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Energy consumption and recovery in reverse osmosis

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ABSTRACT

Energy consumption is a key factor which influences the freshwater production cost in reverse osmosis (RO) process. Energy recovery and reuse options have already been very well explored in the current desalination industry. Achieving minimum theoretical specific energy consumption for water recovery is not feasible due to effects of concentration polarization, membrane fouling and hydraulic resistance to permeate flow. Due to these limitations, energy recovery along with water recovery can be a better alternative to improve energy consumption and economics of the RO process both in small and large scale applications. This paper reviews currently available process configurations, operating strategies, and discusses potential pathways to recover and recycle energy and water to improve the performance of the RO process.

Keywords: Desalination; Reverse osmosis; Energy consumption; Energy recovery; Specific energy and water recovery

1. Introduction

Freshwater supply without any energy investment is almost impossible [1]. Even if freshwater is readily accessible under the ground level, energy is required to pump the freshwater from its source. Freshwater drawn from the groundwater source requires 0.14–0.24 kWh/m^3 (0.5–0.9 kJ/kg) for a pumping head of 100–200 ft. Conventional treatment of surface waters to potable quality requires 0.36 kWh/m^3 (1.3 kJ/kg) [1,2]. The cost of freshwater supply through conventional treatment is around \$0.25/m^3 [1,3]. Conventional treatment of water sources is only applicable in areas where adequate surface and ground water resources are available. Recently, due to excess population growth and rapid industrialization, desalination has been sought as an alternative to fill the gap between demand and supply for freshwater [4]. Desalination is a nonconventional water treatment technology applied to recover freshwater from surface and ground waters that have high dissolved solids concentrations (TDS). In the early 1950s, desalination was predominantly performed by thermal desalting technologies such as multistage flash desalination (MSF), multieffect evaporation (MED) and mechanical vapor compression (MVC) which consumed enormous amounts of thermal energy. With the advent of reverse osmosis (RO) technology and remarkable improvements in the membrane performance and associated energy consumption, RO technology has increased its visibility comparable to thermal desalination technologies and is now a leading technology in desalination industry worldwide both in small and large scale applications [5,6]. Inherent simplicity and elegance of the RO desalination technology is another fundamental cause for its promotion in many parts of the world.

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Membrane processes offer several advantages for desalination applications. They can be listed as: (1) low energy consumption; (2) moderate costs (lower capital and operating costs); (3) easier operation and maintenance; (4) compact and modular units, flexibility in capacity expansion, short construction periods; (5) lower start up and delivery times; (6) advances in RO membranes and technology; (7) decoupling of power and desalination plants; (8) possible hybridization of three or more processes; (9) ambient temperature process; and (10) lower environmental impacts. Apart from the above, the membrane technologies have wide range of applicability, such as desalting, disinfection by-product (DBP) control, disinfection (pathogen removal), clarification and removal of inorganic and synthetic organic chemicals which make membrane process applications universal [3,7–16]. A few drawbacks that accompany the RO technology are, in general, RO is not generally favored for seawater desalination of high saline waters (45,000 ppm of TDS in the Persian Gulf), with high temperatures (40°C in the Persian Gulf), high silt density, high bacteria activity and pollution. The most important disadvantage of membrane systems is membrane fouling. Severe pretreatment of the feed water is very important for RO systems. Despite these drawbacks, membrane technologies are still being considered recently for seawater desalination as a first option whether it is for new plants or hybridization in connection with present MSF plants due to significant reduction in energy requirements and operating costs [15].

1.1. *Energy requirements for separation by membranes*

Consider two compartments separated by a membrane which is permeable to only water, each of the sides containing seawater and freshwater respectively at an ambient temperature of 25°C. It is natural for the freshwater to diffuse through the membrane and dilute the seawater due to differential vapor pressure across the membrane. However, if some external pressure is applied on the seawater side, the reverse phenomenon or equilibrium can be observed. This pressure required to maintain the equilibrium is called osmotic pressure [17]. The amount of work required to apply the osmotic pressure on the seawater can be represented as follows:

$$\mathrm{d}W = P_{\mathrm{os}}\mathrm{d}v, \tag{1}$$

In Eq. (1), P_{os} is osmotic pressure, $\mathrm{d}v$ is the volume of freshwater diffused from seawater side to freshwater and $\mathrm{d}W$ is the work required by the system to achieve separation. It is very clear from Eq. (1) that the amount of work required can be reduced by reducing the volume of water recovered and/or pressure applied.

Membrane technologies utilize high quality electrical and mechanical energies which are, in most applications, derived from fossil fuels. With uncertainty in future supply of these conventional energy sources, it is critical to reduce the energy requirements of the existing processes to expand their availability and for sustainable development. Apart from that, it is very important to bring down the energy cost component which is up to 75% of total operating cost for seawater RO plants [18]. Energy consumption in membrane desalination can be reduced through different approaches. It appears that the energy consumption for membrane processes can easily be reduced until the minimum theoretical energy requirement is reached. However, it has not been achieved to date in the industry. The reasons being: (1) to produce one volume of freshwater with nearly minimum consumption of energy requires several volumes of seawater and this seawater needs to be pre-treated prior to feeding the RO process. This pre-treatment consists of many steps of chemical mixing and filtration operations. Additional energy requirements and costs of pre-treatment for such large volumes of seawater are very high when compared to what has been saved in the RO process. (2) The limitation on the recovery ratio is another factor which influences the energy and cost requirements of the RO process. The significant increase in energy requirement as well as costs for pre-treating the seawater can be improved by increasing the recovery ratio. Higher recovery ratios reduce the pre-treatment costs but increase the energy cost at the membrane significantly and low recovery ratios reduce the energy costs at the membrane [19]. Therefore, for successful operation of a RO process, the design should be based on the optimum values of these two factors. Additionally, desired product water quality is another important factor that influences the energy consumption pattern in the process as discussed later.

1.2. *Specific energy consumption*

Specific energy consumption (SEC) is defined as the energy consumed per unit freshwater (kJ/kg) produced and the term recovery ratio (%) is defined as the volume of the freshwater produced per unit volume of the seawater. Using Eq. (1); for seawater (0%) recovery, that is, the removal of an infinitesimally small amount of freshwater from a very large amount of seawater, the calculated theoretical minimum energy requirement is 0.71 kWh/m^3 (2.56 kJ/kg) of fresh water produced (with a salinity of 3.43% and a temperature of 25°C). This theoretical minimum increases to 0.81, 0.97 and

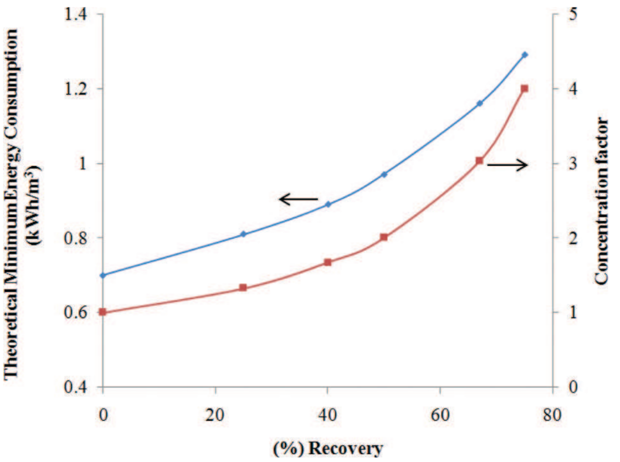

Fig. 1. Minimum energy requirements with respect to freshwater recovery ratio.

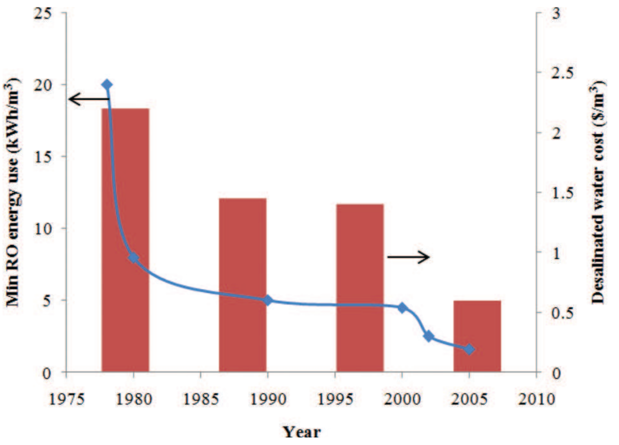

Fig. 2. Specific energy consumption and desalination cost of reverse osmosis over past three decades.

1.29 kWh/m^3 (2.91, 3.5, and 4.64 kJ/kg) for recoveries of 25%, 50% and 75%, respectively, as shown in Fig. 1 [17] and relevant brine concentration increases by a factor of 1, 2 and 4, respectively as shown in Fig.1 [20].This energy requirement is provided to the pump in the form of electrical energy which is converted into mechanical energy to impact a pressure higher than the osmotic pressure of seawater on the membrane to reject freshwater. Typically 50–75% of the energy consumed by seawater RO (SWRO) plant is used to drive the motors of high-pressure feed pumps of the first pass which is at least 35% of the total operating costs [18]. The energy cost per volume of permeate produced, i.e., SEC, is very significant in RO operation due to the high pressure requirement around 6,800 kPa (up to about 1,000 psi or 80–100 bar) for seawater and in the range of 1,379–4,137 kPa (200–600 psi or 15–40 bar) for brackish water desalination [21]. Two ways to reduce the energy consumption in RO technology are: (1) to develop high permeability membranes or low energy membranes and (2) to incorporate energy recovery devices (ERDs). Considerable effort, dating back to early 1960s has been devoted to minimizing the SEC of RO membrane desalination. The introduction of highly permeable membranes in the mid 1990s with low salt passage has led to a significant reduction in the energy required to attain a given permeate flow, with greatly reduced operating pressure that can now approach the osmotic pressure at the exit of a membrane module [22]. In the late 1970s, the SEC for the SWRO system was as high as 20 kWh/m^3 [23]. With continuous improvements in RO membrane water recovery ability, increased pump efficiency and the energy recovery system, the SEC was reduced to 8 kWh/m^3 by the mid 1980s. Although these improvements were dramatic, the energy consumption still accounted for 75% of the total operating cost of the SWRO system. Introduction of new energy recovery technologies have improved net transfer efficiencies up to 93–97%. As a result of these new technologies, the SEC dropped to as low as 2 kWh/m^3 [2,24,25] [Fig. 2]. However, thermodynamic restriction imposes the requirement that the feed-side pressure cannot be lower than the sum of the osmotic pressure (of the exit brine stream) and pressure losses (in the membrane channel) in order to ensure that permeate product water is produced from the entire membrane surface area [26]. The cost of desalinated water has also decreased by four times over past two decades due to improvements in the process design, ERDs, and high efficiency/pressure pumps [Fig. 2] [27,28].

1.3. Energy consumption in RO

The major components of RO process that involve energy consumption are shown in Fig. 3. These include: (1) feed water intake; (2) pretreatment; (3) high pressure pumps (with and without energy recovery); (4) membrane type and module; (5) post treatment; and (6) product supply. The feed water quality and the level of pretreatment play vital role in long term performance of a membrane module. In some cases, where brackish water or seawater has to be conveyed through a distance, the energy consumption and costs associated with it can be significant. Pretreatment systems consist of conventional as well membrane systems. The membrane systems provide high quality feed with SDI (silt density index) of 3.0 to the RO membrane module which is very difficult to achieve in conventional pretreatment process [29–32]. Membrane pretreatment for RO process can be performed using either micro or ultra filtration systems. Membrane pretreatment systems also reduce the footprint of the RO process. Pretreatment

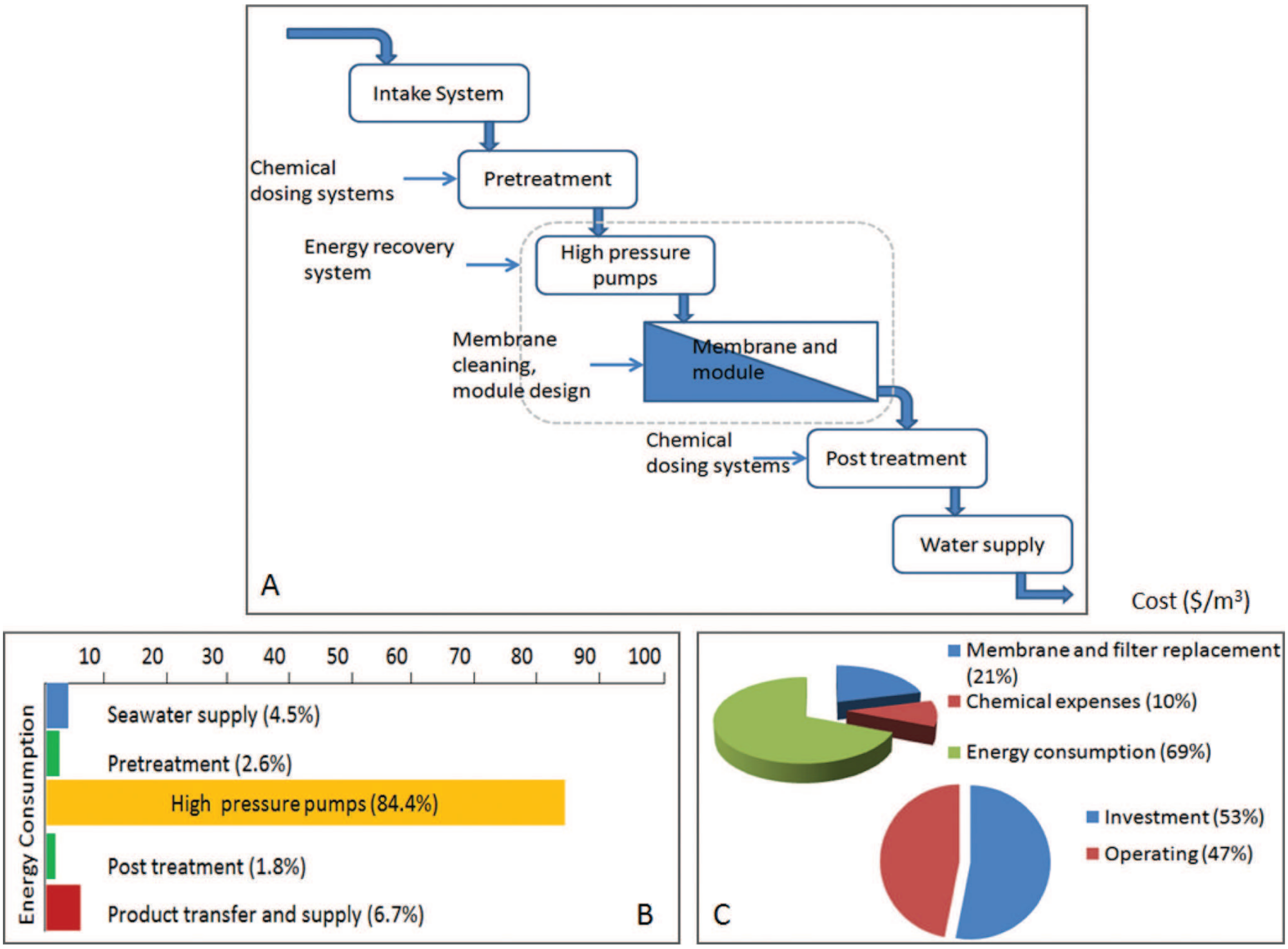

Fig. 3. (a) Major components of reverse osmosis process, (b) energy consumption and (c) production costs.

systems regardless of conventional or membrane systems require chemical dosing, mixing and filtration. The feed to the RO membrane after pretreatment is pumped through a high pressure pump and permeate is released at the atmospheric pressure. The brine is returned to the source or run through an ERD to recover the hydraulic energy associated with the stream. Permeate produced from the module is post-treated to ensure the water quality that meets the supply lines and is pumped through water distribution system. Therefore, the energy requirements for the entire RO process can be expressed as follows [33]:

$$E_T = E_{in} + E_{pt} + E_{hp} + E_A - E_{ERD}, \qquad (2)$$

where E_T is the total energy requirement, E_{in} is the energy required to draw the feed water from the source, E_{pt} is the energy required for pre-treatment and post treatment (micro filtration and pumping), E_{hp} is the energy required by high pressure pump, E_A is the energy required by other accessories (chemical dosing, filter backwashing/cleaning and pumping the product water) and E_{ERD} is the energy recovered by the ERD. Fig. 3 also shows typical energy consumption pattern of the RO process and composition of the desalination costs for small scale RO desalination systems [27,28].

The energy requirements for individual components of the RO process are shown by numerical values in Table 1. A production rate of 1 m^3/h with a typical water recovery of 45% was assumed. Table 1a shows the energy requirements for the pre-treatment, chemical dosing, high pressure pump, post treatment and membrane cleaning. These calculations do not include an ERD [34–37].

2. ERDs

Earlier RO desalination processes did not incorporate ERDs. They consisted of a high pressure feed pump and membrane module as shown in Fig. 4. The membranes

Table 1
(a) Energy consumption in RO process without energy recovery device (ERD)

Process point	Description	Flow rate (m^3/h)	Pressure (bar)	Efficiency (%)		power required (kWh)	Time (h/d)	Energy consumed (kWh/d)	% of Total energy
				Pump	Motor				
1	Seawater intake	2.22	4	80	92	0.34	24	8.0	5.35
2	Pre–treatment supply	2.22	2	80	95	0.16	24	3.9	2.59
3	Pre–treatment chemicals dosing	–	–	–	–	0.10	24	2.4	1.60
4	Microfiltration + HP pump supply	2.22	4	80	96	0.32	24	7.7	5.13
5	High pressure pumping w/o ERD	2.22	64	–	–	4.64	24	111.4	74.16
6	Post–treatment chemicals dosing	–	–	–	–	0.10	24	2.4	1.60
7	Treated water pumping	1	10	85	96	0.34	24	8.2	5.44
8	Concentrate discharge	1.22	2	80	92	0.09	24	2.2	1.47
9	Filters backwashing/cleaning	–	–	80	96	2.00	2	4	2.66
							Total =	150.26	kWh/d
							SEC =	6.26	kWh/m^3
(b) Energy consumption in RO process with Pelton turbine ERD									
5	High pressure pumping	**2.22**	**64**	**–**	**–**	**4.64**	**24**	**111.4**	**73.71**
	Energy recovered by Pelton turbine ($\eta = 89\%$); shaft ($\eta = 85\%$)	**1.22**	**63**			**1.60**	**24**	**–38.43**	**–26.02**
							Total =	111.83	kWh/d
							SEC =	**4.66**	kWh/m^3
(c) Energy consumption in RO process with Pressure exchanger (PX) ERD									
	High pressure pumping	**1**	**64**	**–**	**–**	**1.93**	**24**	**46.38**	**31.40**
	Circulation pump ($\eta = 95\%$) PX recovered energy from 55% brine	**1.22**	**4**			**0.16**	**24**	**3.83**	**2.59**
							Total =	89.03	kWh/d
							SEC =	**3.71**	kWh/m^3

were made of thick film cellulose acetate and required pressures up to 105 bars to separate salts from the seawater [38,39]. The spiral wound RO membrane module was able to recover 25% of the freshwater resulting in disposal of 75% of pressurized brine to the atmosphere [39,40]. The SEC for this operation was 10 kWh/m^3. Modifications in the membrane materials resulted in thin film composite membranes made of polyetherurea and polyamide with permeability rates increased in the order of 1 [22]. The specific energy requirements for such membranes were 6.6 kWh/m^3. Above all, the invention of ERDs have enabled the RO process to desalinate seawater at SECs as low as less than 3 kWh/m^3 and brackish waters at less than 1 kWh/m^3 respectively [41].

ERDs can be classified into two types: (1) Turbine type (centrifugal type) and (2) positive displacement type [42]. Turbine based ERDs are namely Francis turbine, Pelton turbine and Hydraulic Turbocharger. Positive displacement based devices are pressure exchangers and work exchangers. The positive displacement type contributes a higher energy recovery efficiency (ERE) (90–95%) than the turbine type (50–90%) and is a more promising and competitive technology of the field [2,42]. However, the centrifugal based energy recovery technologies are used in more than 98% of the RO capacity in the world due to mechanical simplicity, higher process uptime and operational flexibility [43]. Typical ERDs installed in RO and their efficiencies are as follows: Francis turbine – 76%, Pelton turbine –87%, Turbo charger – 85%, work exchanger – 96% and Pressure exchanger – 96%. Differences between different types of ERDs are presented in Table 2 [2,29,42].

2.1. Turbine or centrifugal type ERD

The turbine type ERD, shown in Fig. 5a, operates due to the pressure exerted by the high pressure brine reject stream. The turbine is composed of a multiple vane impeller which is directly linked through a sealed shaft supported by bearings to the high pressure

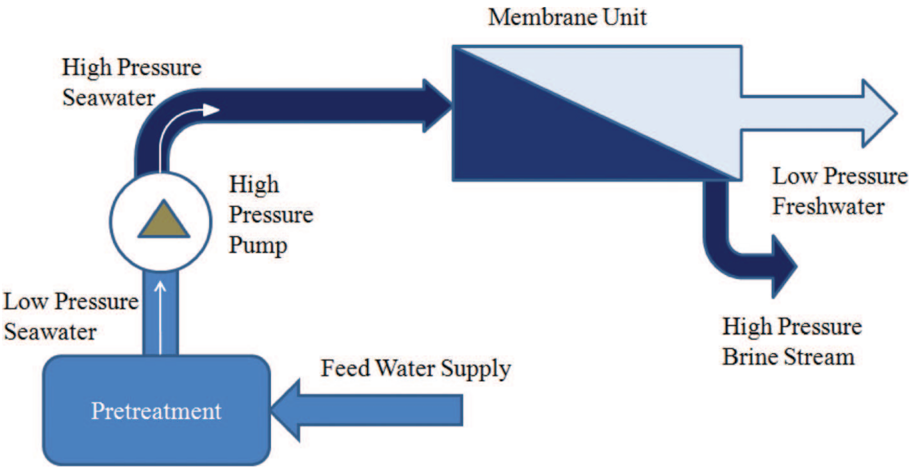

Fig. 4. Single-pass reverse osmosis process without energy recovery device.

feed stream pump [44]. In turbine type ERDs the high-pressure concentrate enters the turbine through the inlet nozzle. The high pressure water stream drives the rotor which then produces rotating power to a shaft connecting turbine and high pressure pump, thus assisting the main electric motor in driving the high-pressure pump (Fig. 6). Brine is discharged at atmospheric pressure [23]. The kinetic energy associated with the high pressure brine stream is converted into rotating mechanical energy with an energy efficiency of 85–90% [44,45]. The energy transfer efficiency of a Pelton turbine recovery system is the product of the efficiencies of the nozzle(s), the turbine and the high-pressure pump. The operating efficiency of the centrifugal pump depends on the pump speed, size, and actual flow rate vs. best design flow rate and surface finish of impellers and volutes [45].

2.2. Turbocharger type ERD

Turbochargers are different from the turbines in that the brine pressure energy is returned by the turbo charger in the form of a boost in the pressure of the feed stream [44,46]. Turbochargers consist of a pump and a

Table 2
Comparison between three types of energy recovery devices

Characteristic	Pelton turbine	Turbocharger	Isobaric energy recovery device (work exchanger)
Working principle	Centrifugal mode	Centrifugal mode	Positive displacement
Overall net energy transfer efficiency	Energy transfer from hydraulic to mechanical; 80% (70–80%)	Energy transfer from hydraulic to hydraulic; 83%	Energy transfer from hydraulic to hydraulic; 95%
Effect of deviation from design point	Wide operating range	Wide operating range	Moderate impact on performance
Discharge	Atmospheric	Pressurized	pressurized
Capital cost	Low	Moderate	High (250% higher than Pelton turbine)
Pumping requirements	Connected directly to SWRO pump/motor, requires full sized SWRO pump/motor		Small size SWRO/pump motor required to pump permeate volume only, requires small booster pump/motor
Material of construction	Metallic construction	Metallic construction	Available in non-metallic construction for corrosion resistance
Specific energy consumption	2.44–4.35 (kWh/m^3)	2.42–4.29 (kWh/m^3)	1.93–2.85 (kWh/m^3)
Capacity	Multi MGD	< 2.5 MGD	<2.5 MGD
Foot print	Compact	Compact	Large

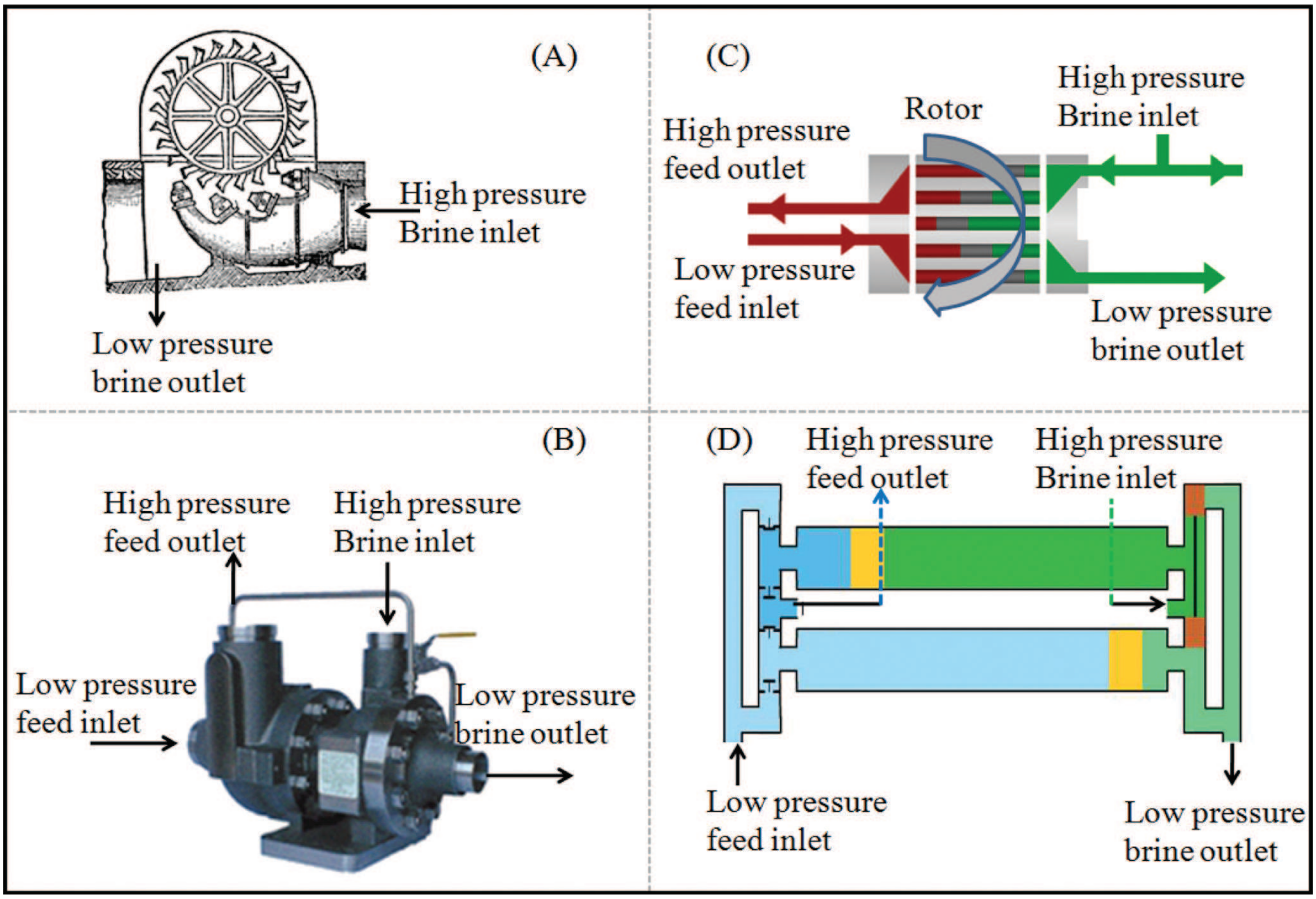

Fig. 5. Different energy recovery equipment for Reverse osmosis: (a) Pelton turbine; (b) Hydraulic turbocharger; (c) Pressure exchanger; and (4) Work exchanger.

turbine section combined in one housing as shown in Fig. 5b. Both pump and turbine sections contain a single stage impeller or rotor. Hydraulic energy from the brine stream is converted to mechanical energy by the turbine rotor. The pumping section re-converts the mechanical energy back to pressure energy supplied

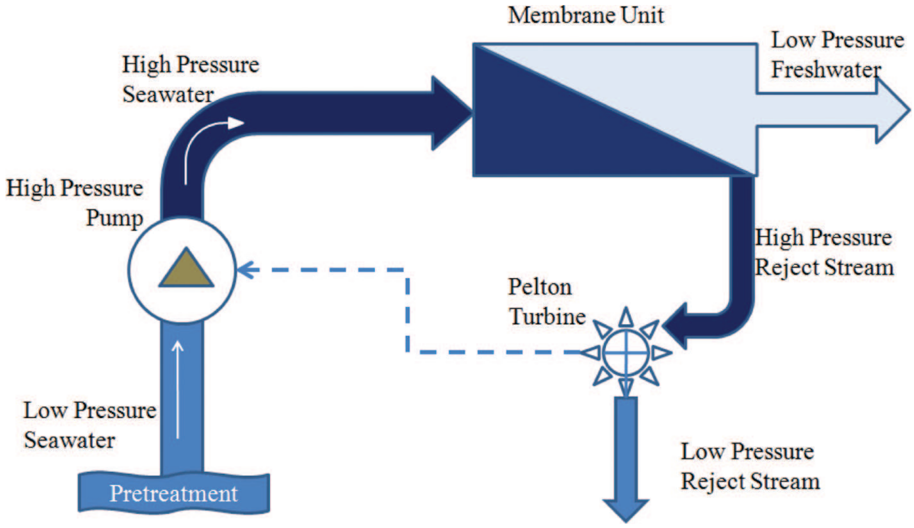

Fig. 6. Reverse osmosis unit with Pelton turbine device.

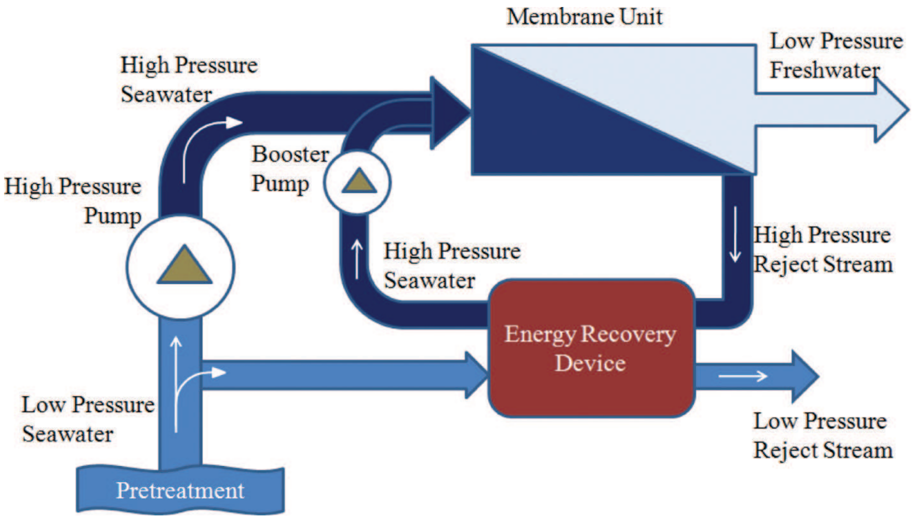

Fig. 7. Reverse osmosis unit with pressure/work exchanger energy recovery device.

to the feed stream. The process of pumping section consists of two steps. At first, all feed is pressurized by high-pressure pumps driven by an electric motor to an intermediate pressure level. The feed pressure is then further increased by the turbocharger to the RO stage inlet pressure [45]. Energy recovery using turbine type ERD is shown in Table 1b.

2.3. Positive displacement, pressure exchanger systems

The energy recovery system which uses the principles of positive displacement are commonly referred to as pressure exchangers or work exchangers (Figs. 5c and 5d). These systems transfer the energy in the reject stream direct to the new seawater stream [47,48]. The pressure exchanger (Fig. 7) allows feed seawater at a low pressure (2–3 bar) to transfer to the high pressure side due to direct contact with the high pressure brine (~64 bar) through a series of longitudinal ducts in a spinning ceramic rotor. This rotor is in a hydrostatic position inside a ceramic sleeve, thus eliminating the need for traditional seals or bearings in the construction. The low pressure feed water is ''charged'' to a pressure slightly less than the brine pressure (~60 bar) at a flow rate comparable to the brine flow. This ''charged'' feed water is then put through a booster (circulating pump) pump to bring the pressure up to match the output of the primary pump at the design feed value for the system (64 bar) [44,48]. Pressure exchangers directly transfer pressure from the brine to the feed achieving efficiencies of around 96–98% [49,50]. Energy recovery using pressure exchanger ERD is illustrated in Table 1c. Energy requirements for this device are the lowest in the RO process configurations. This is mainly due to reduction in high pressure feed pumping, i.e., in this configuration only about 50% of the feed water is pumped at the pressure required by the membrane module which is substantial reduction in energy requirements and high pressure feed pump capital costs [51]. Pressure exchangers show greater potential for future applications due to high ERE compared to turbochargers and centrifugal pumps. However, the drawbacks that influence installation of pressure exchangers are limited reliable operational data, requirement for high pressure circulating pumps and high equipment and maintenance costs [23,52–54].

The energy efficiency of the pressure exchanger can be expressed as shown in Eq. (3) [47,55,56].

$$\eta_{\mathrm{pes}} = \frac{\mathrm{Pressure\_flow_{out}}}{\mathrm{Pressure\_flow_{in}}} \times 100\% = \frac{Q_{\mathrm{bo}}P_{\mathrm{bo}} + Q_{\mathrm{fo}}P_{\mathrm{fo}}}{Q_{\mathrm{bi}}P_{\mathrm{bi}} + Q_{\mathrm{fi}}P_{\mathrm{fi}}} \times 100\% \tag{3}$$

where Q_{bi} and P_{bi} is the hydraulic pressure of the brine stream entering the pressure exchanger, Q_{bo} and P_{bo} is the hydraulic pressure of the brine stream leaving the pressure exchanger, Q_{fi} and P_{fi} is the hydraulic pressure of the feed stream entering the pressure exchanger after pre-treatment and Q_{fo} and P_{fo} is the hydraulic pressure of the feed stream entering the booster pump, respectively. Any process equipped with pressure exchanger device consumes 15–30% less specific energy to operate a comparable process with centrifugal ERD [57].

Pressure exchangers increase salinity of the feed due to mixing of brine and feed water, causing higher osmotic pressures in the RO stage. Increase in salinity of the feedwater is reported in the range 3-5% which requires additional pressure around 2 bar. To estimate the increase in the feed water salinity the following simplified equation can be used:

$$\mathrm{SI} = R^{*}6.15\%, \qquad (4)$$

where SI is salinity increase and R is membrane recovery [47,57]. About 1–2.5% of the brine flow to the pressure exchanger is consumed as leakage or lubrication flow. The exact lubrication flow rate depends upon system pressure, temperature, seawater and brine flow rates, and device characteristics which is supplied by the high-pressure pump [47]. The manufacturers of the pressure exchanger device claim that with one moving part, tough engineered-ceramic construction and exceptionally high efficiency, the PX device is designed for easy, long-term, maintenance-free, low-cost operation. The operational performance of pressure exchangers at different plants worldwide were summarized by Cameron et al. [56]. Apart from this, the positive displacement ERDs contribute to about 16% of energy savings in the RO process [58].

2.4. Positive displacement, work exchanger systems

The work exchanger system is based on moving pistons in cylinders as shown in Fig. 5d. Critical elements in the system are cylindrical piston moving parts, pressure vessels and a nest of check valves. The working principle of the pressure exchanger is shown in Fig. 5d. This device works in cyclic pattern in that each cycle consists of working and filling strokes. Number of these cyclic working and filling strokes results in exchange of brine pressure to the feed stream pressure. Similar to pressure exchangers, a slight mixing of brine stream with the feed is always possible in this device. Although the piston and cylinder arrangement is well suited for a wide range of viscosities and densities, the system, on account of its large foot print and susceptibility of the moving parts to chemical attack, and noise pollution are the major drawbacks of the technology. Energy recovery retrofits are hardly conceivable as well [59]. Work exchangers also require additional controls to operate valves and to limit piston movement and they are usually supplied with a PLC (programmable logic controller) which ensures the cycling of the pistons. A timer is set to provide a signal to LinX valve to operate and sensors are used to detect the over-or under flush [60–62].

Centrifugal type ERDs are most widely used in the RO industry today, although, installation of positive displacement ERDs is on the rise recently [43,57,60]. The pressure exchanger type ERDs show promise for greater energy recovery potential with nearly constant efficiency regardless of changes in membrane recovery, aging, fouling, or seasonal variation of temperature and salinity, which often occur with beach well intake systems [45]. Turbine systems suffer large reductions in efficiency if operated outside the actual design point or best efficiency point (BEP). The Pelton type ERDs provide reasonable ERE. The application of the ERDs depends on the type of application. These may not be of great potential but add to the cost of the desalinated water if the feed stream is brackish water with very low dissolved solids (TDS) or if local energy cost or the production rate is very low. The cost of pressure exchanger group installation is much higher than (almost 2 times) the centrifugal type rendering their applications to only large scale seawater desalination. These require additional booster pump, larger foot print, sound abatement structure and constant monitoring [59].

Table 3 shows energy consumption in RO without and with different types of ERDs. It should be noted that until recently small scale RO processes did not incorporate ERDs due to their high initial capital and installation costs [29,39,44,46,63–71]. Small scale RO processes for seawater desalination have high SEC whereas the SEC is very low for brackish water desalination irrespective of the plant size. The specific energy requirements and desalination costs vary between different plants due to geographical location (which affects the financial package, equipment and labor cost) and feed water characteristics. The inland desalination plants need to operate in stages more than one to improve the water recovery and to reduce concentrate volumes that result from the process. From the data provided in Table 3, it is very clear that positive displacement ERDs show great promise for large scale applications by their low SEC. Centrifugal type ERDs operate with reasonable efficiencies, these are suitable in areas where the energy cost is not so high because they are much cheaper than pressure exchangers or work exchangers.

2.5. Recent developments in ERDs

The concept of energy recovery is not new. ERDs based on centrifugal and positive displacement principles have long been developed and used in many applications. A new concept called 'PROP' for energy control and recovery was developed by Manth et al. [43]. The basic concept of 'PROP' is to utilize the most reliable and field-proven energy recovery or control tools and rearrange the components in a fashion that energy dissipation or energy losses are reduced. These energy recovery tools are Pelton turbines, variable frequency drives and booster pump. The 'PROP' concept

Table 3
Energy consumption and desalination costs in RO process

Location	Capacity (m^3/d)	Salinity (%)	RO configuration	ERD type, Efficiency	Water recovery (%)	SEC kWh/m^3	Cost $\$/\mathrm{m}^3$	Ref
Perth, Australia	0.5–0.7		Single stage	w/o ERD		4-5.8		[63]
Mexico	0.71	0.3	Single stage	w/o ERD	37	6.9		[63]
Jeddah	3.2	4.28	Single stage	w/o ERD		13		[63]
Vancouver, Canada	0.5–1.0		Single stage	w/o ERD		10		[63]
Sadous, Saudi Arabia	5.7	0.57	Single stage	w/o ERD	21-35	18		[63]
St.Lucie, Florida	0.64	3.2	Single stage	w/o ERD	10	13		[63]
Doha, Qatar	5.7	3.5	Single stage			10.6		[63]
Suderoog, North sea	4.8	2.8	Single stage		25	36.3		[63]
Perth, Australia	0.5–0.7		Single stage	w/o ERD		4–5.8		[63]
Athens, Greece	1.7–2.2			w/o ERD	7–10		5.15–7.63	[4]
Hammam-lif, Tunisia	0.1			w/o ERD	25–37		14	[4]
USA	567	0.21		w/o ERD		1.85	0.14	[64]
Canada	1,892	0.16		w/o ERD		2.25	0.3	[65]
USA & UAE	37,850	BW				1.85–3.7	0.925–2.25	[38]
USA & UAE	16,654	SW				9.5–12.7	0.93–2.25	[38]
Loughborough, UK	11	4	Single stage	Clark pump, 97%	35–40	3.5	4.32	[65]
Athens, Greece	2.6	3.5	Two-pass	Clark pump, 97%	20	3		[67,68]
Planier, France	12			Pelton turbine	25	7.8		
Ithaki	9,275			Pelton turbine		9.38	0.11*	[46]
Syros	17, 856			Pelton turbine		6.16	0.04*	[46]
Mykonos	15,000			Pelton turbine		8.36	0.13*	[46]
Oia, Greece	12, 000			Pelton turbine		4.6	0.29*	[46]
Oia	9,000			Pelton turbine		5.28	0.13*	[46]
Las Palmas, Spain	33,000	3.75	Two-stage	Pelton turbine	55	4.44		[69]
Las Palmas, Spain	80,300	3.83	Two-stage	Pelton turbine	52	4.44		[69]
Aqualectra, Curacao	10,200		Three-stage	Pelton Turbine	40	4.2		[71]
Anguilla	3,400			Pelton Turbine	58	4.0		[71
Las Palmas, Spain	10,000	3.75	Single stage	Francis Turbine	40	5.75		[69]
	36,000	3.83	Two-stage	Francis Turbine	45	6.16		
Oia	5,400			Turbocharger		4.65	0.13*	[46]
Grand Cayman	1,071			TurboCharger (67%)	50	3.15		[70]
Ios	15,000			PX-60		3.02	0.12*	[46]
Port Hueneme	50	3.2		Pressure exchanger (95%)	36	2.0		[29]
Perth Australia	160,000	3.5		Pressure exchanger (97%)	42	2.5		[29]
WEB, Bonaire	1,630		Two-pass	Dyprex PX	58	2.85		[29]
Handsome Bay	568		1-pass	Dyprex PX	40	3		[29]
Grand Cayman	1,027			DWEER (89%)	50	2.42		[70]
Grand Cayman	1,699			DWEER (92%)	50	2.31		[70]
	150,000	3.5	Single-stage	DWEER	45	2.01		

(continued)

Table 3 (continued)

Location	Capacity (m^3/d)	Salinity (%)	RO configuration	ERD type, Efficiency	Water recovery (%)	SEC kWh/m^3	Cost \$/m^3	Ref
Las Palmas, Spain								
Larnaca, Cyprus	40,000				50		0.83	[2]
Tampa, Fl	94,600	3.5			60		0.55	[3]
Athens, Greece	1.7-2.2				7–10		5.15–7.63	[4]
Hammam-lif, Tunisia	0.1				25–37		14	[4]
Small trains	1000	4	Single stage	Pelton, 79%	45	4.35		[45]
				HTC, 80%		4.29		[45]
Large Coventional	15,000	4	Single stage	Pelton, 79%	45	3.19		[45]
				HTC, 80%		3.19		[45]
				ERD, >95%		2.79		[45]
Large low-energy	15,000	4	Single stage	Pelton, 79%	40	2.44		[45]
				HTC, 80%		2.42		[45]
				ERD, >95%		1.93		[45]
Kuwait	4,542	SW				12.5	2.3	[38]
Kuwait	4,542			w/ERD		9.25	2.11	[38]
Kuwait	1,892						1.32–1.74	[38]

*Membrane costs only (ϵ/m^3).

can be applied to both single stage and multi-stage RO configurations, i.e. in brine conversion systems (BCS).

Another device called ''Clark pump'' was developed by Keefer, Wilson and Permar [72–74]. Spectra Watermakers of California, USA has developed this technology in late 90's which is covered by US patents 5,462,414 and 5,628,198 [73,74]. The Clark pump is small-scale, in its basic configuration, it is used with a single 2.5- by 40-inch spiral wound seawater RO membrane element. It recovers the mechanical energy from the brine stream and returns it directly to the feed flow. The Clark pump consists of two pistons solidly connected by a rod, and a cylindrical housing. Medium pressure feed and the concentrate pressure both act to push the piston assembly to the right, thus driving the high pressure. At the end of stroke, the ports are reversed and the piston assembly travels back to the left, until it again reverses. The mechanism to operate the ports is built within the Clark pump and the overall operation is very smooth in practice. Two stage hydraulic recovery of the Clark pump unit was demonstrated recently which resulted in SEC of 3 kWh/m^3 of freshwater [67,68]. This device is only suitable for small scale application due to fluctuation limitations in flow and pressure.

The pressure exchangers have also undergone several design improvements after they have been first introduced in 1997 [48,55–57,75–78]. Present single rotor capacity of the pressure exchanger is 50 m^3/h. In May 2004, the SalTec system was installed in a 1,920 m^3/d SWRO plant in Sharm El-Sheikh, Egypt by KSB. The new size of the SalTec DT was developed in 2005, which provides a nominal capacity of 250 m^3/h. In 2007, ERI announced the successful development of the Titan PX-1200^{TM}. This device was designed to operate at flow rates up to 273 m^3/h or 1,200 gpm. A prototype device is now in operation in the Inima seawater RO facility in Los Cabos, Mexico, since October 2008 [57].

A major improvement in the DWEER system has been the development of the linear exchanger (LinX) valve, which has the largest available a single DWEER unit with a capacity of 500 m^3/h [25,48,70]. In a recent study, a fluid switcher component was introduced into work exchanger design and its impact on the hydraulic recovery efficiency was reported. A hydraulic efficiency of 77% was reported in this study. Details of the fluid switch operation can be found elsewhere [25].

3. Reverse osmosis operating strategies

A hydraulic envelope concept which includes all the flow rates and pressures associated with feed water, brine and permeate streams and pumps at different points of RO process operation was discussed in a previous report [43]. The process parameter values within the hydraulic envelope can be manipulated to

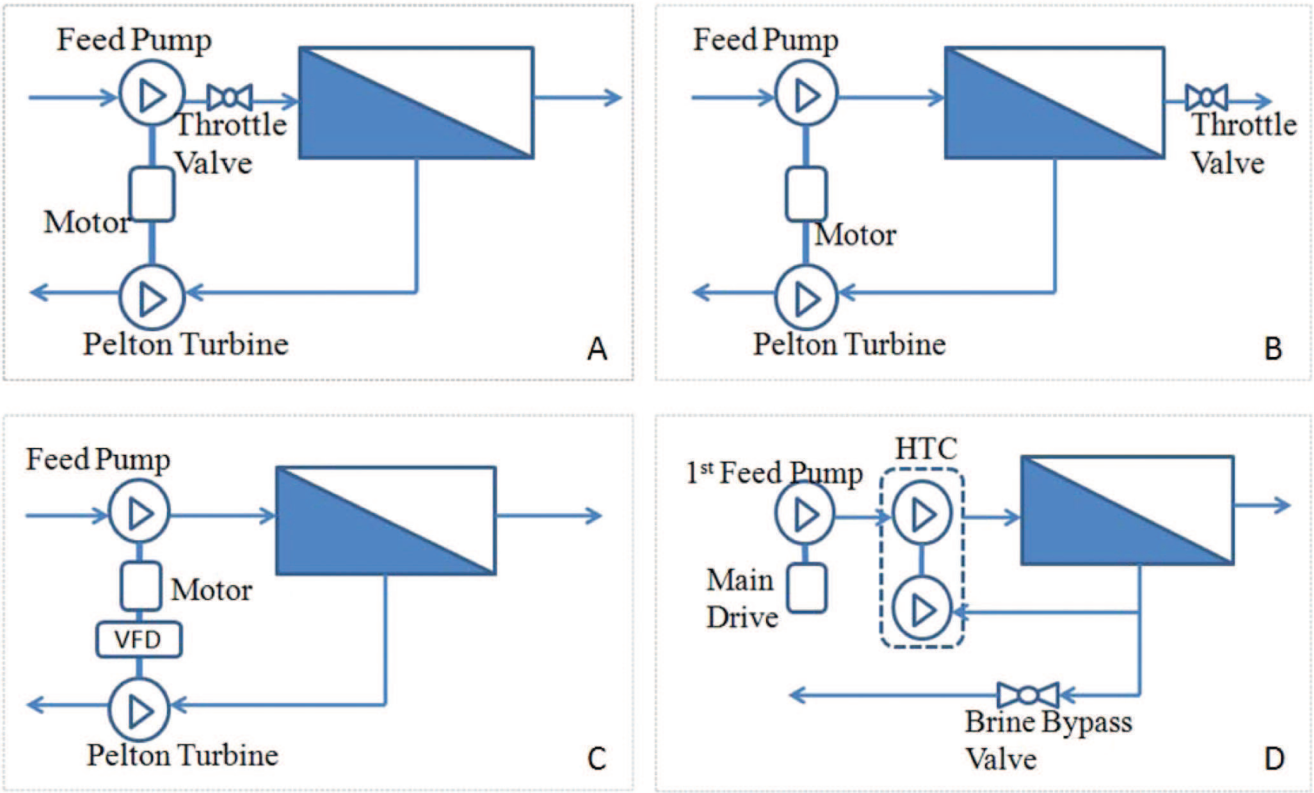

Fig. 8. Reverse osmosis plant operating strategies; (a) control by feed throttling, recovery by Pelton turbine, (b) control by permeate throttling, recovery by Pelton turbine, (c) control by variable frequency drive (VFD), recovery by Pelton turbine, (d) control by throttling, recovery by hydraulic turbine charger (HTC).

produce desired results, for example, change in permeate demand, membrane cleaning schedules, changes in water recovery ratios due to required water quality, and energy recovery. Energy recovery in RO process can be achieved by operating in various configurations that result in either energy dissipation mode or energy control mode. The following typical RO operating strategies are available for successful operation of RO process using ERDs: (i) Control by feed throttling, recovery by Pelton turbine; (ii) Control by permeate throttling, recovery by Pelton turbine; (iii) Control by variable frequency drive (VFD), recovery by Pelton turbine; (iv) Control by throttling, recovery by Hydraulic Turbine Charger (HTC), (v) control and recovery by turbocharger and VFD; (vi) control and recovery by turbocharger and helper turbine; (vii) energy recovery by pressure exchangers controlled by VFD at the booster pump; (viii) energy recovery by pressure exchangers controlled by VFD at the high pressure feed pump; (ix) energy recovery by work exchangers controlled by VFD at the booster pump; (x) energy recovery by work exchangers controlled by VFD at the high pressure feed pump; (xi) energy recovery by work exchangers controlled by VFD at the feed pump to the work exchanger. Four operating strategies utilizing Pelton and turbocharger ERDs are shown in Fig. 8 [43,59].

3.1. Control by feed throttling, recovery by Pelton turbine

In this configuration (Fig. 8a), the feed pressure entering the membrane module is maintained constant by installing a throttling device while running the high pressure feed pump at constant speed. Energy associated with the brine stream is recovered by the Pelton turbine and supplied to the shaft of the high pressure feed pump. This is the simplest working configuration of RO process. Since the inlet pressure to the Pelton turbine varies due to pressure drops in the module and changes in water recovery ratio, whereas the duty point of the feed pump remains constant which needs to be designed to match the BEP of the device.

3.2. Control by permeate throttling, recovery by Pelton turbine

The other configuration with throttling device is to maintain the high pressure feed pump at constant speed and maintain the membrane module pressure by throttling the pressure on the permeate side

(Fig. 8b). In this configuration, the pressure drop is achieved by discharging permeate at lower pressures.

3.3. Control by VFD, recovery by Pelton turbine

In this configuration, the throttling valve is replaced by the VFD which will maintain the pumping speed of the high pressure feed pump to adjust the difference between power dissipated by the brine stream and feed pressure at the membrane module. This is accomplished by varying speed and torque of the pump shaft and pump outlet conditions can be varied in a wide range by utilizing the VFD device (Fig. 8c).

3.4. Control by throttling, recovery by HTC

The turbocharger recovers the energy from the brine stream and transfers to the inlet feed water stream to supply to membrane module as shown in Fig. 8d. This reduces the energy to be dissipated by the high pressure feed pump, thus saving the energy. Turbocharger is a single case integral feed pump and energy recovery turbine. By incorporating a throttling device on the brine stream, the amount of pressure recovered and dissipated to the feed water stream can be well controlled by discharging a portion on the brine stream that matches the requirements at the membrane module.

3.5. Control and recovery by turbocharger and VFD

In this configuration, the need for brine throttling valve can be eliminated by installing a VFD on the high pressure feed pump by regulating the pump operating speed. This converts the system shown in Fig. 8d from energy dissipation mode to the energy control mode. In this case, full brine stream can be allowed to flow through the HTC to recover maximum energy that is released as boost pressure to the feed water stream. The feed conditions for the HTC are varied through the VFD on the feed pump.

3.6. Control and recovery by turbocharger and helper turbine

Combining turbocharger and Pelton turbine in the same system is another method to reduce throttling. This configuration enables to eliminate the need for feed throttling or requirement for VFDs. The throttling on the brine stream (Fig. 8d) can be directed to feed through a helper turbine which in turn is connected to the shaft of the high pressure feed pump as in Fig. 8a. In this configuration, high pressure brine stream flow between the HTC and Pelton turbines are split using variable area nozzles in accordance with the hydraulic requirements.

3.7. Energy recovery by pressure exchangers controlled by VFD at the booster pump

In this configuration, the feed water stream entering the pressure exchanger will be charged by the pressure transferred from high pressure brine stream. The feed water stream leaving the pressure exchanger is pumped through booster pump to match the flow through the high pressure feed pump. This can be achieved by introducing a VFD on the motor of booster pump to regulate the pump speed that will match the high pressure feed pump which is constant. This configuration is similar to that shown in Fig. 8c where the Pelton turbine is replaced by a pressure exchanger and a booster pump.

3.8. Energy recovery by pressure exchangers controlled by VFD at the high pressure feed pump

In this configuration, a VFD is introduced on the high pressure feed pump motor to regulate the speed to control the pressure in the feed stream. This will be regulated in accordance with the membrane pressure required in the module and desired water recovery ratio. Since the high pressure feed pump consumes a large portion of the energy in the process, VFD installation on the high pressure feed pump motor is expected to result in greater energy savings.

3.9. Energy recovery by work exchangers controlled by VFD at the booster pump

This configuration is very similar to that explained in Case (vii). Variable frequency drive on the booster pump assists to control the high pressure brine stream entering the work exchanger and thus energy transfer between the feed water stream and the brine stream to match the feed flow at the membrane module. This configuration is identical to Fig. 8c where the Pelton turbine is replaced by a work exchanger and a booster pump.

3.10. Energy recovery by work exchangers controlled by VFD at the high pressure feed pump

Installing a VFD on the high pressure feed pump motor regulates the pump speed to impact a pressure to balance minor losses in the work exchanger and to match the membrane pressure depending on the water recovery rate. This can also be achieved by product flow rate control valve or a permeate throttling valve (Fig. 8b) on the freshwater discharge as discussed in Case (ii).

3.11. Energy recovery by work exchangers controlled by VFD at the feed pump to the work exchanger

The portion or flow rate of the feed water filling the work exchanger can be adjusted using VFD on the feed

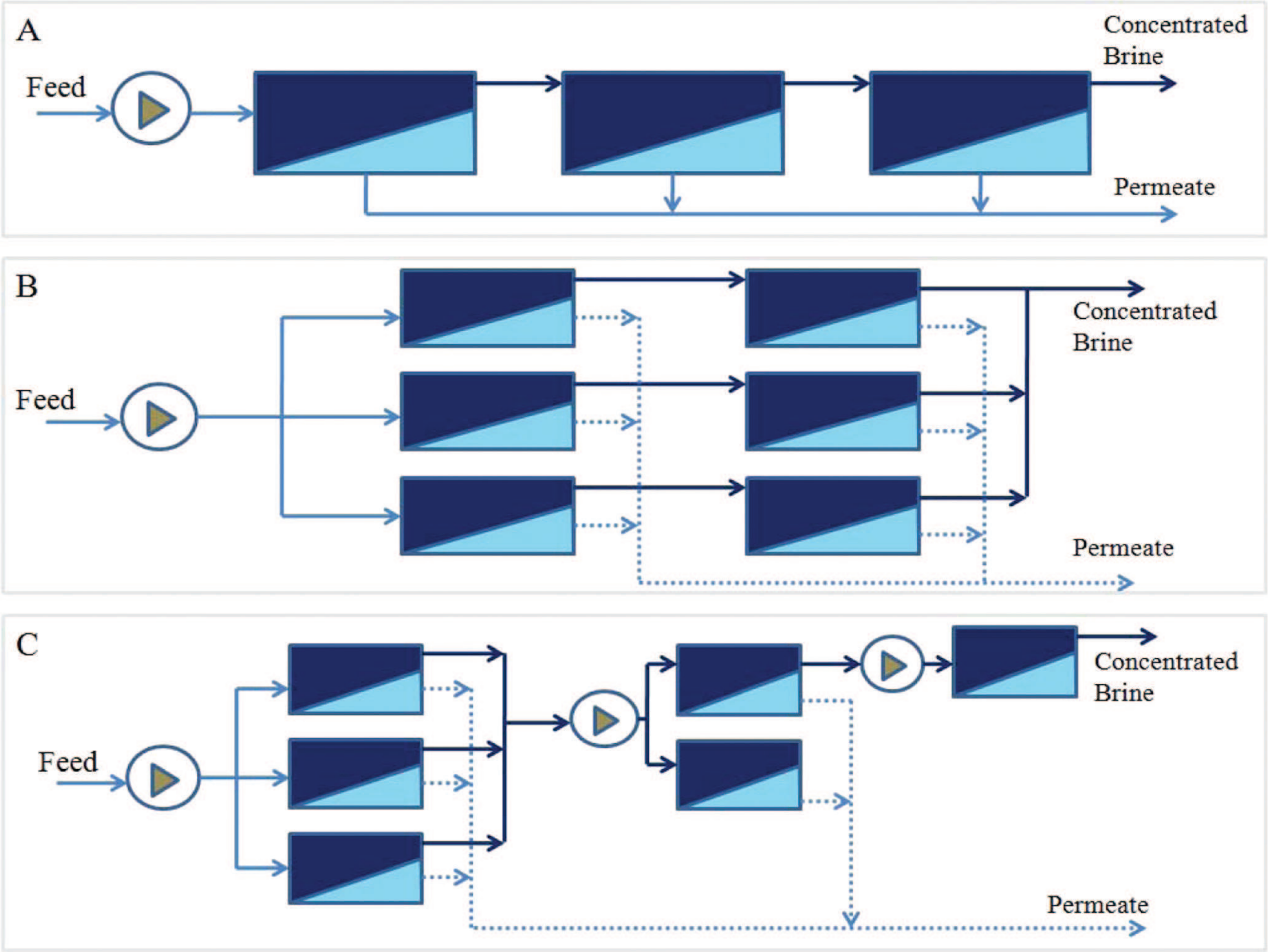

Fig. 9. Different array configurations of reverse osmosis.

supply pump, i.e. two pumps are used to pump part of the feed stream to the high pressure pump and part to work exchanger. This can alternately be achieved by the work exchanger PLC (programmable logistic control) to control brine back pressure valve [56]. These two options are also possible for RO process units with pressure exchanger ERDs.

4. Energy recovery configurations in RO process

To achieve higher water recovery and to meet the stringent permeate water quality, RO processes are arranged in multi-stage and pass configurations. As shown in Fig. 9, they are arranged in series (Fig. 9a), parallel (Fig. 9b), and tapered (Fig. 9c) array type configurations [23]. In these configurations, inlet feed pressure for the first stage is increased considering the trans-membrane losses in the individual RO passes. Few configurations install booster pumps between passes to maintain the trans-membrane pressure losses. This is the simplest configuration contributing to energy recovery without use of ERDs. The critical performance features of membrane modules are salt rejection and water permeability. The average permeate flow per element in seawater system is about 12 m^3/day and in brackish system is about 23 m^3/day. The RO membranes are characterized by high rejection of TDS in the range of 98–99.5% [23].

4.1. Low pressure (low energy) and high recovery (high flow) RO membranes

The energy costs of RO were significantly improved with invention of low pressure membrane systems (nanofiltration or loose RO membranes) [79]. High productivity or permeable membranes with high rejection characteristics and low pressure operation have made the membrane technology applications more practical. Selecting appropriate membranes based on the feed water quality or the desired permeate quality may result in significant energy savings. There are mainly three types of membranes: (1) nanofiltration membranes (suitable for feed < 500 mg/L TDS, 0.74 MPa at 25°C); (2) low pressure RO membranes or brackish water membranes (suitable for feed < 1,500 mg/L TDS, 1.5 MPa, 25°C); and (3) seawater membranes (5.5 MPa, 25°C). The seawater membranes are made up of cellulose acetate, aromatic polyamide, cross-linked polyether, polyamide and other thin-film composite membranes which have salt rejection capacity in the range of 99–99.9%. Low pressure RO membranes such as BW-30 (Film tec), SU-700 (Toray), A-15 (Du Pont) and NTR-739HF (Nitto-Denko) have salt rejection capacity in the range of 99–99.5%. Nano-filtration membranes made up of similar materials as low pressure RO membranes have salt rejection capacity in the range of 50–90% [79,80].

In the middle of the 1990s, elements with flow rates of about 6,000 gpd (1.58 m^3/d) and rejections of 99.6% were introduced as FILMTEC SW30HR-380. The typical seawater element productivity of 6,000 gpd (1.58 m^3/d) became a standard among various membrane suppliers for the second half of the 1990s. Several other low energy membranes were also developed Toray, Du Pont and Aquatech companies which provide 99.8% rejection and 9,000 gpd at standard conditions. Two new higher productivity elements were developed by FILMTEC recently and they rely on the following developments: high salt rejection, low energy element FILMTEC^{TM} SW30HR LE-400 relies on various improvements to the SW30HR-380 membrane and element configuration. FILMTEC SW30HR-320 and FILMTEC SW30HR LE-400 have shifted the productivity by 20–25% while still keeping within the operating windows of most seawater plants with high rejection capacities of 99.7–99.75%. Field studies confirm that new membranes could reduce energy consumption down to levels of 2.0 kWh/m^3 or reduce the capital cost of the membrane stage by up to 30% [81]. Recently, new ultra low-pressure SWRO elements that provide 99.8% rejection and 12,000-gpd flow have been developed. Another recent study with high flow/low energy membranes by Bartels et al. have tested three types of low pressure/high flow membranes [82]. They have tested the ultra low pressure SWRO membranes with seawater from the Pacific Ocean with TDS 33,800 mg/L. The plant considered was a 40-mgd plant with 10 trains operating at 8.1 gfd flux and 50% recovery. The study showed that SEC for ultra low pressure membrane was 2.46 kWh/m^3 with permeate concentration of 372 mg/L and the SEC for high pressure, low flow membrane was 2.69 kWh/m^3 with permeate concentration of 181 mg/L. Hybrid element design combining three types of membranes with the goal to achieve permeate concentration less than 450 mg/L and the economic analysis were also reported [82]. Thirty month research and evaluation study of new thin film nanocomposite (TFN) hand-cast membranes was reported recently [83]. Improved flux and rejection capacity over current commercial high-flux SWRO membranes was reported.

4.2. Two pass RO system for energy recovery

In small scale RO operations and brackish water desalination processes, it may not be advantageous to install an ERD. Depending on the feed water quality, low pressure membranes with lower energy consumption rates can be employed to produce freshwater from low TDS feed waters. This can be done in two stages. In a 2-stage RO desalination plant, the first one is of high permeate flow with less salt rejection to produce permeate of 700–1100 ppm, which is entirely used as a feed to low energy brackish water membranes as shown in Fig. 10. The brackish water membrane can produce salinity of 50 ppm. The product pressure of the first stage can be raised in the range of 9–15 bar to go through a second product stage without pumping [84,85]. By doing this, the SEC can be reduced to as low as 1 kWh/m^3 for low TDS brackish waters. In a study by Cardona et al. the SEC of a two-pass membrane desalination process, which they termed ''double-stage'', was compared to a single-pass RO process, both without the use of an ERD. Based on a specific case study using standard process model calculations for a target salt rejection of 98.3% and 41.2% water recovery, it was concluded that the two-pass process has a potential for energy savings on the order of 13–15% for the specific case of less than 50% total water recovery. A recent report on extensive pilot studies of a two-pass seawater NF desalination process by the Long Beach Water Department suggested that the two-pass process would require about 20% less energy, when operating at 42% product water recovery, compared to a single-pass RO membrane desalination process [86].

4.3. Two stage brine conversion SWRO system

A new technology called brine conversion two-stage SWRO system (BCS) was developed [12,71]. This system includes several new components such as system configuration, energy recovery, operating condition, high-performance membrane technology, anti-biofouling technology and a new analysis method. The brine generated from the first stage is pumped through the second stage to recover the freshwater out of brine. In the first stage, a 40% recovery is achieved

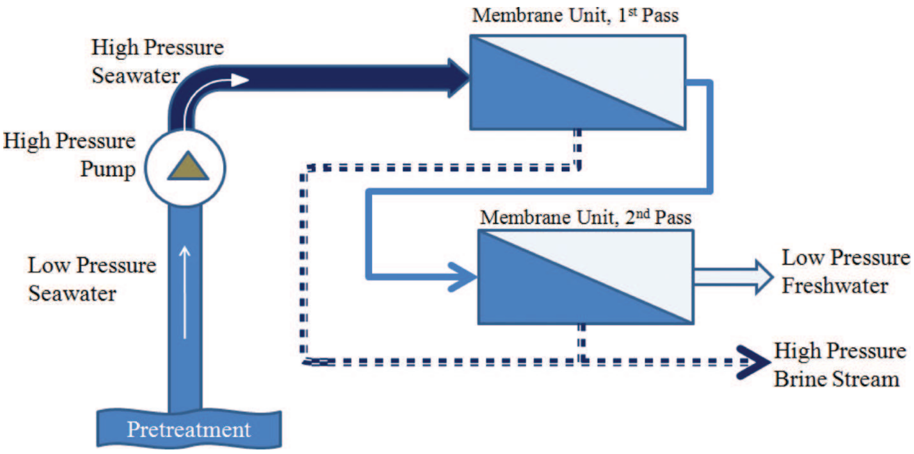

Fig. 10. Schematic of the two-pass RO system.

while in the second stage an additional 20% recovery of total intake is achieved (Fig. 11). Thus a total of 60% freshwater recovery of the total seawater intake is possible with this technology. A pilot plant has been operated successfully at Toray's Ehime plant site since 1997. The first commercial plant of 4,500 m^3/d (1.2 mgd) has been operating successfully since March 1999 in Mas Palomas (Gran Canaria, Spain) [71]. Some other plants are in operation in the Caribbean, Japan and Spain which produce bottled drinking water. The BCS is presumed to be the standard SWRO system for the 21st century. For high pressure RO systems, the possibility of extracting 2nd stage energy by a pressure exchanger or a turbocharger is under investigation. Energy audits conducted on the case studies reveal that the brine stream may have up to 22% recoverable energy in one stage RO units [87]. The 'PROP' technology discussed earlier in Section 2.5 can be applied to recovery energy from the exit brine stream [43].

4.4. Inter-stage energy recovery

An extension of the above process with energy recovery from the second stage concentrate with the help of an inter-stage booster pump will improve the SEC of the overall process. The function of the inter-stage booster pump is to increase the pressure of the first stage concentrate stream prior to it being directed as the feed stream to the second stage. This is accomplished by routing the second stage concentrate through a reverse turbine or pressure exchanger (Fig. 12) and utilizing residual pressure from the second stage concentrate stream to increase the feed pressure to the second stage. This source of ''free energy'' allows the second stage to be operated at higher feed pressure than that of the first stage, which permits both stages to operate more efficiently and produce higher quality finished water. Field studies conducted at the Marco Island ROWTP demonstrated that a membrane train with an inter-stage boost pump between the first and second stages is more efficient than the process

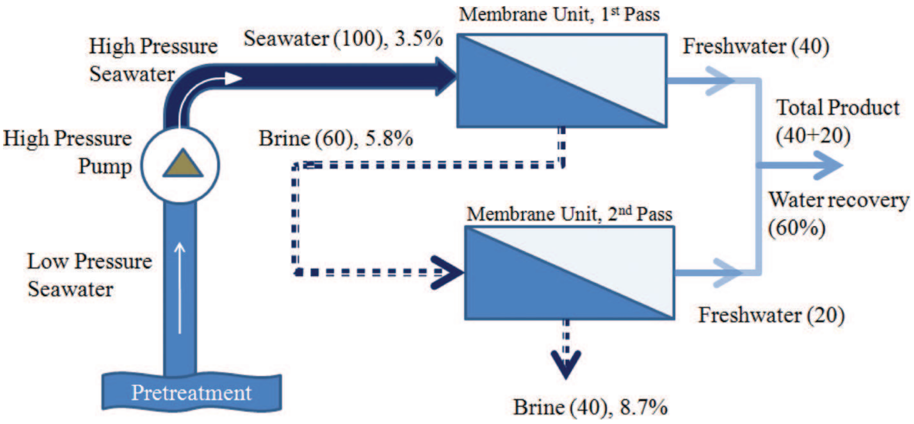

Fig. 11. Schematic of the two-stage brine conversion SWRO system.

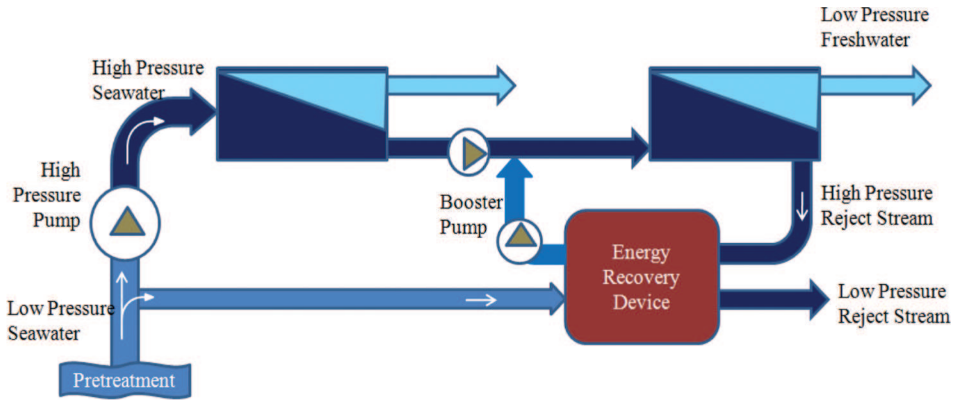

Fig. 12. Inter-stage booster-pressure exchanger hybrid configuration.

train without inter-stage device. The inter-stage hydrid configuration improved the first and second stage recoveries to 55% and 45%, respectively, compared to recoveries in the configuration without this device which are 60% and 35%, respectively [88].

4.5. Other issues in energy recovery

Some investigations carried out on SWRO plants in the middle east reveal that the maximum energy losses in the SWRO plants is in the form of throttling wastes which counts as high as 21.8% of the total energy requirements. The average overall efficiency of the ERDs ranged from 3.2% to 65% which enabled savings of about 1.5% to 27% of total energy consumed by the high pressure pump. The average power consumed by the high pressure pump was in the range of 5.56–7.93 kWh/m^3. This study suggested that reducing the throttling losses as well as incorporating better ERDs can improve the energy requirements of SWRO process [18,40]. Another study highlighted the fact that the real-time operation of an RO plant depends on various parameters such as feed water concentration and actual permeate requirements. This means that the required feed, brine and permeate pressures vary depending on the feedwater salinity, temperature, membrane condition and desired recovery rate. Another important aspect is that plant hydraulics and operating conditions have to be adjusted based on the variations in the duty range. This study suggested utilizing a control device that can tune the process parameters in response to the actual process demand; it can be a throttling device or VFD. Reducing the speed of the VFD will improve the capacity of pumps and motors so that the capacity of RO units is increased. The purpose of throttling device is to dissipate the energy which counteracts the purpose of ERDs as observed in the study conducted by Farooque et al. Another recommendation is that when considering an ERD for a desalination plant, the entire range of process parameters and process control strategies need to be accounted [43].

5. Water recovery

Low recovery rates of seawater RO plants have resulted in 60–65% of the pretreated, high pressure concentrated stream to be disposed without recovery of hydraulic energy. Limitations on the membrane design prevent the seawater RO processes from operating at higher water recoveries. As the water recovery increases, the concentration of salt in the brine stream also increases. Hence, the pressure that must be applied to overcome the osmotic pressure of the brine stream increases. Most spiral wound RO membranes can operate up to 82.7 bar (1,200 psi) at temperatures below 29°C (84.2°F). If water recovery is increased, the pressure limitation of the membrane becomes a limit on recovery before any limits on water chemistry are reached. If water recovery were to be increased to the water chemistry limit, rather than the membrane pressure limit, then the RO membrane would have to be capable of operating at pressures up to 98 bar (1,420 psi) [29,71].

For inland brackish water applications where the recharge rates are slow, similar to energy recovery, water recovery is important to manage the limited water resource wisely. It should be noted that for inland brackish water applications, the intake is similar to mining and resource may not be renewable depending on the local precipitation and geographic conditions. If raw water salinity and recovery are low (brackish waters), then the reject stream can most likely be used for washing, cleaning and toilet flushing. However, as either of these values increase, this concentrate is less and less usable and requires treatment

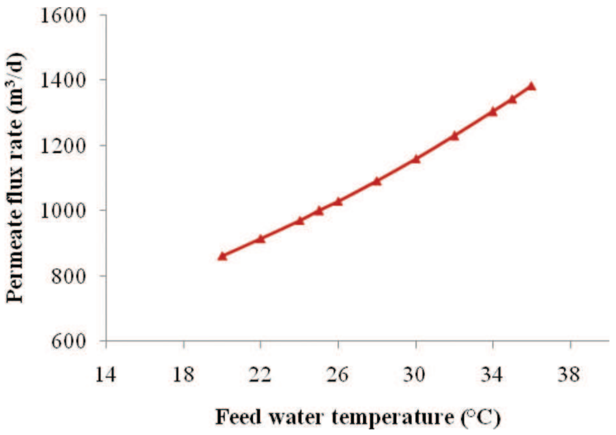

Fig. 13. Effect of feed water temperature on the water recovery.

prior to disposal. This can be a severe constraint to membrane applications in any community [89]. Apart from this, other options would be to recover more water in the second stage supported by a positive displacement pump or to increase the temperature of the feed water to enhance the recovery rate.

5.1. Water recovery in small and low pressure systems

In small capacity RO systems, for example, in domestic applications with low water recovery, it may not be economical to incorporate ERD into the system. The process economics may not permit either having additional pumps with higher capacities. As such, small RO systems are often built without any energy recovery mechanism. They have a needle restrictor valve to provide the backpressure in the concentrate. This keeps the capital cost down but is very wasteful of energy. Typically, 70% of the input power is wasted in the valve and, consequently, such systems often consume more than 10 kWh/m^3, making them very expensive to run. In order to recover the energy in the brine stream, a small secondary positive displacement pump can be adopted to raise the pressure up to the feed water pressure entering the RO module and can be added to the line after the primary pump. It is known that only about 0.5–2 bar pressure drop is possible across the membrane which can be provided with the help an additional positive displacement pump of smaller capacity [89,90]. In high recovery systems the brine can be recycled back to the piston before the primary pump assisting it on its upstroke and thus reducing the power consumption of the pump significantly [91]. Another alternative to energy recovery is to improve water recovery in the RO process by improving the membrane performance. Dead-end ultrafiltration (UF) unit as a pretreatment to the RO process has shown promise in improving energy-efficiency and membrane performance. A requirement set by the RO membrane suppliers for successful operation of membrane is that the 15 min silt density index (SDI$_{15}$) should be less than 3. Since conventional pretreatment configurations cannot provide such high quality feed water, hollow fiber UF membranes can be used to provide a high quality, low SDI feed water regardless of the incoming seawater quality. Since the process operates in dead-end mode the SEC is as low as 0.1 kWh/m^3 for the pre-treatment [92].

5.2. Effect of feed water temperature

Water recovery in RO process can be improved by increasing the feed water temperature. An increase in the permeate flux of 60% was reported when the feed temperature was increased from 20 to 40°C [93]. The relation between permeate flux rate and the feed water temperature is shown in Eq. (5) [85]. However, the temperature tolerance of the RO membranes is in the range 20–35°C. Fig. 13 shows the effect of the feed water temperature on the permeate flux rate. The permeate flux rate increases by 34% when the feed temperature is increased from 25°C (1,000 m^3/d) to 35°C (1,344 m^3/d) theoretically. In other words, roughly 6.1% increase in permeate flow rate for every 2 degree temperature difference which can be achieved by utilizing process waste heat sources. When process waste heat is not available, utilizing solar collectors is a feasible option.

$$Q = Q_0 * 1.03^{(T_f - 25)} \tag{5}$$

In a recent study, the effect of operating pressures as well as the operating temperature was investigated for a steady-state operating case of RO process. The operating pressures ranged from 30 to 50 bar and temperatures ranged from 22 to 28°C. As expected, increasing the pressure resulted in improvements in the water recovery, salt rejection and energy consumed by the feed pump per unit volume of permeate produced. The improvements were larger for operation at low to moderate pressures than at high pressures. Both the permeation rate and salt rejection changed linearly with temperature; the permeate flux increased by 2.8%/°C whereas the salt rejection decreased by 0.007%/°C [94]. The permeate flux increase rate in this study is close to the estimated theoretical value. Concentration polarization, feed water concentration, feed temperature and pressure effects were studied recently [95–97]. Another study considered hybrid desalination plant in which thermal energy extracted from a MSF process was used in RO by mixing with the feed water. As a result, substantial energy savings in terms of reduced feed pressure in the range of 10 bar under the control measure of permeate flow rate were found [98].

5.3. Other water recovery options

Pretreatment by membrane filtration has shown increase in water recovery rates, long term performance of the membranes and lower energy consumptions in many field studies conducted by several researchers and companies [99–104]. Periodic operation is another method that has been found to substantially improve the productivity of the process [105]. Such improvements result from the fact that periodic operation yield fluid instabilities which, in turn, disturb the flux-limiting effects of concentration polarization and fouling. Kennedy et al. showed that improvements in RO of sucrose solution can be obtained by pulsing the feed flow over a tubular cellulose acetate membrane according to a harmonic function. At a frequency of 1 Hz, they obtained a 70% improvement in the permeate flux over steady-state operation [105]. Al-Bastaki and Abbas obtained a 13% increase in the permeation flux by varying the feed pressure of a simulated brackish water (10 kg NaCl per m^3 of distilled water) to an old FilmTec BW30 membrane which was in operation for over four years [106,107]. Cyclic operation has been found to produce significant improvements over steady-state operation for a variety of other processes including chemical reactors, distillation, adsorption and heat exchangers [95]. Other options of considerable interest are oscillatory flow, rotating RO and back-pulsing for membrane cleaning [108–112]. Recently, large diameter RO membranes were developed and tested in few field studies. These studies have shown that the installed costs of a RO plant can be reduced by up to 27% using larger diameter elements [113,114]. Large diameter elements provide savings in footprint and building costs, as well as savings in the number of connections, to reduce the installed cost of a RO system.

6. Summary

Energy consumption and recovery play vital role in the economics of RO desalination process. Several devices and process configurations for energy-efficient RO desalination operation are discussed. Depending on the type of feed water and freshwater capacity and desired permeate quality, different options incorporating both energy and water recovery can be implemented. ERDs reduce both SEC and product costs in large scale RO applications and water recovery options are suitable for small scale applications. Utilizing low energy, high permeable membranes reduce required feed pressures, thus energy requirements. Two-pass and two-stage RO operation along with a booster pump is also a viable option for small scale applications. Above all, reusing and recycling the permeate water for multiple uses will prevent additional energy consumption in the RO process. For large scale applications, installation of large diameter RO modules may reduce the installation costs by up to 27% due to savings in footprint, building costs and number of connections and pipelines.

Desalination by RO process has been accepted as a feasible option particularly in areas where transportation cost of freshwater and high living standards override the negative impacts of desalination. A recent evaluation for the city of Los Angeles, California concluded that freshwater supply based on RO desalination technology requires same amount of energy requirements (2.8 kWh/m^3) that would be required to transport surface water (2–3 kWh/m^3) from the delta region. Although, energy requirements for RO process have been reduced greatly over past few decades, yet significant portion of desalinated water cost is due to energy consumption. Therefore, process implementations including components such as energy dissipation, control and conservation methods still need to be developed.

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