Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2018.22403

118 (2018) 49–60
June

SWRO system performance optimization: part I – energy recovery devices

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Received 27 August 2017; Accepted 25 April 2018

ABSTRACT

Specific energy consumption (SEC) of seawater reverse osmosis (SWRO) is explored in relation to classes of energy recovery devices (ERDs), under different operating conditions. A test system of one array, 100 pressure vessels containing 7 SW30HR–380 elements is used via retrofitting the results of ROSA9.1 design software for calculations of SEC for different ERD categories of pressure exchanger (PX), hydraulic turbocharger (HTC) and Pelton turbine (PT), and their relevant equations. Parameters ranged as: feed temperature 15°C–45°C, feed flow rate 30–60 gpm (6.8–13.63 m^3/h), and feed salt concentration 32–52 g/L. SEC increases with increasing feed salinity and/or feed flow rate, and SEC decreases with increasing feedwater temperature. ERD saves SEC by 38%–63%. In terms of SEC, for a system withdrawing water with a salinity of 42 g/L, using ERD saves from 48% to 54%, 37% to 42%, and 36% to 41%, for PX, HTC, and PT, respectively. At different operating conditions, PX has the lowest SEC, followed by HTC and PT. Moreover, a new approach leads to determine the curves of SEC as a function of the system recovery, with and without using ERDs, has been carried out.

Keywords: SWRO optimization; Energy recovery device; Pelton turbine; Hydraulic turbocharger; Pressure exchanger; Specific energy consumption; SW30HR–380

1. Introduction

Desalination by seawater reverse osmosis (SWRO) is a valuable mean to deal with water scarcity. The adoption of membrane technologies over thermal technologies continues globally, aided in part by the reduced capital costs and versatility of reverse osmosis (RO), surpassing 30% of total awarded capacity in 2015 for the first time in 6 years, and can also be attributed to the slew of new large-scale projects in the last year [1,2]. Desalination processes are energy-intensive. Therefore, improvements in RO include optimized process design, higher permeability and salt rejection membranes, and higher efficiency energy recovery devices (ERDs) [3].

Over the last 20 years, energy consumption for SWRO has decreased due to ERD's optimization of recovery rate with respect to required feed pressure and performance improvements in high-pressure pumps. At the prevailing prices of seawater membrane elements, the major cost contribution results from the cost of process equipment and power consumption. An important parameter for SWRO process is permeate recovery ratio. The feed flow is inversely proportional to design recovery ratio, which directly affects power consumption. However, the recovery ratio cannot be increased as well, as higher recovery results in higher average feed salinity and higher osmotic pressure and increased, permeate salinity. The system recovery ratio has to be optimized with respect to membrane performance and process economics. With increasing recovery ratio to attain a minimum specific energy consumption (SEC) operation for SWRO process was impacted by the deployment of ERD, membrane and brine management costs and operation at lower recovery rates will increase the pre-treatment cost [4].

Design efforts to reduce power consumption and system cost result in a single-stage configuration and increase the number of elements per vessel. The majority of current SWRO system designs are single stage with seven elements per vessel.

Commercial SWRO membranes are characterized by salt rejection in the order of 99.7%–99.8%. Still for some

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applications, due to high feed salinity or temperature, a two-pass process is required to produce consistent permeate quality. Recent improvements in seawater membrane products have resulted in feed pressures in the range of 65 bar for the same design, which is a 4.5% overall reduction in pressure, based on published information from operation of actual RO seawater installations and recent studies [5]. However, the actual reduction in net driving pressure required for permeation has decreased by 14%. The main technological improvements have come from the optimized process design, higher permeability and salt rejection membranes, and higher efficiency ERDs [6,7].

SWRO system performance optimizations focus on system design and operation, energy reduction, and feed and discharge configuration.

2. SWRO design and optimal energy options

2.1. SWRO design considerations

Treating water often requires more than one technology to achieve the desired water quality for a specific application. Individual water treatment technology design tools make it difficult to optimize systems with multiple technologies to produce water reliably and at the lowest possible cost. As there is no single software for all membrane manufacturers and the majority of system designers understand the performance of individual pumps, membranes, valves and ERDs, the performance of complete SWRO systems can be complex and counter-intuitive [8].

A change in the output of one system component changes the input to other components, and the feedback can alter the outputs of all the components and with the availability of many software (e.g., GE-Winflows, Fluid System (Koch)–KMS ROPRO, Hydranautics–IMS, CSM–CSM PRO 200, Toray–Carol RO Design, TriSep–TROI, LG NanoH$_2$O–Q+, Filmtech–ROSA or WAVE).

ROSA 9.1 software was chosen to determine membrane performance and energy requirements for desalination. The use of software is influenced by the need to design a technically feasible RO system as ROSA software has been used for projecting desalination plants for its reliability more than 3 decades in many plants all over the world. The program runs multiple times (iterative process) under different water flow rates and pressures. The main program inputs include the source water, chemical characteristics, feedwater flow rate, feedwater and concentrate pressures, temperature, and pH. Then, a configuration of the number of membranes, pressure vessels, and type of membrane and feed is determined. After performing calculations, the program provides the amount of water produced and the energy required without ERD. The energy required to produce an intended amount of drinking water with acceptable water quality is then determined by running the program multiple times (iterative process). Booster pumps and an ERD can also be included in the design. Using ROSA, we determined several RO design options capable of producing potable water. After examining several design alternatives, the test case is a one-stage design 100 pressure vessels with 7 membrane elements. Choosing a one-stage system enables increased water productivity by applying a booster pump that recovers a significant amount of energy. Membrane used is SW30HR–380 with flow 6,000 gpd (23 m^3/d; at standard testing conditions) and high rejection (99.70%) for seawater desalination and resists up to about 83 bar of pressure. Moreover, the membrane is designed to properly function under intermittent energy supply, resists fouling, and enables effective cleaning. Any SWRO system containing ERD is affected by different operating parameters, which contributed to assigning the system performance as the product quantity, quality, and SEC, which is governed by the system's operating parameters, such as feed, temperature, flow rate, pressure, salt concentration, and the capability of the specified ERD to recover energy from rejected brine. In this study, the operating parameters range as: feed temperature T_f varied from 15°C to 45°C, feed flow rate Q_f varied from 30 to 60 gpm (6.8–13.63 m^3/h), feed salt concentration C_f varied from 32 to 52 g/L, and membrane fouling factor 0.9. The feed salinity of 38.6, 42, and 45 g/L represents salinities of Mediterranean Sea, Red Sea, and Arabian Gulf, respectively. The choice of these ranges of feed salinities for two reasons (1) representing desalination plants sites of most Arab Countries and (2) emphasis the importance of site selection in SWRO system design which differs from site to site according to temperature. The greater the feed temperature, the lower the feed pressure, to achieve membrane integrity, where the membrane fluxes increases by feed temperature increase. This results in lowering system operating pressure and eventually decreasing system productivity [9]. Projection results were taken at maximum pressures and respective membrane constraints.

2.2. Main groups of energy recovery devices

Energy recovery significantly improves the SEC. A distinguishing characteristic of RO desalination process that brine rejected by the membranes contains almost 50% of the energy required for desalination.

This is why the efficiency with which the energy contained in brine pressure can be transferred to the feedwater pump is critical for energy recovery [10].

Energy for desalination by RO is obtained from the following major contributors:

- Kinetic energy losses on membranes
- System kinetic energy losses
- Kinetic energy losses caused by membrane fouling
- Osmotic energy

Kinetic energy is energy needed to apply to RO system to have sufficient energy in the RO concentrate and to overcome losses caused by membrane elements, energy losses in the RO system, energy losses caused by the membrane fouling, and osmotic power. Energy losses caused by the membrane elements are a major focus of research and improvements by membrane manufacturers.

Energy losses due to membrane fouling are the focus of the operational companies and one of the key areas of research and improvements. Membrane fouling may cause significant energy losses during system operation and shorten lifetime of the membrane elements due to the increased frequency of membrane cleanings.

Energy required to overcome osmotic power is a function of the water salinity, temperature, and system recovery. The higher salinity and recovery, the more pressure is required to operate RO system. Most advanced SWRO systems are equipped with ERDs, which allow recovery of kinetic energy carried by the rejected RO concentrate [11].

ERDs can be classified according to physical principles. There are three categories: PX, hydraulic turbocharger (HTC), and PT.

The first category is the devices that use the centrifugal approach to convert the hydraulic energy found in the reject stream into rotational energy, which is delivered in the form of mechanical shaft power. Instead of being applied within a stand-alone package, however, they are typically applied as an add-on package in the form of a shaft assist mechanism. In an SWRO system, the recovered rotational mechanical energy must be transferred back to the seawater feed stream through the main high-pressure pump. Commercial examples of these devices include Pelton wheels and Francis turbines. The efficiencies of these devices can be quantified as the hydraulic energy out minus the motor shaft power in all divided by the hydraulic energy in. However, some manufacturers short-circuit this definition as the rotational/mechanical energy out of their device alone divided by the hydraulic energy in. This definition of efficiency leads one to believe that these systems can reach efficiencies between 80% and 88%. Although it is true that Pelton wheels can be 80%–88% efficient in converting hydraulic energy into rotational mechanical power that must be converted back to hydraulic energy to be useful. Therefore, the real net energy transfer efficiency equation must account for the efficiency losses of the pump and couplings. This results in real net energy transfer efficiencies between 63% and 76% over the flow range of Pelton-type systems [12].

A working formula of Sharm El-Sheikh SWRO units, Pelton turbine (PT) efficiency typically as ($\eta_{PT} = 2{,}684 + 0.008\,P_b$), where P_b is the brine pressure in bars will be considered in the present study [13].

The second category is centrifugal in nature and is commonly referred to as turbochargers. Commercial examples of such systems are pump engineering's TURBO and FEDCO's hydraulic pressure booster. An energy saving is achieved because the main high-pressure pump's required discharge pressure is reduced. HTC is mutually receiving the brine from one side, pumping the feed from the high-pressure pump on the other side (reverse pump and pump on the same shaft). Practically, there is discrepancy in HTC efficiency value, which ranged between 50% and 81% (as 81% [14], 80% [15,16], 75%–80% [17], 70% [10], 71% [18], and 50%–70% [12]). In the recent study, a typical HTC efficiency for brine energy recovery value of 68.4% ($\eta_T \times \eta_N \times \eta_P = 0.9 \times 0.95 \times 0.8$) is considered. The maximum capacity of commercial available HTC is up to 84,000 m^3/d [12].

The third category employs the principle of positive displacement and is commonly referred to as pressure exchangers (PXs). Commercial examples of such systems are ERI or isobaric PX, and Desalco's work exchanger energy recovery system. These technologies transfer the energy in the reject stream directly to incoming seawater stream that combines with the total feed stream to the RO membranes. An energy saving is achieved by reducing the volumetric output required by the main high-pressure pump. The efficiencies of these devices can be quantified as the ratio of hydraulic energy out to the hydraulic energy in. Most of the positive displacement devices achieve relatively similar net energy transfer efficiencies between 92% and 96% over the entire flow range of the systems [13].

3. Mathematical modeling

SWRO system performance is allocated through the productivity (quantity), salt rejection (quality), and SEC. SWRO system performance is affected by the system different operating parameters, such as the feed, intake type, temperature, flow rate, pressure, and salt concentration. The SEC is affected by the SWRO system performance, which is changeable from one system to another even under the same operating conditions, which sequentially depends upon SWRO membrane manufacturer, type, and system configuration. Therefore, in this recent work, the membrane permeability and system configuration are excluded to get a new approach for SEC and energy consumption of SWRO system at the different operating parameters. Moreover, a system of 1 array of 100 pressure vessels each containing 7 SW30HR–380 elements was used [19–21]. SW30HR–380 membrane is a proven technology for 3 decades all over the world, and choosing one type of membranes is to exclude the effects of membrane permeability and array configurations. The study is performed via ROSA 9.1 design software [22]. It is worth to mention that ROSA is a specific software for Filmtech membranes of Dow Chemical Company; meanwhile, most major membrane manufacturers have their own software. Unfortunately, chosen design software deals with SEC and does not deal with ERD. However, the results demonstrate system productivity (q_p), total consumed energy (E_{ROSA}) for high-pressure pump (E_{hpp}), and the brine energy content (p_b and q_b) available for conversion by ERD. Therefore, retrofitting ROSA results for calculation of SEC for different categories of ERD is required.

To depict a realistic comparison between different ERD groups, it is noticeable that SEC is affected by system operating parameters and ERD used. Therefore, a new approach leads to explore SEC simultaneously by linking consumed energy with system performance and remarkable ERD categories, at different operating parameters. Therefore, SEC can be calculated for different types of ERDs via the net energy content of rejected brine, the total system energy consumed from ROSA (E_{ROSA}) for high-pressure pump (E_{hpp}), and system productivity (q_p) for each ERD.

The pre-treatment flow pressure to high-pressure pumps and post-treatment has to be neglected when comparing SECs and assuming the following typical values:

$$\eta_{PT} = (0.25 + 0.0006\,p_b), \text{ for } p_f \leq 1{,}000 \text{ psi [13]}, \eta_{HTC} = 0.684, \eta_{hppt} = 0.8, \eta_{PX} = 0.92, \eta_{bp} = 0.6, \eta_{bpm} = 0.95, p_{be} = 7.5 \text{ psi}$$

SEC is determined by the net energy consumed divided by the product water (permeate), for each ERD, and described following equation in correspondence to Figs. 1–3.

3.1. Pressure exchanger

The efficiencies of all these devices can be quantified as the hydraulic energy out divided by the hydraulic energy in.

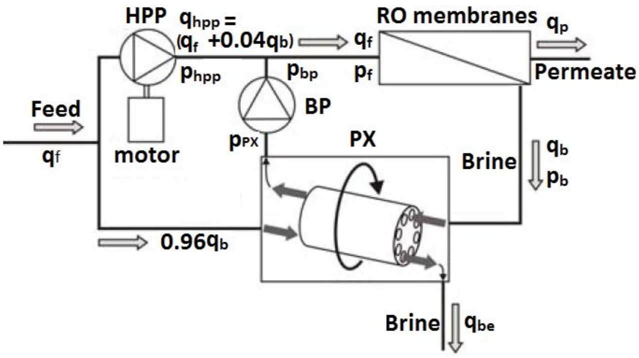

Fig. 1. Schematic diagram of PX.

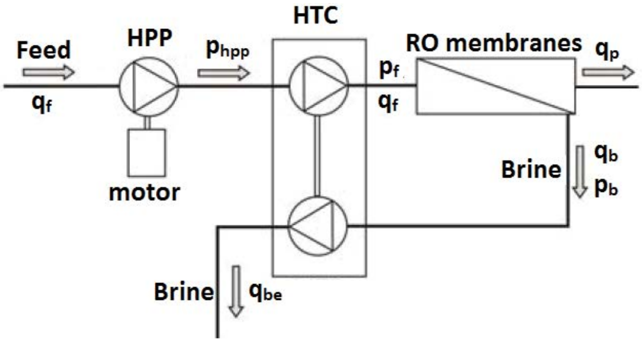

Fig. 2. Schematic diagram of HTC.

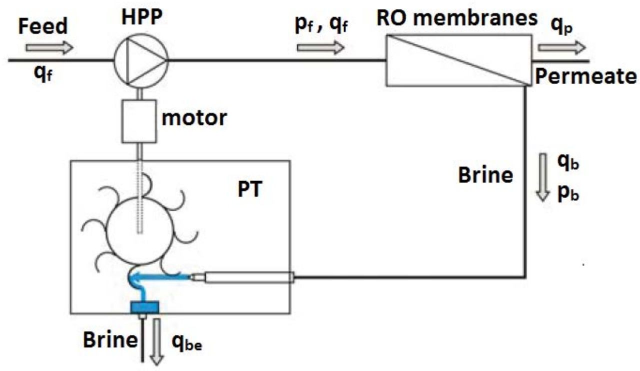

Fig. 3. Schematic diagram of PT.

As shown in Fig. 1, where PX feed flow is (q_p + 0.04 q_b) gpm, PX useful brine flow for work is 0.96 q_b gpm, and PX useful brine pressure is (p_b – 27) psi.

PX energy balance gives the booster the inlet pressure = $\eta_{PX}.(p_b - 27)/0.96$.

$$\mathrm{SEC_{PX}} = \frac{E_{\mathrm{hpp}} + E_{\mathrm{booster}}}{q_p}$$

$$\mathrm{SEC_{PX}} = \frac{E_{\mathrm{Rosa}} \times \dfrac{[Y + 0.04(1-Y)].q_f}{q_f} + \dfrac{0.227124 \times 0.068948 \times 0.96(1-Y)q_f.\left(p_f - \dfrac{\eta_{\mathrm{PX}}}{0.96}(p_b - 27)\right)}{36\eta_{\mathrm{bp}}.\eta_{\mathrm{bpm}}}}{0.227124 q_p} \quad (1)$$

$$\mathrm{SEC_{PX}} = (0.176 + 4.227\square)\frac{E_{\mathrm{Rosa}}}{q_p} + 3.2256 \times 10^{-3}\frac{1-Y}{Y}\left[p_f - \frac{31}{32}(p_b - 27)\right]$$

3.2. Hydraulic turbocharger

The efficiency of these devices can then be quantified as the hydraulic energy out divided by the hydraulic energy in.

HTC energy balance:

$$\mathrm{SEC_{HTC}} = \frac{E_{\mathrm{hpp}} - E_{\mathrm{HTC}}}{q_p}$$

$$\mathrm{SEC_{HTC}} = \frac{E_{\mathrm{Rosa}} - q_b.(p_b - p_{\mathrm{be}}).\dfrac{\eta_{\mathrm{HTC}}}{\eta_{\mathrm{hpp}}\eta_{\mathrm{hppm}}}}{q_p} \quad (2)$$

$$\mathrm{SEC_{HTC}} = \frac{E_{\mathrm{Rosa}} - 4.3499 \times 10^{-4} \times q_b.(p_b - 7.5) \times \dfrac{0.684}{0.8}}{0.227124 q_p}$$

$$\mathrm{SEC_{HTC}} = 4.4029\frac{E_{\mathrm{Rosa}}}{q_p} - 1.637 \times 10^{-3}\frac{1-Y}{Y}(p_b - 7.5)$$

3.3. Pelton turbine

The efficiencies of these devices can be quantified as the hydraulic energy out minus the motor shaft power in all divided by the hydraulic energy in.

PT energy balance:

$$\mathrm{SEC_{PT}} = \frac{E_{\mathrm{hpp}} - E_{\mathrm{PT}}}{q_p}$$

$$\mathrm{SEC_{PT}} = \frac{E_{\mathrm{Rosa}} - \dfrac{0.227124 \times 0.068948 q_b.(p_b - p_{\mathrm{be}}).\eta_{\mathrm{PT}}}{36}}{0.227124 q_p} \quad (3)$$

$$\mathrm{SEC_{PT}} = 4.4029\frac{E_{\mathrm{Rosa}}}{q_p} - 1.91521 \times 10^{-3}\frac{1-Y}{Y}(p_b - 7.5) \times (0.25 + 0.0006 p_b)$$

4. Results and discussions

4.1. Operating parameters effect on SEC for different ERD

Any SWRO system containing ERD is affected by different operating parameters, which contributed to assigning the system performance as the product quantity, quality, and SEC, which is governed by the system's operating parameters, such as feed type, feed temperature, flow rate, pressure, salt concentration, and the capability of the specified ERD to recover energy from rejected brine. In the present study, operating parameters ranges as: feed temperature T_f varied from 15°C to 45°C, feed flow rate Q_f varied from 30 to 60 gpm (6.8 to 13.63 m^3/h), and feed salt concentration C_f varied from 32 to 52 g/L. The feed salinity of 38.6, 42, and 45 g/L represent salinities of Mediterranean Sea, Red Sea, and Arabian Gulf, respectively.

4.1.1. Feed salinity effect on SEC for different ERD, at different feed flow rates

Fig. 4 depicts feed salinity effect, at different feed flow rates, on SEC, without and with ERD. The feed temperature

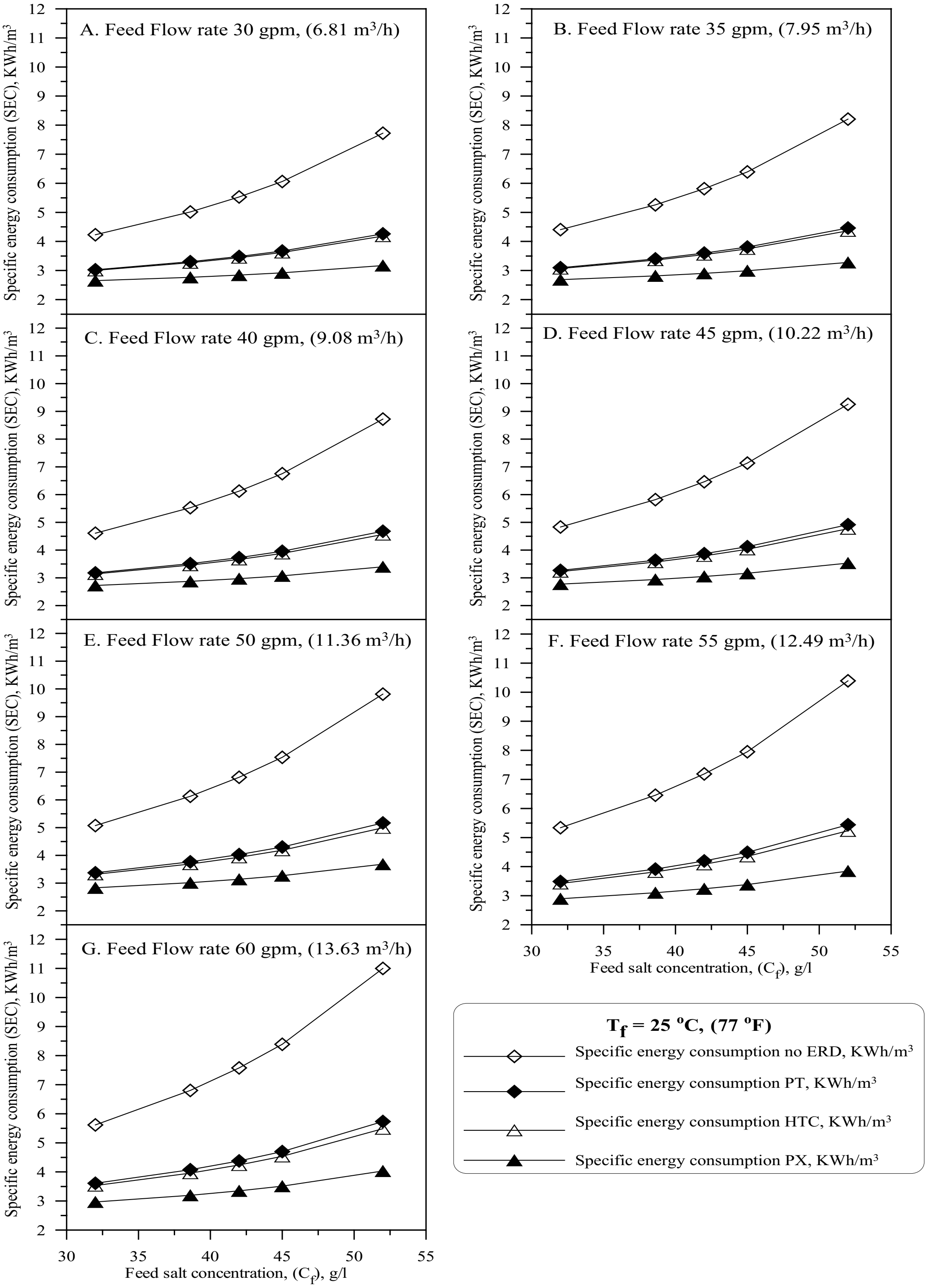

Fig. 4. Effect of feed salinity on SEC with different ERD.

is 25°C; the figure shows that SEC increases by feed salinity increase and/or feed flow rate. Using ERD to recover energy from rejected brine energy is reducing SEC by 38%–63%. At all different operating parameters, the group of PX has the lowest SEC, followed by HTC and PT.

4.1.2. Feed flow rate effect on SEC for different ERD, at different feed salinities

Fig. 5 depicts feed flow rate effect, at different feed salinities, on SEC, without and with ERD. The feed temperature

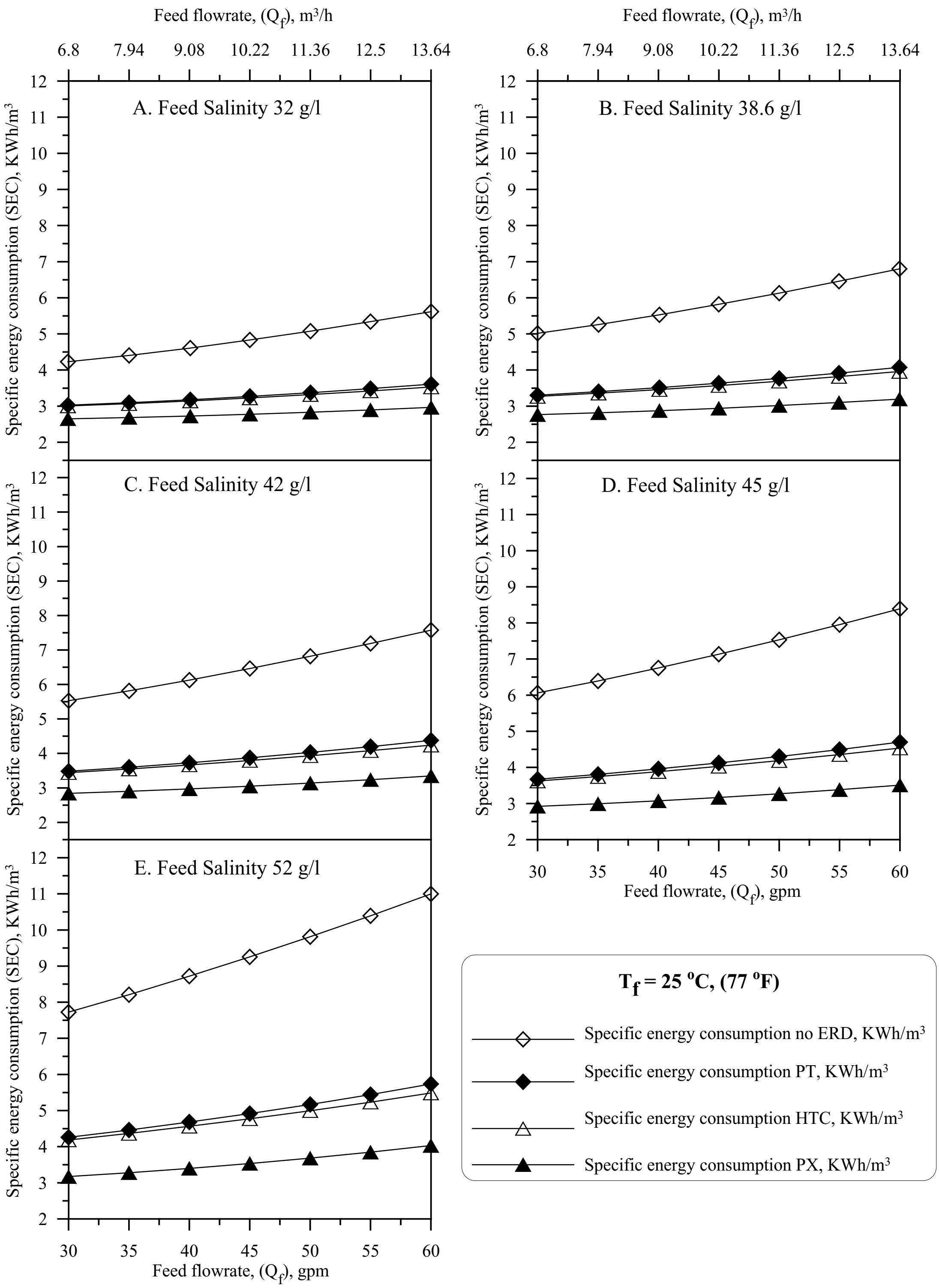

Fig. 5. Effect of feed flow rate on SEC with different ERD.

is 25°C; the figure shows that SEC increases by feed salinity increase and/or feed flow rate. Using ERD to recover energy from rejected brine energy reduces SEC by 38%–63%. At all different operating parameters, the groups of PX, followed by PT and HTC, give the lowest SEC.

4.1.3. Feed temperature effect on SEC for different ERD, at different feed flow rates

Fig. 6 depicts feed temperature effect, at different feed flow rates, on SEC, without and with ERD. The feed salinity is 42

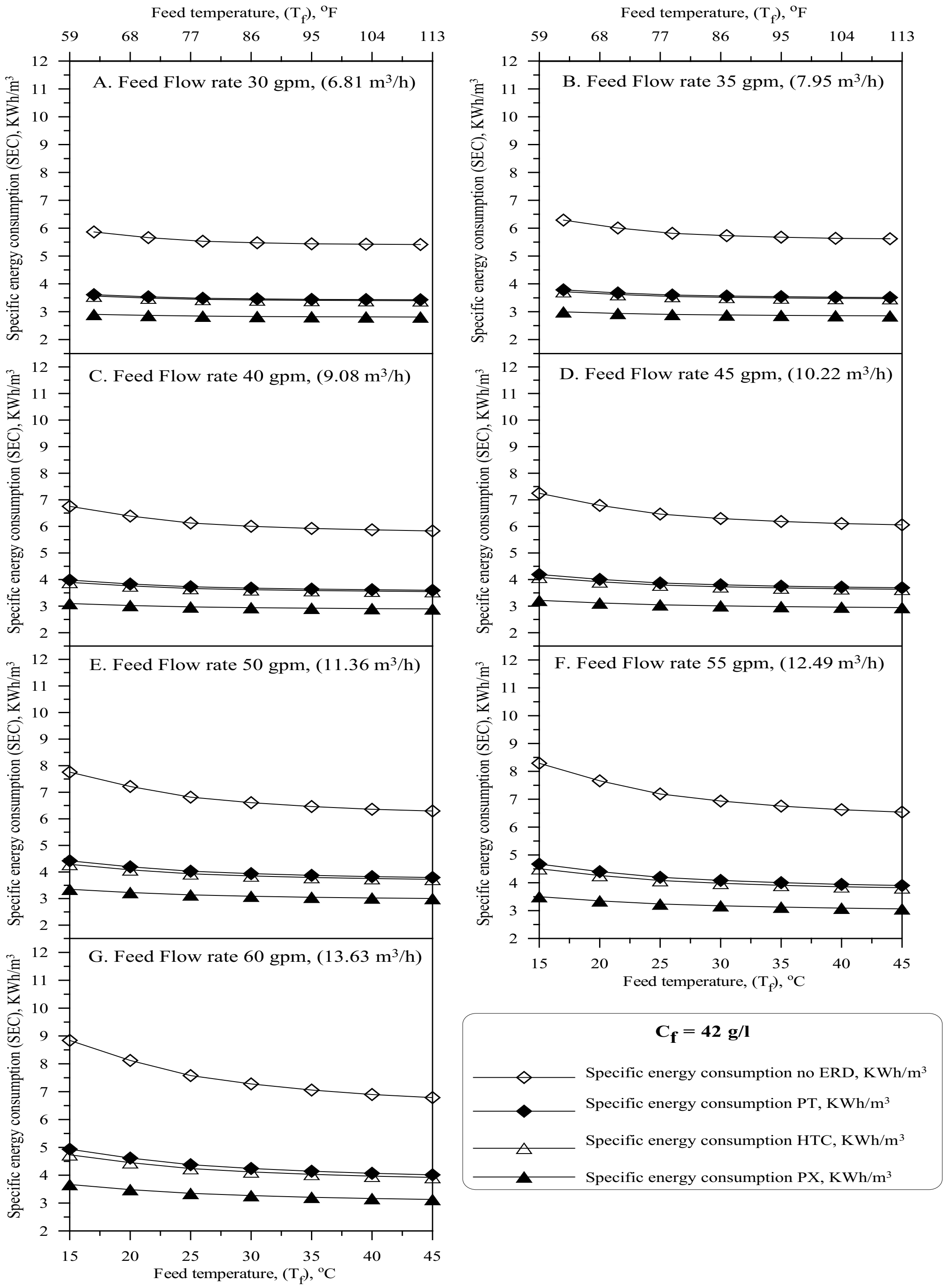

Fig. 6. Effect of feed temperature on SEC with different ERD.

g/L. The figure shows that SEC decreases by feed temperature increase and/or decrease of feed flow rate. Using ERD to recover energy from rejected brine energy is reducing SEC by about 48%–54%, 37%–42%, and 36%–41%, for PX, HTC, and PT, respectively. Meanwhile, at all different operating parameters, the PX, followed by HTC, and PT, give the lowest SEC.

4.2. *Effect of operating parameters on SWRO system performance*

Figs. 7–9 depict the effect of feed temperature on system performance at different operating parameters for the feed flow rate, pressure, and feed salt concentrations of 38.6, 42, and 45 g/L, which represent salinities of Mediterranean Sea,

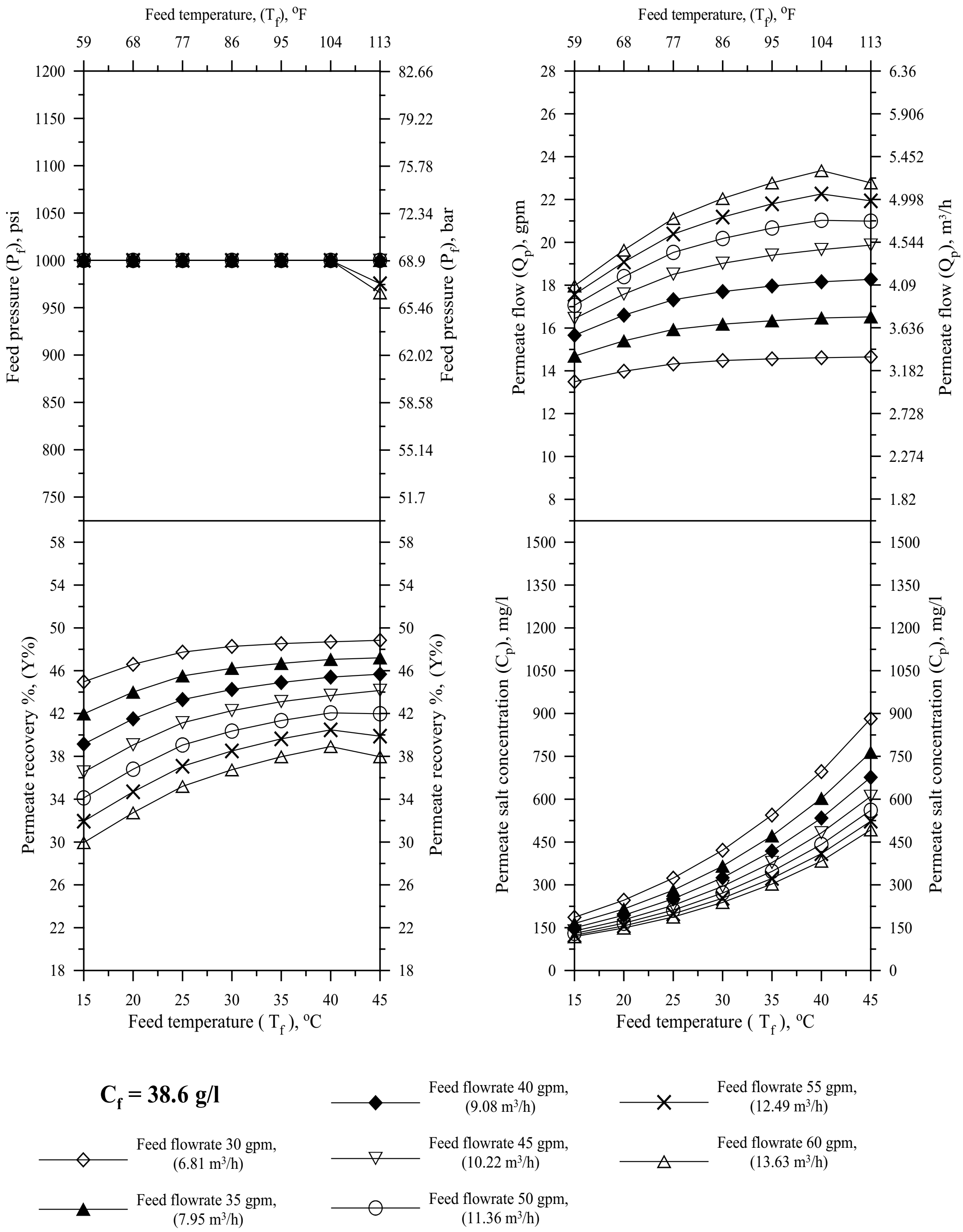

Fig. 7. Effect of feed temperature and flow rate on system performance with feed salinity 38.6 g/L.

Red Sea, and Arabian Gulf, respectively. The figures illustrate that the operating pressures are at almost 1,000 psi, maintaining the operating conditions limits and membrane maximum flux. The figures demonstrate that system permeate flow rate increases by feed flow rate increase and/or feed temperature, and decreases by feed salinity increase. Meanwhile, the system recovery increases by feed temperature increase and decreases by feed flow rate increase and/or the feed salinity. Also, the permeate salinity decreases by feed flow rate increase, and increases by feed temperature and/or the feed salinity increase.

4.3. Effect of SWRO system permeate recovery on the specific energy recovery

Fig. 10 depicts the effect of SWRO system permeate recovery *Y* on SEC with and without using ERDs. The figure represents 450 ROSA runs, at different operating conditions

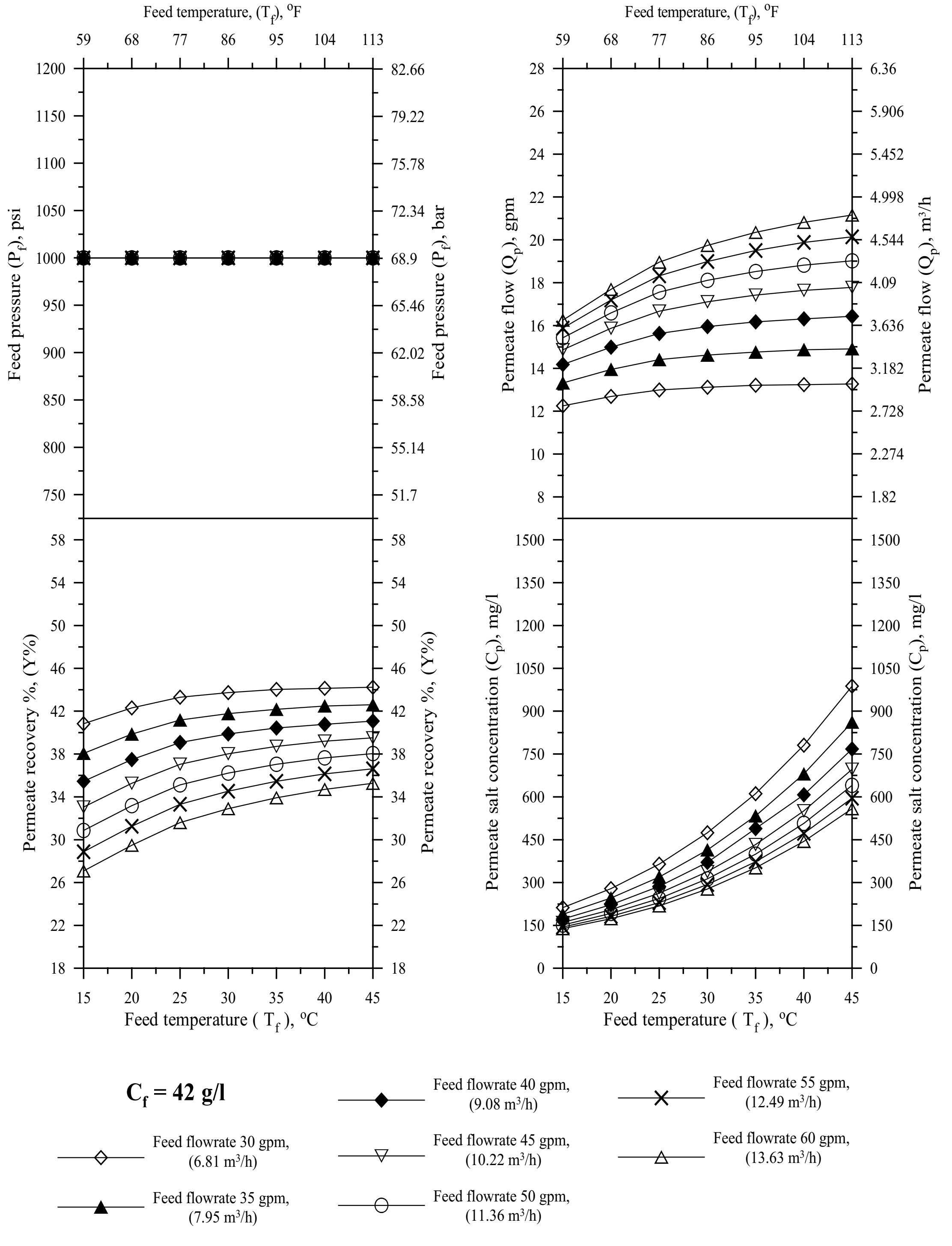

Fig. 8. Effect of feed temperature and flow rate on system performance with feed salinity of 42 g/L.

of feed, temperature, flow rate, pressure, and salinity as assigned in section 4. The figure shows that as SEC decreases by system recovery increase, and the maximum SEC without energy recovery. For PT, HTC, and PX, are at a system recovery ratio of 19.15%, and reached 12.5, 6.426, 6.094, and 4.446 kWh/m^3, meanwhile, the minimum are at a system recovery ratio of 52.23%, and reached 4.00, 2.864, 2.732, and 2.37 kWh/m^3, respectively. It is observed from the figure that there are multiple values for SEC at the same system recoveries in all cases. Also, the same notice is observed from recovery curves in Figs. 5–7, where there are multiple recoveries for the same feed, temperature, flow rate, and salinity. Therefore, SEC is not only assigned by the product system recovery as represented in a lot of references [23,24] but also assigned by

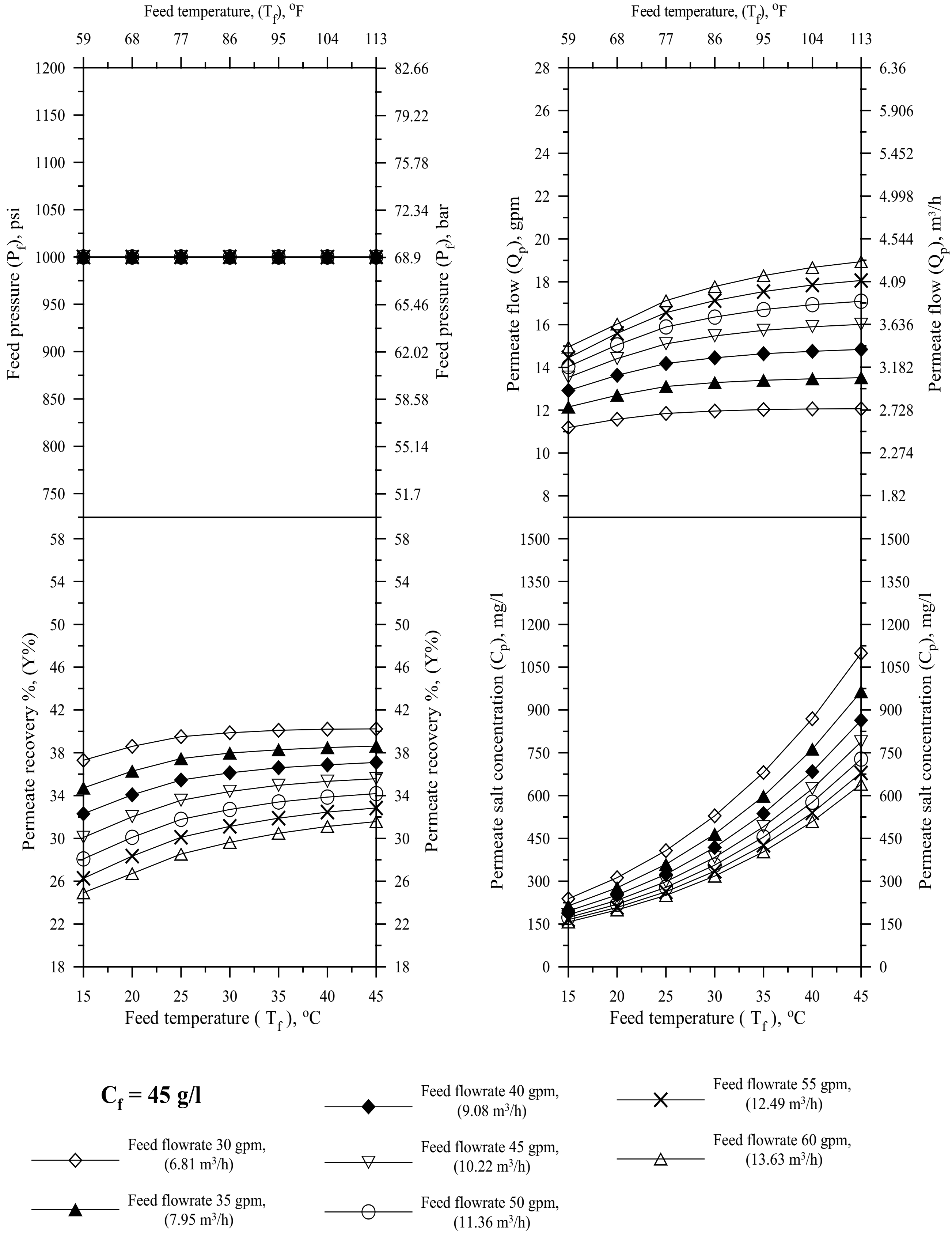

Fig. 9. Effect of feed temperature and flow rate on system performance with feed salinity 45 g/L.

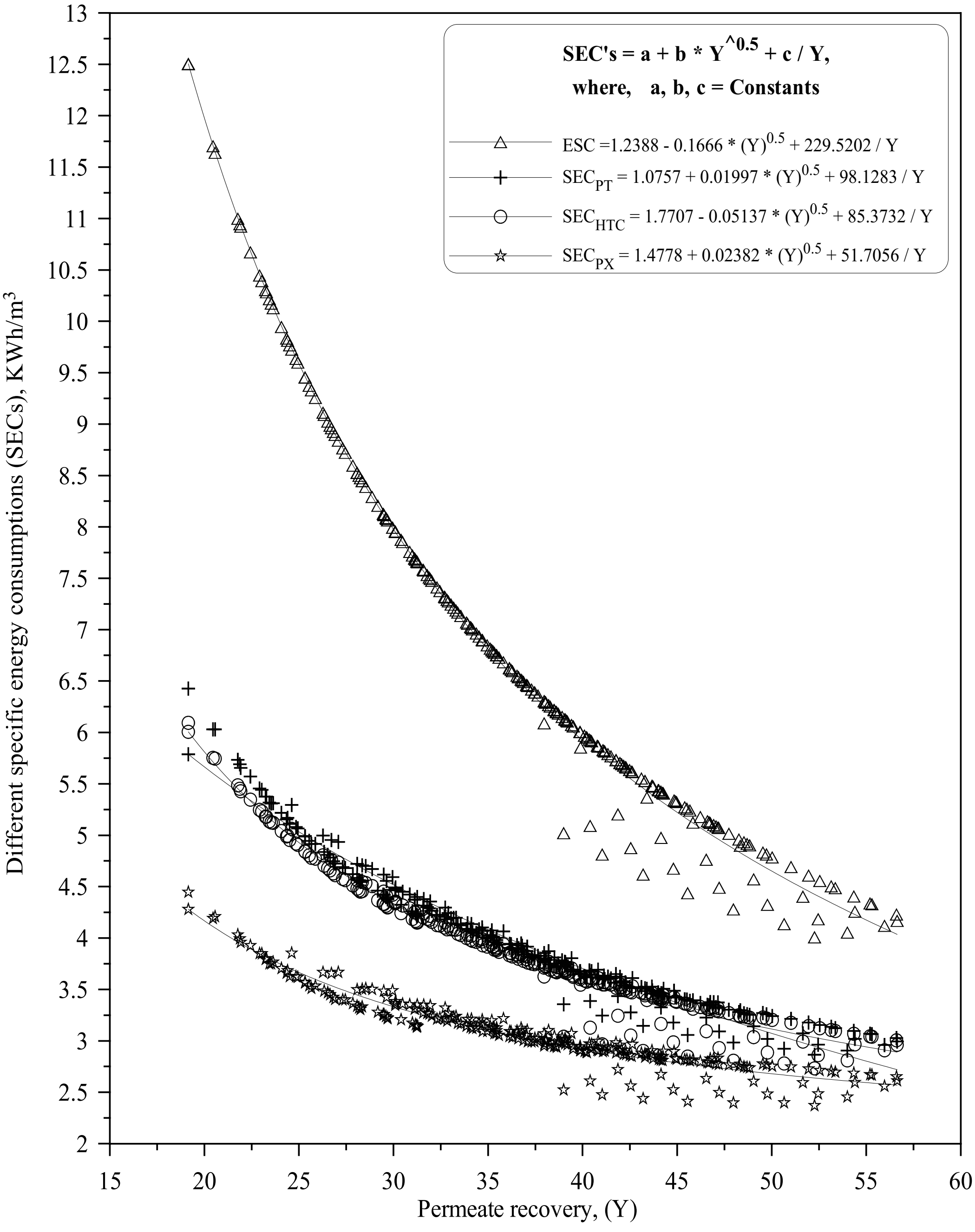

Fig. 10. Effect of permeate recovery on the different SECs.

another system operating conditions. As an example, if Y has a constant value, if decreased from this constant value it can be restored by decreasing, feed flow rate and/or decreasing feed salinity and/or increasing feed temperature, and/or increasing feed pressure, for the same system configurations. Moreover, a new approach leads to determine the curves of SEC as a function of the system recovery, with and without using ERDs, has been carried out.

5. Conclusions

The results indicate SEC increases with increasing feedwater salinity and SEC decreases with increasing feedwater temperature. ERD is saving SEC by 38%–63%. Moreover, at Red Sea water salinity of 42 g/L, using ERD can saves SEC by about 48%–54%, 37%–42%, and 36%–41%, for PX, HTC, and PT, respectively. Under different operating parameters, the group of PX has the lowest SEC, followed by HTC and PT.

Moreover, a new approach leads to determine the curves of SEC as a function of the system recovery, with and without using ERDs, has been carried out.

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