desalting processes determined by its specific power demand based on the product output of the whole SWRO plant. This parameter SEC (itemized) is calculated from the specific power demand SECPRF (or SEC(itemized), referred to treated filtrate as shown in Fig. 13.

Large SWRO DP consists of a number of trains. Each train has HP feed SW pump supplying group of pressure vessels (PV) containing the membrane elements connected with permeate and concentrate headers, and instrumented to measure flow rates, pressures, and SW conductivities. Each train is preceded by pretreatment feed SW system and followed by post treatment of the produce permeate. The pretreatment, membrane assembly, and post treatment are designed to supply adequate quality of feedwater to the membrane elements in order to maintain stable

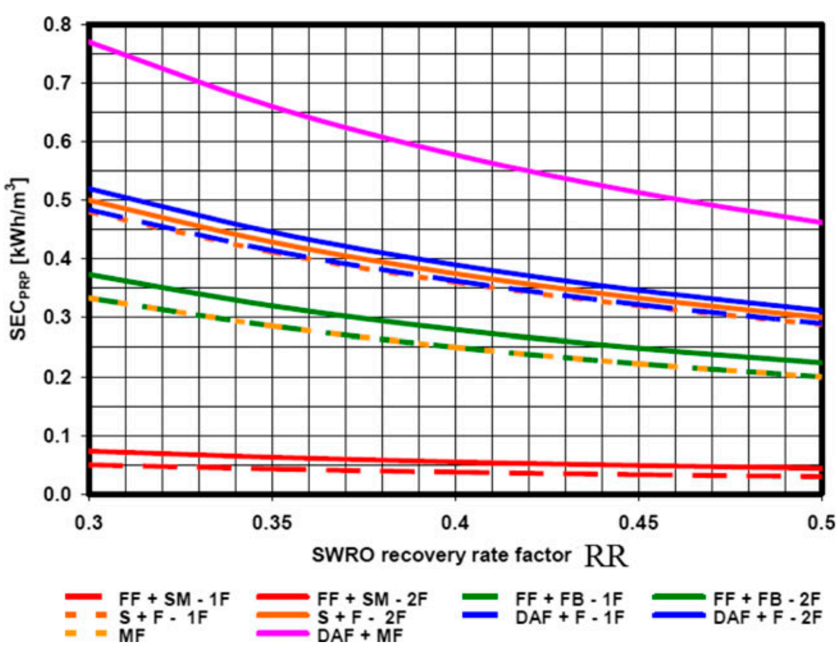

Fig. 13. Pre-treatment SEC based on the product output of the whole SWRO—plant, SECPRP = SEC (itemized) [36].

performance and produce the design permeate flow and quality, respectively.

The number of membrane elements in each PV in large desalting system is typically 6–7, and can reach up to 8. The permeate tubes of the first to the last membrane element in each PV are connected to form practically one long permeate pipe inside the vessel. The salt concentration and the osmotic pressure in the feed-brine side increase as permeate flows through the membranes, and brine flows along each subsequent membrane element. High feed flow rate to the PV can cause HP drop and possible structural damage of the elements; while low flow rate of the feed-brine creates insufficient turbulence, and thus high concentration polarization causing excessive salt concentration at the membrane surface. Therefore, there are limits of maximum feed flow to each PV and minimum brine flow rate at its exit for a given membrane element type, usually given by the manufacturers.

The first step in the design of the SWRO system is to check the SW analysis. This includes electric neutrality, and allowable maximum recovery ratio to avoid $CaSO_4$ scale formation. Typical TDS in Qatar is equal to 43,313 ppm.

Now, consider as example, an SWRO DP of typical train capacity of 0.1 m^3/s (8,640 m^3/d or 1.9 MIGD) and spiral wound type membranes known as SW30HR-LE are chosen for this plant. The membranes according to the manufacturer test conditions have specific permeability $K_w = 1.2$ L/m^2 h bar and membrane area $A = 35$ m^2. For flux rate 14 L/m^2 h, feed salinity $X_F = 43{,}313$ ppm and the recovery ratio $R = 1/3$ (calculated according to Qatar water analysis to avoid $CaSO_4$ scale formation), the brine salinity X_B is 63,696 ppm, and the average feed brine salinity $X_{FB} =$ 53,505 ppm.

The average osmotic pressure is approximated as 41.2 bar. The net pressure difference (NPD) required to drive the flow is at least 11.67 bar. If the pressure drop per vessel is equal to 2 bar and the permeate side pressure $P_p = 2$ bar, then a feed pressure of 68 is high enough to give the required permeate. Calculations of the SWRO consumed energy are illustrated for four cases shown in the next section for average osmotic pressure equal to 41.2 bar. The NPD required to drive the flow is at least 11.67 bar. If the pressure drop per vessel is equal to 2 bar and the permeate side pressure $P_p = 2$ bar, then a feed pressure of 68 is high enough to give the required permeate. Now different configurations for the SWRO are considered and the SEC per m^3 permeate is calculated.

Parameter	Value
Feed flow rate	0.3 m^3/s
Feed concentration	43,313 ppm
Recovery	1/3
Number of stages	1
Number of pressure vessels	105
Number of elements in each pressurized chamber	7
Feed pressure	68 bar
Permeate flow rate	0.1 m^3/s
Permeate concentration	326 ppm

3.2. Case A: Simple SWRO train with no energy recovery

A simple SWRO system having 0.1 m^3/s permeate capacity with conventional pretreatment and no energy recovery used to recover the brine pressure energy leaving the membranes is shown in Fig. 14 and represents case A.

The energy consumed by the HP pump supplying the feed (F) with pressure drop (ΔP) is: $W_{HP,\ pump} = F$ (m^3/s) $\times$ pressure drop ΔP (kPa)/($\eta_p \times \eta_m$); η_p and η_m are the pump and motor efficiency respectively of typical values given in Table 7.

Now for permeate $Pr = 0.1$ m^3/s, recovery ratio $RR = Pr/F = 1/3$, the feed F is 0.3 m^3/d, and Brine reject $(B) = 0.2$ m^3/s, and by taking $\eta_p = 0.85$ and $\eta_m = 0.95$, then: $W_{HP,pump} = (0.3) \times (6{,}800)/(0.85 \times 0.95)$ =2,526.316 kW; HP pump (SEC) = $W_{HP,pump}$/Pr = 2,526.316/(3,600 × 0.1) = 7.0175 kWh/m^3.

cBy taking pumping energy equal 85% of total energy, then all consumed energy, other than RO pumping energy 1.24 kWh/m^3; SEC (total) = 8.256 kWh/m^3.

3.3. Energy recovery devices

The SEC (RO pumping) for case A is 7.0175 kWh/m^3 gives real high SEC (total) of 8.256 kWh/m^3 when all specific consumed energy, other than pumping energy of F to membranes (=1.24 kWh/m^3) is added. The consumed energy is one of the most important factors which affect the water cost, and efforts to lower this energy are to be considered.

The brine flow rate leaving the RO membrane for 1/3 recovery ratio, is twice the permeate. The brine pressure is equal to the feed pressure minus pressure drop in the feed-brine stream in the membranes, ΔP_m, (say in the range of 3 bar). So, the brine leaves the membranes at 0.2 m^3/s flow rate and say 65 bar pressure. The pressure energy of the brine can be recovered by different ERD. Turbines were initially used to

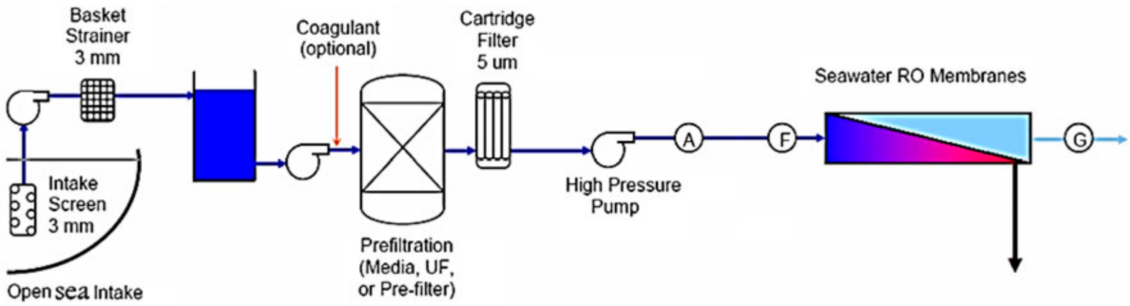

Fig. 14. Schematic of a simplified SWRO DP without ERD.

Table 7
Typical values of the efficiencies of pumps η_p, motors η_m and ERD [37]

Type of pumps/ERD	Unit	State-of-the-art efficiency range	Selected value/range	Comments
RO 1st pass				
HP feed booster pump	%	82–85	84	
HP pump	%	85–88	87	Depending on pump size
ERD feed booster pump	%	82–85	84	
ERD booster pump	%	82–84	83	
Permeate intermediate pumps	%	82–85	83	
RO 2nd pass				
2nd pass feed pumps	%	84–86	85	
Permeate pumps	%	82–85	83	
ERD				
Pelton turbine	%	86–88.5	85	
Turbocharger	%	75–83	80	Depending on capacity
Motor drives				
Motor and drive	%	94–96	95	

utilize this energy in driving the feed HP pump shaft. The main turbine used as ERD is the Pelton wheel type, which is considered as next case B. A reversed centrifugal pump (or centrifugal turbine) mounted on the same shaft of the HP feed pump is another arrangement known as turbocharger and is considered as case C. Other ERD include rotary type ERI PX as well as piston type dual work exchanger energy recovery (DWEER) are to be considered later. Selection of the energy recovery system for the SWRO process is the deciding factor for the base level of consumed energy as shown in the next examples. The efficiencies of the pumps, Pelton turbine, or turbocharger are important factors affecting the ERD performance. The Pelton turbine is well known as hundreds of them are used as ERD in SWRO worldwide, besides it is easy to operate and has low price. However, it faces hard competence from new generation of ERD such as PXs of rotary and piston types in big plants since Pelton wheels have less flexibility, size limitation, and less energy efficiency compared with PX.

3.4. Case B: Using Pelton wheel

Fig. 15 shows the Pelton wheel added to the SWRO system. The energy recovered by Pelton wheel can be calculated as:

$W_{\text{Pelton wheel}}$ = B (m^3/s) (ΔP across the wheel) $\times \eta_t \times \eta_d$,

where η_t and η_d are the turbine and drive efficiencies, respectively. For $\eta_t = 0.88$ and $\eta_d = 0.95$,

SEC (RO pumping feed) = 7.0175 kWh/m^3,

$W_{\text{Pelton wheel}} = (0.2) \times (6{,}800 - 300) \times 0.88 \times 0.95 =$ 1,086.8 kW

Net pumping energy $W_{\text{HP net}} = W_{\text{HP, pump}} - W_{\text{Pelton wheel}}$ = 2,526.316−1,086.8 = 1,439.516 kW

SEC (Pelton wheel) = 3.089 kWh/m^3

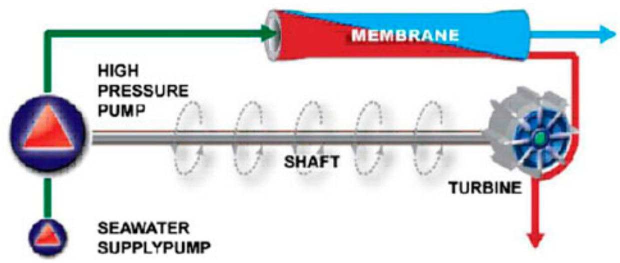

Fig. 15. Schematic of a simplified Pelton wheel added to simple SWRO train [37].

SEC (net pumping) = 7.0175 − 3.089 = 3.929 kWh/m^3, by adding all auxiliaries consumed energy of 1.24 kWh/m^3

SEC (total) = 5.169 kWh/m^3

3.5. Case C: Using turbo charger

The turbocharger arrangement is shown in Figs. 16(a) and (b). The calculations used in case B is repeated here but for low centrifugal turbine efficiency of 0.75.

The energy recovered by the centrifugal turbine is calculated as 926.25 kW (2.573 kWh/m^3), when η_t (turbine) = 0.75 and η_d = 0.95, and the

SEC (pumping) = 4.445 kWh/m^3, by adding all auxiliaries consumed energy 1.24 kWh/m^3

SEC (total) = 5.685 kWh/m^3.

3.6. Case D: Using the PX or dual work exchanger energy recovery DWEER

The deficiencies inherited in the energy recovery of both centrifugal and Pelton turbines are avoided by

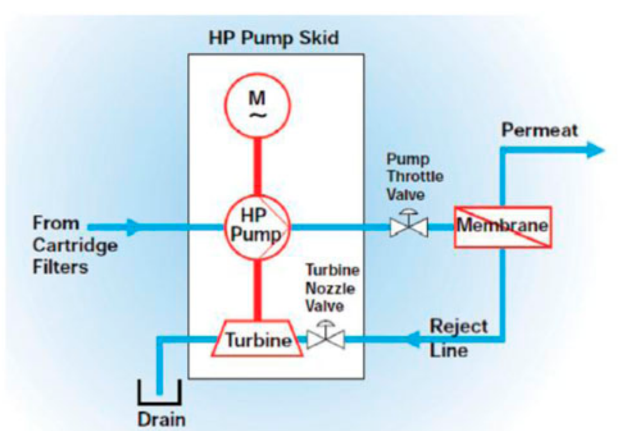

Fig. 16(a). Energy recovery turbine is coupled with the HP feed pump [38].

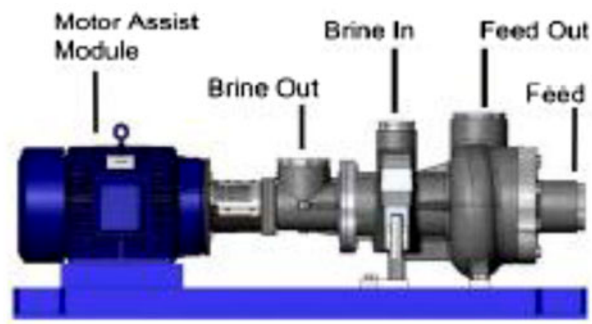

Fig. 16(b). Schematic of a simplified turbocharger consisting of HP feed pump and reversed centrifugal pump working as turbine [39].

using positive-displacement isobaric devices as ERD. These were developed and deployed widely for SWRO, since 2002. Isobaric ERDs place the RO brine reject and LP feed water in contact inside pressure equalizing or isobaric chambers. There are two available commercially types of isobaric ERDs including the rotary PX (Fig. 17 [37]); and the piston-type work exchanger energy recovery (Fig. 18 [40]) and both are arranged in the SWRO as shown in Fig. 19 [39]. The HP pump is sized to supply feed SW equal to permeate flow rate and the pressure required by the membrane elements. The concentrate B rejected from the membrane flows to the ERD. Feed water at flow rate equal to the rejected brine B is also fed to the ERD. The ERD raises the feed SW pressure by the rejected brine. The pressurized SW feed from the ERD is driven by a circulation pump to raise its pressure to that required at the membrane inlet. A small amount of HP water, typically less than 2% of the permeate volume, passes through the seals of the ERD. The HP pump flow and permeate flow remain nearly equal regardless of membrane feed pressure or booster pump flow rate. Decoupling of the HP pump flow rate and the membrane-feed flow rate allows the system operator to vary membrane recovery just by adjusting booster pump flow.

The rotary PX, Fig. 20, transfers pressure from the HP brine reject to a portion of feedwater by putting them in direct, momentary contact in a rotor. The rotor is fit into a ceramic sleeve between two ceramic end-covers with narrow clearances that create an almost frictionless hydrodynamic bearing. As the rotor turns, the ducts pass a sealing area that separates HP and LP. A schematic representation of the ceramic components of a PX device is given in Fig. 20.

The PX rotor contains no pistons or barriers. When the rotor is not spinning, flow passes directly through the device making PX operation during SWRO startup

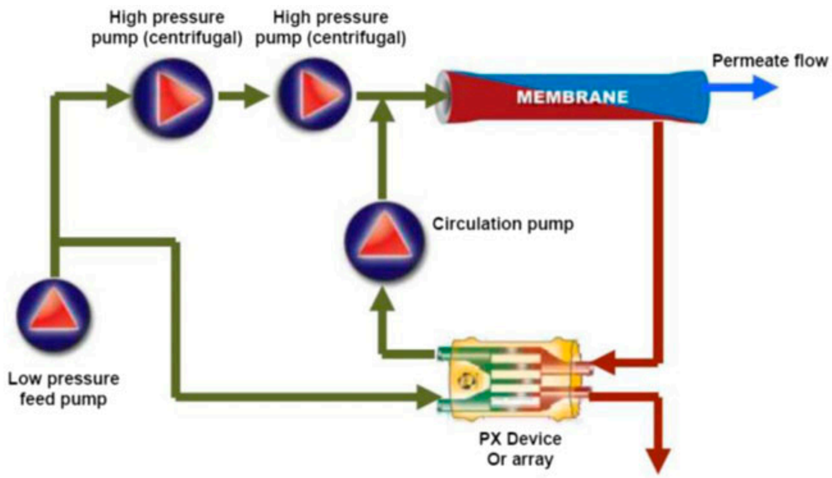

Fig. 17. Schematic of arranging the PX Flow device in the Qadifa and Zawrah SWRO in UAE [37].

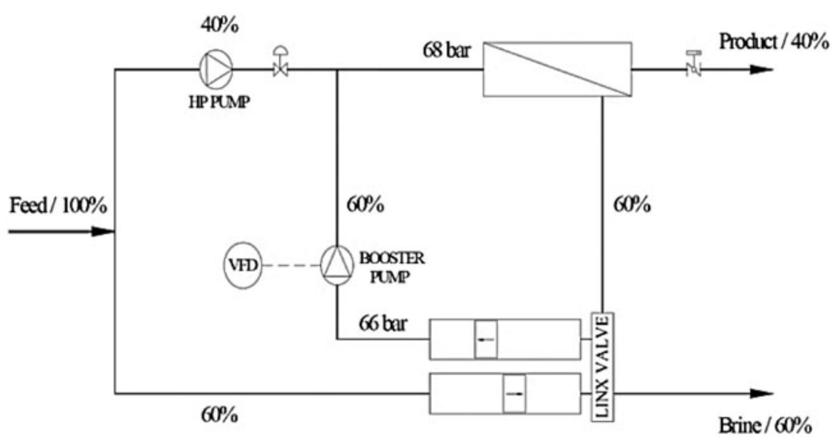

Fig. 18. Schematic of arranging the DWEER into SWRO [40].

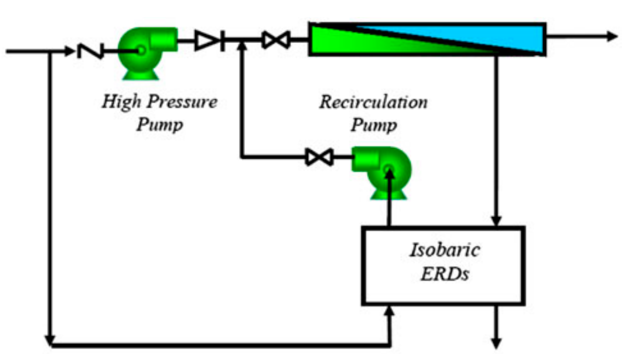

Fig. 19. Isobaric ERD [39].

and shutdown almost automatic. Mixing between the brine and SW streams is limited by the aspect ratio of the rotor ducts which are long and narrow. The PX rotor is designed so that the interface between the brine and SW never reaches the end of the rotor before the duct is sealed. The largest SWRO trains operating today is the 25,000 m^3/d (6.6 million gal/d) in Hamma, Algeria, and are supplied with PX devices operating in arrays [42]. The PX® ERD mixes about 2% of the high-pressure brine (concentrate) from the membranes with the SW supply to the booster pump. This flow is then mixes with the feed SW flow from the HP centrifugal pump. This mixing yields a net increase in salinity of about 2.5%.

This increase in salinity raises the pressure required by the RO membranes by a similar fraction, causing the main HP pump to consume more electric power. The piston-type devices [40], have large chambers, pistons separating the concentrate and SW, and

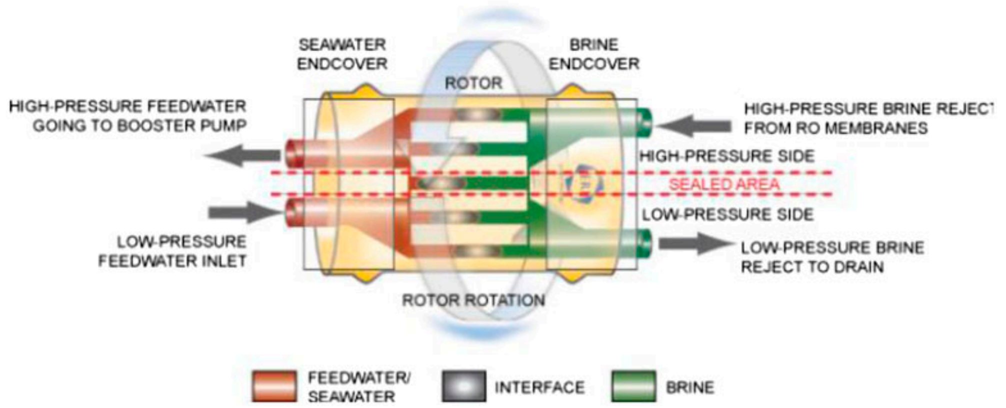

Fig. 20. Schematic of rotary PX flow device [41].

valves and control systems to switch flow between the chambers and limit the travel of the pistons as shown in Fig. 18. In the piston-type device, there is no inherent mixing of brine and SW, and if any leakage occurs, it is from the SW to the brine. The result is that the water to the membranes is at SW salinity and the membranes operate at lower pressure, requiring lower pumping power.

The energy calculations can be obtained by finding the energy consumed by the HP of part of the feed equal to 0.1 m^3/s and slightly raised P_F as 866.9 kW = (2,526.316/3) × 1.025.

The second feed is equal to 0.2 m^3/s and is dealt with the recirculation pump that raises the brine pressure from 62 bar, say, to 70 bar, and its consumed energy is 198.14 kW, and the total pumping energy is 1,065.02 kW, and thus, the specific pumping energy is 2.96 kWh/m^3.

SEC (HP pump) = 2.4 kWh/m^3.

SEC (recirculating pump) = 0.55 kWh/m^3.

SEC (net pumping) = 2.96 kWh/m^3, by adding all auxiliaries consumed energy 1.24 kWh/m^3.

SEC (total) = 4.2 kWh/m^3.

Similar calculations were given for one train of Barcelona SWRO plant, when Pelton wheel and Rotary PX, and cylindrical PX known as DWEER. The results are shown in Fig. 21(a–c), [43].

Like reciprocating pumps, the positive-displacement pressure transfer mechanism used in isobaric ERDs delivers high efficiency despite pressure and speed/flow rate variations. As a result, most SWRO plants being designed and built today utilize isobaric ERDs. Many plants built with turbine ERDs have been retrofitted or are considering the conversion of isobaric devices to reduce energy consumption and increase production capacity. An energy recovery efficiency of 98% can be achieved with state-of-the-art isobaric ERDs. Isobaric ERDs can reduce the amount of energy required to desalinate SW by up to 60%, resulting in more economical production of drinking water.

3.7. Results of cases A–D

The results of cases A–D are tabulated in Table 8.

Fig. 22 shows how pumping energy is affected by the recovery ratio when both Pelton wheel and PX are used as ERDs.

3.8. SWRO membrane modules arrangement

There are innovative ideas in the design of the SWRO plants, other than the single-stage SWRO configuration given in Fig. 14. These configurations include, besides high energy recovery, internally staged elements design, partial second passes, and new cleaning and disinfection procedures. These new ideas are in operation in some plants worldwide and theoretical analysis should be conducted to justify their adoption or not.

At a given recovery rate, the feed pressure is affected by water permeability of membrane material. In SW applications the usual selection is between a single pass system using low permeability, high rejection membranes, or partial two pass system utilizing high permeability SW membranes in the first pass and LP brackish elements in the second pass. The relative benefits of these two configurations will depend on seasonal variability of feedwater salinity and temperature during the operating cycle. Higher feed salinity and higher temperature of SW feed sources, combined with stringent permeate quality limits, will in most cases require a partial or complete two pass system

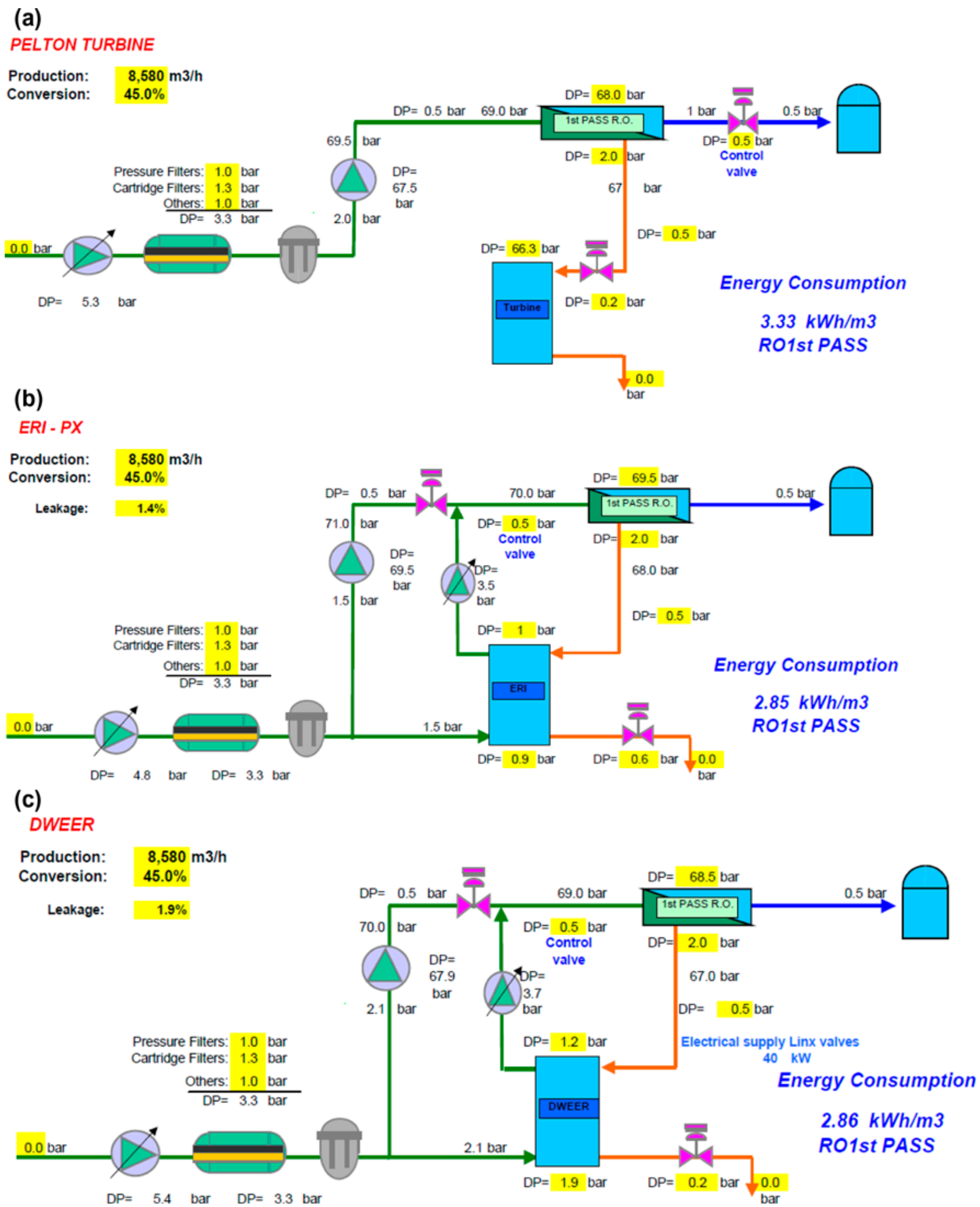

Fig. 21. Pelton turbine vs. rotary PX vs. cylinder PX known as DWEER [43].

configuration. Membranes with higher water permeability usually have also higher salt passage. The partial two pass system could be configured to take part of the first pass permeate, process it with a second pass unit and blend with the remaining permeate, as shown in Fig. 23.

In this figure, the conventional approach, part of the combined first pass permeate is processed with

Table 8
Results of cases A, B, C, and D

Case number	HP pump (kWh/m^3)	ERD (or recirculating pump) (kWh/m^3)	RO Net pumping (kWh/m^3)	RO total SEC (kWh/m^3)
A—(no ERD)	7.0175	0.0	7.0175	8.256
B—Pelton Wheel ERD	7.0175	3.089	3.929	5.169
C—Turbo-charger	7.0175	2.573	4.445	5.685
D—Rotary or piston PX	2.3392	0.413	2.752	4.0

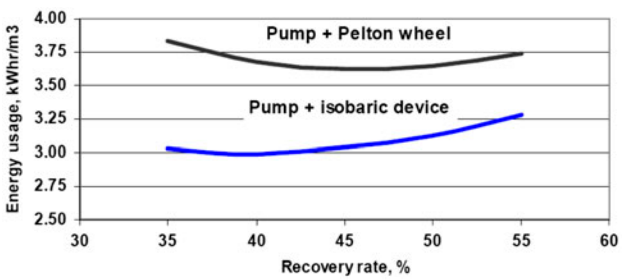

Fig. 22. Pumping energy requirement vs. product recovery rate in SWRO unit with Pelton wheel and isobaric device.

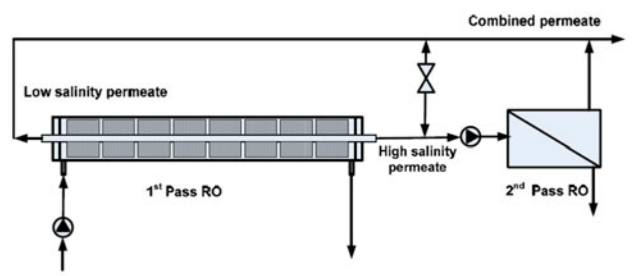

Fig. 24. Configuration of “split-partial” two pass SWRO unit.

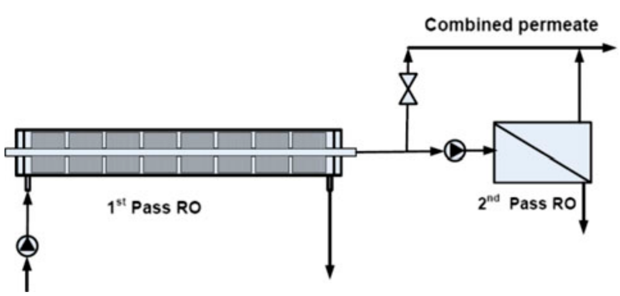

Fig. 23. Configuration of conventional partial two pass RO unit.

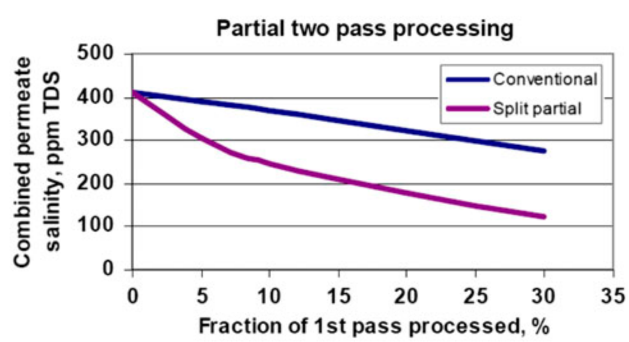

Fig. 25. Permeate salinity as a function of fraction of first pass permeate processed in the second pass in conventional and “split-partial” two pass configuration.

the second pass. The feed to the second pass RO unit and the permeate flow from the first pass used for blending have the same salinity.

The other approach is to utilize the so-called “split-partial,” (Fig. 24). In this configuration, feed to the second pass is the permeate taken from the concentrate end of the first pass unit. The feed to the second pass RO unit has a significantly higher salinity than the salinity of the first pass permeate used for blending.

The “split-partial” configuration, commonly used in commercial RO SW systems result in more efficient salt separation process, resulting in lower combined permeate salinity, as shown in Fig. 25. Correspondingly, in split-partial configuration both the first and the second pass are smaller for a given permeate equality requirement.

Another reason of staging is the boron removal. In SWRO treatment, one of the most challenging issues is to remove boron. Boron is difficult to remove by SWRO membranes, since it naturally exists as a non-ionic species. Boron rejection can be increased by increasing the feedwater pH. However, increasing the pH can cause salt precipitation and subsequent membrane scaling (i.e. deposition of salt precipitates on the RO membrane). Therefore, multiple RO stages are often required to enhance boron removal at different

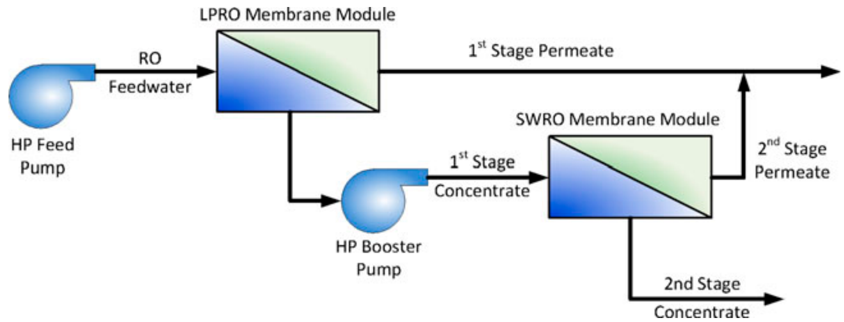

Fig. 26. Schematic of the "two-stage LPRO/SWRO configuration", which utilizes LPRO membranes in the first stage instead of SWRO membranes.

pH conditions, where the first stage (at lower pH) achieves salt removal and the second stage (at higher pH) achieves boron removal. pH adjustment can effectively control calcium carbonate scaling, while scale inhibitors using antiscalant have been used to control various carbonate, magnesium hydroxide, sulfate, and calcium scaling.

The objectives of the projects concerning using different configurations are:

(1) Evaluate the energy use of several SWRO configurations.
(2) Assess the salt rejection of the RO membranes and system configurations in terms of achieving required water quality in terms of sodium, chloride, and boron contents.
(3) Several types of SWRO membranes are to be selected for the study to provide the lowest energy use, while achieving water quality requirements.

The single stage would be tested to check that the boron concentrations of less than 1.0 mg/L. One of the configurations to be considered in Fig. 26 is the two-stage LP SWRO membranes in the first stage instead of SWRO membranes to assess the potential energy savings of utilizing LP RO membranes in the first stage which require less pressure, and therefore, energy use.

4. Conclusion

The ability of SWRO feedwater pretreatment to provide suitable-quality, pre-filtered SW to the RO membrane is perquisite for successful operation of any SWRO desalination plant. Pilot facilities should be installed to assess the feed water quality and its potential influence on the design, selection, and operation of the pretreatment system and SWRO system at full scale.

Although conventional multi-media filtration has been a standard treatment for SW pretreatment, operation of these systems can be onerous at best in order to maintain suitable feedwater quality to a downstream SWRO facility. Membrane pretreatment and DAF offer the potential to eliminate some of the operational and filtrate issues over traditional media filtration systems treating SW. Research work is necessary to compare the performance different membrane pretreatment systems in Qatar site. More research is needed for the choice of membranes' configurations and the needed ERD.

The lesson gained from several pilot plants' studies showed the need to consider each site on a case-by-case basis to better understand how feedwater quality affects sustainability and how that in-turn affects economics and life cycle costs. Building SWRO pilot plant in Qatar enables accurate prediction of life cycle costs, besides more effective comparison between treatment types with the most viable treatment configuration. The pilot plant study would help designers to have a comprehensive understanding of the feedwater quality challenges and/or seasonal changes.

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