Desalination and Water Treatment
www.deswater.com

51 (2013) 759–765
January

Taylor & Francis
Taylor & Francis Group

doi: 10.1080/19443994.2012.699338

Optimized train configuration for mega-scale seawater RO systems with turbocharger energy recovery

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Received 18 March 2012; Accepted 29 May 2012

ABSTRACT

Construction of mega RO facilities (train capacity of 5,000 m^3/day and larger) faces many challenges including cost-effective utilization of energy recovery devices (ERDs) and high-pressure pumps. Recently, mega system owners and integrators have selected turbochargers with single train capacity exceeding 20,000 m^3 of daily permeate output. This study analyzes several ERD configurations in single- and two-stage arrays with a capacity of 20,000 m^3/day. In particular, two-stage (brine staged) configurations are extensively explored to establish the limits of specific energy consumption (SEC) reduction under realistic operating scenarios. Commercially available membrane projection software was used to develop a mathematical model of membrane array performance including the effects of feed total dissolved solids, temperature, age, and polarization. Software was developed to evaluate tens of thousands of membrane configurations along with hundreds of operating conditions to identify ERD applications and array configurations that provide the lowest SECs. A figure of merit was defined to ensure unbiased comparison of results. The findings showed that two-stage arrays provide an SEC reduction of about 3% with optimal recovery around 47% relative to single-stage arrays with the same number of membrane elements. Perhaps the most interesting finding from a practical perspective is that turbochargers in an optimized two-stage array have an SEC about the same as isobaric chambers in optimized single-stage arrays.

Keywords: SWRO; ERD; Motor assisted turbocharger; Energy consumption; Train configuration

1. Introduction

Turbochargers (Turbo's) are energy recovery devices (ERDs) that consists of integral turbine and pump sections on a common shaft. High-pressure (HP) brine energizes the turbine. The pump section driven by the turbine boosts the pressure of the feed stream between the high-pressure pump (HPP) and membrane array or boosts the pressure between brine stages. The brine stream and feed stream may be of different flow rates and pressures.

Turbochargers have been selected for several recent mega-scale seawater reverse osmosis (SWRO) projects such as Jeddah III (261,000 m^3/day), Ras Al-Khair (366,700 m^3/day—1st pass), and Maagta in Algeria (500,000 m^3/day).

These recent developments arise from the realization—among system owners, builders, and consultants—that modern turbochargers have

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Presented at the International Conference on Desalination for the Environment, Clean Water and Energy, European Desalination Society, 23–26 April 2012, Barcelona, Spain

demonstrated increased transfer efficiencies (80+% in commercially available units), have very low capital expense (CAPEX) relative to other ERDs, and allow simple and easily operated control systems. The combination of these factors results in the lowest life cycle cost (LCC) among available ERDs [1].

A goal of this analysis is to identify the membrane configuration that minimizes the specific energy consumption (SEC) of isobaric chambers (ICs) and turbochargers as well as their variants in mega-scale SWRO systems. Optimization of single-stage arrays is a relatively easy exercise, but two-stage arrays with variable interstage pressure boosts and exponentially greater permutation of membrane configurations with constraints such as full utilization of brine energy complicate such analysis.

A key enabler of this research is a software package developed by the authors, which can examine tens of thousands of membrane configurations over hundreds of duty points (i.e. millions of combinations of element arrangements and operating conditions) to identify array and ERD configurations that display minimized SEC.

2. Review of recent ERD advances

2.1. Mega-scale turbochargers

The Jeddah III SWRO project located adjacent to the pioneering Jeddah I and II SWRO facility in Jeddah, Saudi Arabia, has a capacity of 261,000 m^3/day of permeate. The facility is owned by Saline Water Conversion Corporation (SWCC) with Doosan Heavy Industries of Korea as the EPC contractor. Sixteen trains each yield 16,320 m^3/day of permeate at 42% recovery. SWCC selected turbochargers to provide brine energy recovery. Plant start-up is anticipated in mid-2012.

The Jeddah III ERDs achieved up to 81% total transfer efficiency on a certified test loop. As the turbocharger consists of integral turbine and pump sections, transfer efficiency equals the turbine efficiency multiplied by the pump efficiency. Thus, the pump and turbine component efficiencies average 90%. Although quite high by conventional standards, these efficiencies are reasonable given the unique design and manufacturing methods applied to modern RO turbochargers [2]. Mega-scale turbochargers under active development display a transfer efficiency of about 83% with average component efficiencies of about 91% [3].

2.2. Turbochargers variant: the HP-HEMI

The combination of an electric motor with the turbocharger, called the HP-HEMI, allows regulation of feed and brine pressures as required for optimal membrane operation using a HPP operating at constant speed. A HPP and HP-HEMI package eliminates the need for a feed throttle valve or variable frequency drive (VFD) for the HPP. The elimination of the losses associated with throttle valves or VFDs allows the HP-HEMI to provide the lowest SEC of any ERD for systems that require substantial variation in membrane feed pressure.

Another variant called the HP-HEMI-R employs a regenerative VFD that permits the HP-HEMI motor to act as an induction generator. This capability allows the unit to convert brine energy in excess of the requirement for optimal feed pressure boosting into electrical power. Note that the HEMI-R can also operate as a standard HEMI when more feed boost is needed than available brine energy can provide. As such, the HEMI-R can provide a very wide hydraulic range with optimal SEC performance.

3. Analysis of configurations

3.1. Membrane array configurations

Membrane array configurations in SWRO systems have seemingly converged on the use of a single membrane stage with typically seven elements per housing.

From time to time, two-stage configurations have been used in SWRO systems that typically have operated at recoveries over 50% [4]. One intention is to reduce the size of pretreatment systems for a given permeate production resulting in more favorable capital and operating costs. As with brackish water systems that use multiple stages, a pressure boost between each stage pair provides the following benefits:

- higher recovery;
- more uniform flux rates;
- lower fouling potential; and
- lower permeate total dissolved solids (TDS).

Andrews provided a useful analysis of membrane performance in multiple-stage systems from the perspective of potential reductions in SEC [5]. The analysis indicated that two-stage arrays with optimal interstage pressure boost achieve a 16% SEC reduction relative to a single-stage system with both systems using "ideal" membranes operating at 47% recovery. The advantage drops to about 13% at 40% recovery. Andrews noted that minimum SEC is achieved when recovery is the same for each stage in a multistage array. An "ideal" membrane displays permeate production at near-zero net driving pressure (NDP) and has zero feed pressure loss along the membrane channel.

A major objective of this research is to determine whether arrays can be designed based on the performance of currently available membranes, HPPs, and ERDs that tap into the theoretical energy savings from multistage systems.

3.2. Membrane array configurations

Two-stage systems are relatively rare despite the theoretical promise for improved SEC. The authors considered the possibility that, given the enormous permutations in membrane housing arrangement and first- and second-stage feed pressures and flows, the optimal configurations may not have been discovered, especially with the use of recently available high-efficiency turbochargers. For the analysis to have high significance to system designers, the optimal configurations must be based on the demonstrated membrane performance as well as HPP and ERD efficiency. Note that pretreatment feed pump power consumption, which is a function of array recovery, is included in all SEC calculations in this study.

3.3. Finding the optimal configurations

The definition of optimal configuration in this study is simple—the number of membrane housings and number of elements per housing in the first stage and the second stage, if used, that yields the lowest SEC. The optimal configuration can be influenced by the type of ERD, as some ERDs are suitable for providing interstage pressure boosting while others are not suited.

The optimization study must eliminate any variable that can skew the results. Therefore, only a single type of membrane is used and all pump efficiencies were derived from consistently applied formulas. Please refer to Chart 1 for pump efficiency as a function of capacity. These efficiencies represent the "best efficiency point" at every point on the curve. The HPP and the HP booster pump required by ICs have identical curves. Pretreatment pumps have a lower efficiency reflecting the author's experience. Again, the critical factor is that all optimization analyses in this study use consistent membrane and pump performance parameters. Please refer to Table 1 key assumptions.

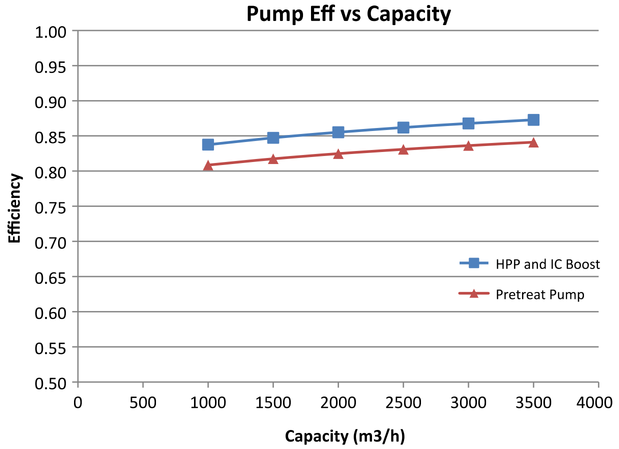

Chart 1. Pump efficiency as a function of capacity.

3.4. Case study

A hypothetical system has a permeate flow of 840 m^3/h (20,172 m^3/day) per train. The analysis software evaluated all recoveries from 30% to 60% for each membrane configuration. For two-stage systems, interstage boost was varied from about 1 bar to the maximum possible, from the available brine hydraulic energy not to exceed 41 bar.

For each element/ERD configuration, the lowest SECs were captured along with the corresponding feed flow, brine flow, interstage flow (for two-stage systems), pump and ERD performance, and pressures at various points in the process as well as other parameters. A complete analysis of an ERD with all permissible membrane arrangements, flows, and pressures may easily exceed 20,000,000 cases.

The adopted strategy was to test every reasonable membrane configuration with hydraulic matched HPP, ERD, and pretreatment pumps. Membrane configurations were restricted to no less than four

Table 1
System design parameters

Pretreatment pump DP	4.8 bar	Pressure loss in pipes and valves	Nil
HPP inlet pressure	2.0 barg	Turbo and HEMI transfer efficiency	83%
Brine outlet pressure	1.0 barg	Motor efficiency	96%
IC feed TDS increase (brine mixing)	3.0%	Turbocharger feed TDS increase	0.0%
Feed TDS	34,000 ppm	Feed temperature	17 C
Pump efficiencies	From Chart 1		

Table 2
ERD applications

ERD	Application	Stage	Comments
Turbo	Interstage boosting	2	Provides interstage boost sufficient to consume all available brine energy—Fig. 1
HEMI-R	Interstage boosting + Power generation	2	HEMI provides interstage pressure boost plus converts excess brine energy into electricity—Fig. 2
Twin turbo	Turbo for interstage and turbo for feed boosting	2	One turbo boosts interstage pressure and other turbo boosts feed pressure between HPP and 1st stage membrane array—Fig. 3
Turbo	Feed boosting	1	Provides feed boosting between HPP and 1st stage—Fig. 4
IC	Partial feed flow press	1	Standard application (not suitable for two-stage arrays)—Fig. 5

elements and no more than seven elements per membrane housing. The number of membrane housings ranged from approximately 70% to 200% from a nominal design.

Reasonable efforts were made in the software to optimize iterations and loop structure (the deepest being six nested loops plus additional iterations associated with element simulation). The longest computer runs were about 12 h on a reasonably fast desktop computer. The program was compiled to reduce the execution time. Improvement in iteration efficiency is expected to substantially reduce the run time in future versions of the software.

Table 2 summarizes the five ERD/array configurations evaluated. Three configurations employ two stages and two others use single-stage arrays, which provide reference SECs. Note that all configurations were analyzed to find the optimal array configurations.

Figs. 1–5 present simplified Process and Instrumentation diagram (P&IDs) for each evaluated system. ICs were not considered for two-stage configurations as no efficient application of the IC appears possible in such systems.

4. Results

4.1. Figure of merit

The authors propose a simple figure of merit to compare ERDs and array designs. For all membrane housing and element counts over the specified flow ranges, the lowest SEC was found for each of the five configurations. The chosen figure of merit is SEC vs. the number of elements, which is plotted in Chart 2. The number of membrane elements ranges from about 1,300 to about 1,900.

It is interesting to note that the analysis was skewed in favor of the IC in that there were no variations in membrane operating pressure for any given array configuration. ICs have no capability to adjust feed pressure while Turbo's and HEMIs display a strong capacity for such. Real-life scenarios involve significant pressure variations to accommodate the changes in feed temperature salinity as well as membrane fouling. Variable operating pressure favors the HEMI in particular due to its ability to eliminate the loss of energy in feed throttling or the VFD for the HPP otherwise required with IC operation.

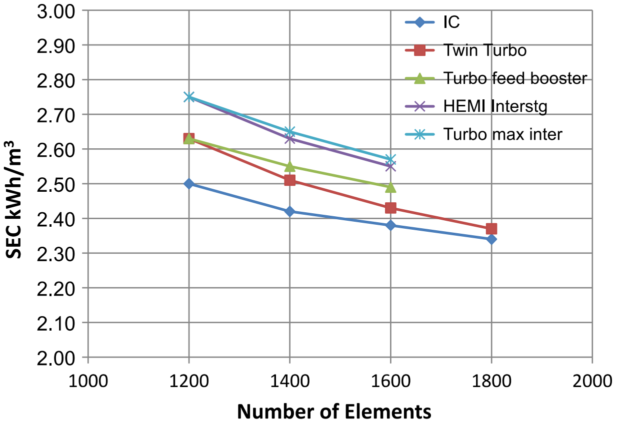

Chart 2. SEC vs. the number of elements.

4.2. Results

Chart 2 plots SEC as a function of the number of elements with more detailed results presented in Table 3. The two best ERDs in terms of SEC were the IC and twin turbo. As the membrane array became more efficient (i.e. more elements), the SEC values converged. The two single-stage ERD combinations showed essentially identical improvement in SEC with the IC having a 0.11 kWh advantage (4.3%) due to its higher hydraulic efficiency.

The twin turbo in a single-stage system has a 2.5% lower SEC than a single turbo in a single-stage system. The reduced SEC is due to the superior thermodynamic performance of the two-stage system. Note

Table 3
1,600 Elements

ERD		Stage	1st array	2nd array	Recovery	1st recovery	2nd recovery	SEC
HEMI-R	Interstage boosting + Power generation	2	210–4	152–5	0.508	0.258	0.337	2.554
Turbo	Interstage boosting	2	230–5	156–6	0.489	0.112	0.425	2.572
Twin turbo	Turbo for interstage and turbo for feed boosting	2	234–4	166–4	0.471	0.306	0.238	2.429
Turbo	Feed boosting	1	319–5	na	0.378	na	na	2.491
IC	Partial feed flow pressurization	1	391–5	na	0.357	na	na	2.377

that the HEMI-R was slightly better than the turbo interstage booster but less efficient than the twin turbo configuration. This suggests that generation of electrical energy is less effective than returning excess brine energy to the system in the form of a pressure boost. However, the HEMI-R likely has a substantial capital cost advantage.

The turbo configuration for interstage boosting used all available brine for boosting thus resulting in very high recoveries. Although the SEC results are not impressive, the authors believe that there is still potential for improvement in SEC values when membranes with different flux coefficients are used (subject of a future study).

The IC in this analysis has an efficiency of about 95%, yet its SEC was only 1.2% better than the twin turbo/two-stage configuration with 83% for turbochargers. The effect of two-stage arrays (2.5% savings), loss of HPP efficiency for the IC due to reduced flow (3.9%), high feed pressure from brine/feed mixing (2%), HP booster pump power consumption, and increased pretreatment pump energy erode the IC efficiency advantage to a negligible value in this analysis.

The twin turbo system has an optimal recovery of 0.471 vs. 0.357 for the IC. Higher recovery favors reduced capital and operating costs of the pretreatment system.

Andrew's theoretical analysis suggests that the two-stage configuration should provide between 10 and 15% SEC reduction. The actual 2.5% savings may be that real membrane performance reduces the theoretical advantage of staging. In addition, the present search algorithm was too coarse and/or may not be broad enough to find the absolute optimal configuration. Newer membranes that deliver higher permeate flux for a given NDP should allow performance approaching the theoretical gains.

Chart 3 illustrates the effects of permeate flux coefficients on SEC performance. As expected, increased permeate flux coefficients result in lower SEC and the twin turbo SEC reducing at a greater rate than the IC due to the increasing advantage of the two-stage design. At the highest permeate flux coefficient considered, the twin turbo had the lowest SEC of all ERDs considered.

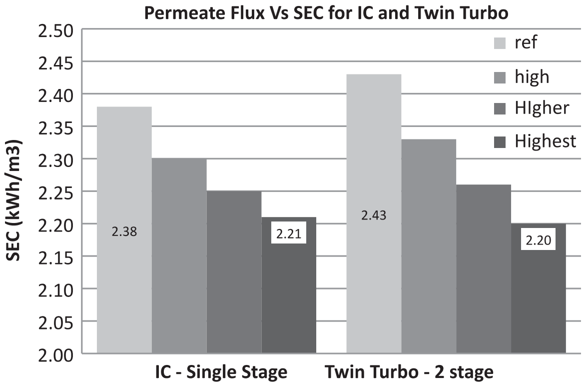

Chart 3. Permeate flux vs. SEC performance for IC and Twin turbo.

Hydraulic characteristics of the IC do not allow optimal application to two-stage systems due to the following characteristics:

- Feed flow pressurized by the IC must equal brine flow passing through the IC which does not match interstage flow;
- Feed outlet pressure must be close to brine inlet pressure rendering interstage boosting with the IC essentially impossible.

Therefore, of the ERDs considered in this analysis, only turbochargers provide hydraulic characteristics that match the requirements of two-stage systems.

4.3. Cautions

The flood of data produced by the analysis needs to be better organized and visualized to capture important trends. For example, even though the SEC generally shows continuous reduction with increasing

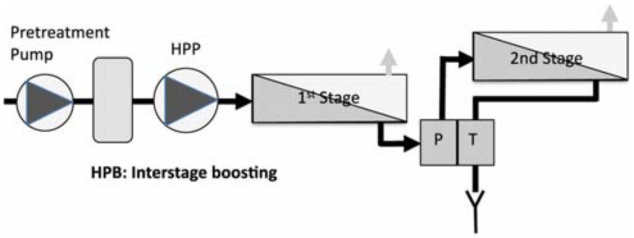

Fig. 1. HPB: Interstage boosting Process and Instrumentation diagram (P&ID).

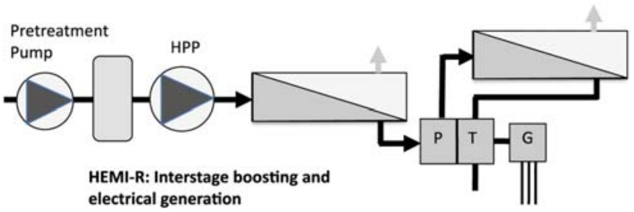

Fig. 2. HEMI-R: Interstage boosting and electrical generation P&ID.

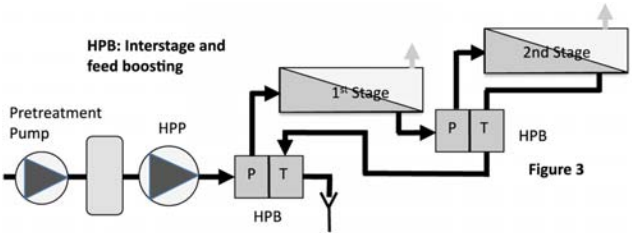

Fig. 3. HPB: Interstage and feed boosting P&ID.

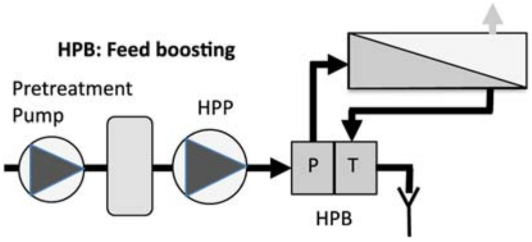

Fig. 4. HPB: Feed boosting.

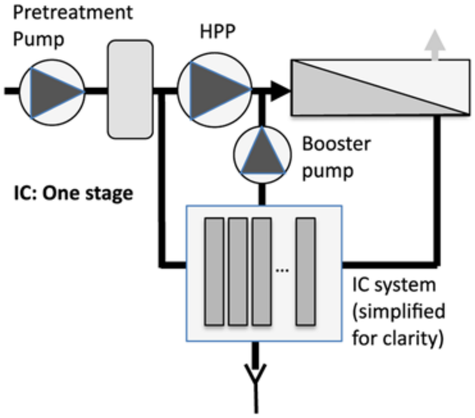

Fig. 5. IC: One stage.

element count regardless of the type of ERD, significant variations occur due to different element configurations. It is possible to miss an optimal configuration in the present analysis due to inappropriate limits on the search range.

The rate of change in SEC can become very small as elements are added while permeate TDS continues to degrade. It is quite likely that the optimal array defined as providing the lowest cost permeate does not provide the lowest possible SEC but rather provides a balance of SEC, permeate quality, capital costs, membrane replacement costs, etc.

The element analysis needs further refinement to better match membrane projection software at high NDP/high salinity conditions without adding significantly to the computational load. Membranes with different performance characteristics should be included to permit optimization of mixed membranes in two-stage performance.

5. Conclusions

5.1. *Future research*

Further research will be performed on array optimization with stronger analytical linkage to theoretical array performance analysis. Also, cost of the membrane array (pressure vessels, elements and frequency of replacement, support structure, interconnecting piping, etc.) will be modeled to include cost factors in identifying the optimal membrane array in terms of the cost of permeate. Essentially, the LCC of each configuration will be calculated to find the most cost-effective combination of membrane configuration and ERD type.

There is sufficient evidence to conclude that two-stage mega SWRO systems are warranted based on improved SECs, higher recovery yielding smaller pretreatment costs, and potential for improved SECs with new membrane technology that particularly benefit two-stage systems.

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