Optimization of seawater RO systems design

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Introduction.

In the last few years RO seawater desalination technology went through a remarkable transformation. The number and capacity of large RO plants have increased significantly. Systems with permeate capacity up to 300,000 m3/day are currently being built. In a parallel shift the capital and operating cost has decreased. Desalted water cost, supplied to customer, decreased from $2.0/m3 in 1998 down to current (2004) price of about $0.5/m3. This decrease of water cost is even more remarkable if one considers, that on the average, the permeate water quality requirements are more stringent now than they were five years ago. The drivers behind these economical improvements are competition and improvement of process and membrane technology. A majority of large RO systems are built to provide water to municipalities, usually in the framework of build, own and operate (BOO) arrangements. The desalination projects are awarded as result of a very competitive bidding process. Competitive bidding process affected prices of every equipment component of RO systems (including membrane elements) and resulted in a broad price decline. Better performance of equipment and optimization of process design resulted in lower operating cost. The recent trend water of cost from large seawater RO installations is summarized in Fig. 1 and Table 1.

Table 1. Water cost in recently built RO seawater plants.

Location	Permeate capacity, m3/day	Status	Water price, $/m3
Eilat Israel	20,000	10,000 m3/day commenced operation in June 1997	0.72
Larnaca, Cyprus	56,000	Commenced operation in May 2001	0.83
Tampa, Fl	106,000	Commenced operation in May 2003	0.56
Ashkelon, Israel	272,000	Under construction, to be completed in 2004	0.54

The current large RO systems are characterized by the following technical features:

1. Utilization of high efficiency pumping and power recovery equipment, including use of variable speed drivers (VFD).
2. Optimization of recovery rate in respect of power consumption.
3. Increased number of elements per pressure vessel combined with shift to a single stage array.
4. More efficient two pass configuration.
5. Utilization of power plant cooling water as a feed to RO.

6. Widespread field testing of UF/MF as pretreatment for seawater RO.
7. Stringent permeate quality requirements, sometimes including limits on maximum boron concentration.
8. Better performance of seawater RO membranes: higher permeability and higher salt rejection.

Water cost distribution

The contribution of various components to cost of product water from a seawater RO system are presented in Fig. 2. The largest components are power and fixed charges costs. Fig. 3 shows breakdown of power consumption in a partial two pass system. As expected, first stage pumping system is the major power consumer. The overall power consumption can be reduced by utilizing more efficient pumping system and by optimizing the recovery rate.

Configuration of high pressure pumping system

In seawater RO systems the feed pressure required to produce design output capacity fluctuates with feed water salinity, temperature, degree of membrane surface fouling and membrane compaction. The last two parameters are usually bundled together into a “flux decline” factor (FDF), which reflects membrane permeability decline with time. To accommodate variability of required feed pressure with time, without necessity to throttle high pressure pump or power recovery turbine, a flexible high pressure pumping system is required. The suitable equipment should be able to process constant flow in the projected range of feed and concentrate pressures without significant losses of transformation efficiency. The flexibility on the feed water supply side is usually achieved by incorporating a variable frequency drive (VFD) into electric motor unit that drives the high pressure pump. The Pelton wheel or positive displacement devices can provide sufficient operational flexibility as a power recovery device. The advantage of Pelton wheel is the flat efficiency curve in wide range of concentrate flow. However, concentrate exits the Pelton wheel at atmospheric pressure, therefore gravitation head or additional pumping is required for concentrate disposal. Fig. 4 contains a diagram of RO system equipped with high pressure pump and Pelton wheel power recovery unit. In such system the required pressure of the feed stream (F) is generated by a centrifugal pump (HP). Product (P) leaves the RO unit at pressure required to flow to the storage tank (~ 1 bar). The pressure of the concentrate (C) is lower than the feed pressure due to the hydraulic friction loses in the RO unit. The concentrate flows through the Pelton wheel power recovery unit (T) where its energy turns the drive of the electrical motor (M) and connected high pressure pump (HP). A higher efficiency positive displacement power recovery devices (pressure exchangers), that in the past were only used in small RO seawater units, are slowly gaining acceptance also in large desalination plants. Hydraulic efficiency of this type of equipment is in the range of 94% - 96%. Some of these devices utilize pistons, other transfer energy through a direct contact between concentrate and the feed stream. A diagram of RO unit utilizing such equipment is shown in Fig. 5. According to the diagram feed (F) is split into two streams. One stream (F1), which has flow rate equivalent to the permeate flow (P) is pumped to the feed pressure by the main high pressure pump (HP). The second stream (F2), which flow rate is equivalent to the concentrate flow, flows through pressure exchanger and exchanges pressure with the concentrate stream (C). The pressure of the stream F2 at the exit from the pressure exchanger is a function of concentrate pressure and efficiency of the pressure exchanger device. The pressure of stream F2 is lower by 3 – 5 bars than the pressure of stream F1 at the discharge of pump HP. The pressure of stream F2 is increased to the pressure of stream F1 by a booster pump (B). Both streams (F1 + F2) are combined at the entrance to the membrane feed manifold. The pressure exchangers are positive displacement devices and therefore have high transfer efficiency. However, so far their flow capacities are limited to less than 100 m3/hr, and large system require significant number of parallel units. The units that operate with direct contact of concentrate and feed, experience some mixing, which results in increased feed salinity, in the range of 3%. The other type of the pressure exchange device, that utilizes pistons, does not experience any significant salinity increase due to mixing, but it requires flow regulating valves. These devices operate at high frequency of open/close cycles and may require significant degree of maintenance. Regardless of some operational problems, these power recovery devices provide significant reduction of power usage. Fig. 6 shows specific power consumption calculated for seawater RO system, assuming use of low efficiency conventional pumping equipment (A), high efficiency conventional pumping equipment (B) and pumping equipment, which includes pressure exchanges (C). The efficiencies of pumping equipment and parameters of calculations are listed in Table 2. The calculations were conducted for a RO system processing Mediterranean feed (40,600 ppm TDS)

Table 2

Case	A	B	C
Configuration	Low efficiency pump + Pelton wheel	High efficiency pump + Pelton wheel	High pressure pump + pressure exchanger
Pump efficiency, %	82	88	88
Pelton wheel/pressure exchanger efficiency, %	82	88	94
Electric motor efficiency, %	94	96	96
VFD efficiency, %	98	98	98
Raw water and pretreatment pressure losses, bar	4	4	4
Concentrate discharge pressure, bar	0.5	0.5	0.5
Permeate pumping, bar	10.0	10.0	10.0
Auxiliary equip., kWhr/m3	0.05	0.05	0.05

at temperature of 22 C, average permeate flux rate of 13.8 l/m2-hr utilizing Hydranautics SWC3+ elements and assuming 3-year membrane age which corresponds to 20% flux decline. For the calculations corresponding to a system utilizing pressure exchanger a 3% feed salinity increase was applied. The results in Fig. 6 show the effect of pumping equipment efficiency and recovery rate on power consumption. The power consumption decreases with increase of pumps and motors efficiency and the minimum shifts to a lower recovery rate. It is evident that in respect of power consumption alone, pressure exchanger equipment has significant advantage over the conventional configuration i.e. high pressure pump combined with Pelton wheel power recovery unit. Additionally, operation at lower recovery will result in improved permeate quality. Decreasing recovery rate from 45% to 35% will result in decrease of permeate salinity by 10%. However, it should be noted that operation at lower recovery rate will increase the pretreatment cost.

RO unit configuration

Configuration of the membrane unit has significant effect on performance and economics of the RO plant. The usual design considerations include the array: should seawater RO trains be configured as a single or two stages units? How many elements per pressure vessel should be used? If a partial two pass processing is required, how it should be configured?
In the past, the seawater units were usually configured as a two stage, six elements per vessel units. The rationale behind two stage design is that it results in a high feed-concentrate flow, which reduces concentration polarization. In seawater RO systems scaling is not a recovery limiting factor, but lower concentration polarization will result in lower ions concentration at the membrane surface and therefore somewhat lower permeate salinity. However, with higher feed flow, higher feed pressure is required due to increased pressure drop across the RO trains. Design efforts to reduce power consumption and system cost, resulted in transition of seawater plant design to a single stage configuration and increased number of elements per vessel. Majority of current seawater RO system designs are single stage with seven elements per vessel. Some, even very large systems, are designed and operating with eight elements per vessel. There is obvious cost advantage in increased number of elements per vessel. RO system using six elements per vessel will require 34% more pressure vessels than a system employing the same membrane area but configured with eight elements per vessel. Comparing the above configurations, the cross system pressure drop in a single stage unit will be only 1.1 bar compared to 3.4 bar for the two stage unit, resulting in 2.5% higher power requirement of the latter configuration. In the past the eight element, single pass configuration, was criticized as resulting in uneven flux distribution: lead elements operating at very high flux, which may result in excessive fouling. However, examining the feed salinity and pressure distribution, it is evident that the flux difference between the lead and tail position in a single stage system is lower than in a two stage system operating at the same recovery rate. Additional pressure drop in a two stage system results in higher feed and lower concentrate pressure as compared to single stage configuration. The only practical way to improve flux distribution in a seawater two stage system is to use an interstage booster. The above solution is sometimes applied but it results in higher equipment cost without any significant benefits of reduced power consumption.

Optimization of two pass design.

Recent commercial seawater membrane elements are characterized by very high salt rejection: 99.7 – 99.8%. Still for same applications, due to high feed salinity or temperature, a two pass processing is required to produce consistently design permeate salinity. Two pass configuration is also necessary for RO systems with stringent limits on permeate quality, such as very low chloride concentration or low boron limits. For RO system design as a full two pass configuration, a partial two pass processing may be sufficient during the operating period when membranes still maintain sufficiently high rejection or during the seasons of low feed water temperatures. The conventional partial two pass system operates in the same way as a full two pass design. Permeate from the first pass is collected in a storage tank and the required fraction is processed by the second pass. It is known that permeate salinity along the system increases parallel to the increase of feed salinity. It is lowest at the feed end of the pressure vessel and highest at the concentrate outlet. Typical permeate salinity distribution along an eight element pressure vessel is shown in Fig. 7. It is possible to take advantage of this salinity distribution by collecting permeate from separate stages or from both ends of pressure vessels in a given membrane stage. This process has been proposed in the past by D. Bray (1). Recently, it has been implemented in a large seawater system (2). In this configuration the high salinity fraction (collected from the concentrate end) is processed with the second pass RO unit and blended with the low salinity fraction (collected from the feed end). A diagram of such system is shown in Fig. 8. The advantage of this spilt partial, two pass, design is smaller permeate capacity required from the first and second pass unit, higher effective recovery rate of the combined system and lower power consumption. Table 3 summarizes an example of such design. In this particular case the spilt

Table 3. Conventional and split partial two pass configuration of RO systems processing Mediterranean seawater for total permeate capacity of 10,000 m3/day and Cl concentration in combined permeate of 100 ppm.

Conventional design	**First pass**	**Second pass**
Permeate flow, m3/d	10,580	5,000
Recovery ratio, %	50	90
No. of pressure vessels	120	20
No. of elements	**960**	**160**
Feed pressure, bar	66.3	12.4
Combined power requirement, kwr/m3	**3.25**	
Split partial design		
Permeate flow, m3/d	10,250	2,000
Recovery ratio, %	50	90
No. of pressure vessels	116	8
No. of elements	**928**	**64**
Feed pressure, bar	67.3	14.4
Combined power requirement, kwr/m3	**3.07**	

partial system is smaller with 13% lower number of elements and pressure vessels and 6.5% lower power consumption then the equivalent conventional partial two pass system configuration.

Feed water supply and treatment

Selection of seawater supply source for RO desalination systems depends to some extend on site conditions but is mainly determine by system size. For large systems the only viable source of seawater supply is from an open intake. The possible options are either as a stand alone system or contiguous to some larger seawater user such as power plant. Supply from dedicated intake usually implies a dedicated outfall facility as well. Current regulations require careful design that will minimize any potential environmental effect (3). The lengthy permitting process for construction and operation of intake and outfall facilities makes location of RO plant adjacent to on shore located power plant a very convenient solution. In this process configuration the RO system utilizes as a feed, seawater discharged from the heat reject section of the power plant before it flows to the ocean. In a similar fashion, RO concentrate is discharged to the same line, downstream of the feed uptake. The temperature of seawater at the outlet from the power plant is usually higher by 3 – 5 C than the water at the intake. For the location of low seawater temperature, the temperature increase due to power plant operation is beneficial as it increases membrane permeability, and RO system can operate at lower feed pressure. During the periods of high seawater temperature, above 30 C, further increase of feed water temperature does not result in any significant decrease of feed pressure. Depending on feed salinity and recovery rate in the temperature range of 30 – 40 C, higher membrane permeability at higher temperature is adversely compensated by increased osmotic pressure. Higher feed water temperature results in higher salt passage (shown in Fig. 9). If this increase of salt passage requires increased operation of the second pass, higher feed water temperature can actually result in higher power consumption of the plant. Location of RO system, contiguous to power plant, my result in some feed water quality problems. It is common practice of power plant to intermittently chlorinate intake structure to reduce biogrowth. An additional periodic event, that may affect seawater quality, is cleaning of the heat transfer surfaces of the condenser. As a result of cleaning, small particle fragments are released to the cooling seawater and could end up in the RO feed. Both periodic events at the power plants, intake chlorination and cleaning of the condenser heat exchange surfaces, should be addresses in RO system design and operation to prevent potential membrane damage.

So far large seawater RO plants have been built exclusively with feed water pretreatment that includes media filtration as colloidal particles removing step. The performance record of this approach, with few exceptions, is mainly positive. However, at some locations, with difficult feed water, media filtration, even in two stage configuration, is not sufficient to produce satisfactory quality feed water. This leads to excessive membrane fouling. Fouling results in rapid increase of pressure drop and/or decrease of membrane permeability. As a result, higher than design feed pressure has to be applied to produce rated output. Frequent membrane cleaning results in higher consumption of chemicals and decrease of on line plant factor. For those plants, usually, frequency of cartridge filters replacement increases as well. These conditions may result in sharp increase of the operating cost. In the Built, Own and Operate (BOO) type commercial arrangement such situation may result in a heavy financial losses to the plant operator. Membrane pretreatment technology, that has been successfully applied in large scale wastewater reclamation systems, is being extensively tested for seawater applications. A large number of seawater pilot study of microfiltration (MF) and ultrafiltration (UF) have been conducted (5, 6) with very positive results. Recently two large RO seawater plants (30,000 m3/d and 125,000 m3/d), one on the Red sea and another on the Mediterranean have been designed and will be built with UF/MF pretreatment. The impediment of widespread implementation of MF/UF pretreatment in RO seawater systems is equipment cost that is still higher than media filtration. However, membrane pretreatment system prices are decreasing, and if in addition to two stage filtration, another pretreatment step is required, MF/UF technology can already be cost-effective alternative. The major advantage of membrane pretreatment is the existence of a barrier that has complete rejection of water born colloidal particles that could otherwise foul the membrane surface or block membrane element feed channels. The MF/UF membrane technology could be pressure or vacuum driven, and it can operate reliably at low driving pressure, in a wide range of raw water quality. The schematic diagram of a RO system incorporating submersible, vacuum driven, membrane pretreatment is shown in Fig. 10. A recent pilot study, which included parallel operation of submersible membrane filtration and conventional, two stage, dual media filtration (DMF), demonstrated that the performance of membrane filtration is more reliable than DMF system during the periods of poor quality seawater. Also, the membrane filtration system is capable to maintain stable capacity and produce good quality effluent utilizing much lower quantity of chemicals compared to a conventional filtration system. Table 4 provides comparison of filtrate

Table 4. Comparison of submersible MF membrane filtration unit with gravity media filtration system. Gravity filter footprint 3,700 m2, filtration area 2,300 m2

Gravity filter average filtration rate m3/m2-hr	Gravity filter net capacity, single stage filtration, m3/d	Gravity filter net capacity, two stage filtration, m3/d	Hydrasub™ net capacity @ 17 lmh filtration rate, m3/d	Capacity ratio: Hydrasub™/two stage gravity filters
4.9	270,000	135,000	708,000	5.2
7.4	401,000	201,000	708,000	3.5
9.9	534,000	267,000	708,000	2.7
12.3	666,000	333,000	708,000	2.1
14.8	799,000	399,000	708,000	1.8

capacity between conventional gravity filters and submersible membrane unit (Hydrasub™, made by Hydranautics), installed in the same footprint, as a pretreatment for a large seawater RO plant. Table 4 illustrates that even in comparison to a single stage DMF filtration; membrane pretreatment has higher capacity per unit of filtration system area. For locations with poor seawater quality, where a two stage dual media filtration is required, membrane pretreatment would have definite footprint advantage.

Permeate quality

Current requirements of permeate quality usually include stringent specifications for a number of constituents, including boron. Because boron is poorly rejected by RO membranes at ambient pH, specifications for boron concentration in permeate affects system configuration and the scope of the second pass treatment. A number of process configurations have been proposed to effectively achieve low boron concentration in the permeate (6) of seawater RO systems. A majority of these involve RO treatment of first pass permeate at elevated pH and/or utilization of boron specific ion exchange. Boron rejection by RO membranes is a function of pH, closely following the dissociation ratio of boric acid. Fig. 11 shows dissociation ratio of boric acid to borate versus pH. This figure also shows that the dissociation ratio increases with the feed salinity (ionic strength). With increased salinity the equivalent dissociation ratio shifts to lower pH. Accordingly, relatively minor increase of pH of seawater feed will result in significant decrease of boron passage. Table 5 summarizes results of monitoring boron passage in commercial seawater RO system as a function of feed pH. In the feed pH range of 7 to 8.8, boron passage has decreased by 50%. Natural seawater has pH of about 8.1 and low alkalinity of about 140 – 160 ppm. Therefore, a relatively small quantity of NaOH is required to increase pH that would result in significant boron passage reduction.

Membrane performance restoration

It is a common occurrence that membrane performance deteriorates with operating time. Both membrane permeability and salt rejection may decline at a rate that depends mainly on feed water quality. Initially membrane performance can be restored with effective cleaning. However, after prolonged exposure to the fouling conditions, performance restoration through membrane cleaning is becoming less effective, and the limits of

Table 5. Boron rejection in seawater RO system as a function of feed pH

Feed pH	System boron rejection, %	Relative boron passage
7.0 (acidified feed)	78.6	1.0
8.1 (no acid dosing)	81.6	0.86
8.3 (caustic addition)	83.5	0.77
8.6 (caustic addition)	86.6	0.63
8.8 (caustic addition)	89.6	0.49

system performance (feed pressure and/or permeate quality) is exceeded . Then, replacing old membranes with the new elements is the only means to restore system performance. Table 6 demonstrates the effect of membrane replacement on permeate salinity. In this particular case RO system with new membranes produced a permeate salinity of 240 ppm. The current permeate salinity is 500 ppm and the design permeate salinity is 400 ppm. As can be expected, to restore salt passage to the initial value all membrane elements in the system have to be replaced. To achieve design permeate salinity value of 400 ppm, 37% of membrane elements would have to be replaced. Table 7 demonstrates effect of membrane replacement on system capacity. To improve system capacity from 70% of nominal flow to 80% (design value), 33% of membrane elements will have to be replaced. Correction from 60% to 80% would require 50% elements replacement. This extensive element replacement can be reduced if system is design to enable elements

Table 6. Membrane replacement schedule for salt rejection restoration.
RO seawater system, Mediterranean seawater 40,000 ppm TDS, temp 29 C, recovery 45%, flux 13.8 lmh, nominal salt rejection of new elements 99.7%.
Initial permeate salinity 240 ppm, design permeate salinity 400 ppm, current permeate salinity 500 ppm.

Target permeate salinity after replacement, ppm	System salt passage, %	Elements to be replaced, %
240	0.43	100
300	0.38	80
400	0.71	37
500	0.88	-

addition. To perform above corrections, 10% and 20% of new membrane elements would have to be added, respectively. However, as a result of membrane addition, membrane area increases and salt passage will increase proportionally. This effect on performance has to be considered when selecting the most effective method of system performance correction.

Table 7. Membrane replacement schedule for salt rejection restoration.
RO seawater system, Mediterranean seawater 40,000 ppm TDS, temp 29 C, recovery 45%, flux 13.8 lmh.
Design flux decline 20%, actual flux decline 30 – 40%

Flux restoration mode	Current permeate capacity, %	Target permeate capacity, %	Elements to be replaced or added, %
Replacement	70	80	33
Replacement	60	80	50
Addition	70	80	10
Addition	60	80	20

Improved RO Membranes

Recent advances in membrane technology have resulted in more efficient production of potable water from seawater. In a typical seawater RO system, the osmotic pressure may vary from 34 to 59 bar from the feed inlet to the brine outlet. In the past 5 years, it would be reasonable to use about 68 bar feed pressure to achieve 13.6 lmh flux at 25 C on a 40,000 mg/L seawater. Thus, on average, about 21 bar was used to permeate water through the membrane and 47 bar was used to overcome osmotic pressure. 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. However, the actual reduction in pressure required for permeation has decreased by 14%, a very substantial improvement. The above 3 bar decrease of feed pressure is equivalent to pumping power reduction of about 0.12 kWhr/m3, which in large RO plant, which leads to significant energy cost savings. At the same time, the improvements in seawater RO membrane have led to even higher rejection products. Many vendors offer seawater membranes which have 99.7 to 99.8% rejection at standard test conditions of 32,000 mg/l NaCl at 800 psi and 25 C. This combination of increased water permeability and lower salt passage has contributed to the reduced cost of potable water production.

Conclusions

The cost of seawater desalination by reverse osmosis has significantly decreased. Both greater competition and improved technology have contributed to this reduction in desalted water price. The main technological improvements have come from the optimized process design and improved equipment. Process development such as two-pass, split partial permeate treatment, one-stage array configuration, and high pH seawater feed for boron removal have proven to be cost effective. Finally, desalination cost has declined due to higher efficiency energy recovery devices and higher permeability high rejection membranes.

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