Permeate Recovery Rate Optimization at the Alicante Spain SWRO Plant

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Abstract

The permeate recovery rate in a reverse osmosis (RO) process is generally defined as the permeate flow rate divided by the membrane feed flow rate. An alternative definition is the permeate flow rate divided by the process feed flow rate. Historically, the process and membrane feed flow rates have been equal.

A high recovery rate means a high process yield. However, in a desalination process, operation at high recovery results in higher average concentrate salinities in the membrane elements, higher osmotic pressures and higher membrane feed pressures compared to operation at low recovery. In addition, supersaturation of the concentrate can result in more scaling and high membrane flux can result in more fouling. On the other hand, low recovery rate operation directly reduces process yield and can result in excess pretreatment and supply-pumping expenses. Permeate recovery rate optimization, therefore, is a critical exercise for RO process design and operation.

In most seawater RO processes being built today, such as the seawater RO plant built and operated by Inima (Grupo OHL) in Alicante Spain, isobaric energy recovery devices (ERDs) are applied to save energy. The flow rates of the high- and low-pressure streams through the devices to be unequal or unbalanced. Earlier turbine-based ERDs did not allow this flexibility. As a result, permeate recovery rate and process recovery rate can be set separately in RO processes equipped with isobaric ERDs. This feature adds a degree of freedom to recovery rate optimization and an opportunity for reducing energy consumption and/or improving process yield.

The authors present a detailed consideration of permeate recovery rate optimization in seawater RO processes equipped with centrifugal high-pressure pumps and PX Pressure Exchanger energy recovery devices. Optimization models are developed using practical process controls as independent variables. Modeling results are verified with process data collected at the Alicante seawater RO plant.

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I. INTRODUCTION

In a reverse osmosis desalination process, the recovery rate or conversion rate is the ratio of membrane permeate flow rate to the membrane feed flow rate. Historically, these processes were operated at the highest possible recovery rate to obtain the maximum amount of permeate possible from the pressurized membrane feed water. However, the introduction of “isobaric” or pressure-equalizing energy recovery devices (ERDs) changed this practice (1).

In a seawater reverse osmosis (SWRO) process operating at a 45% recovery rate, isobaric ERDs supply 55% of the membrane feed flow, reducing the load on the high-pressure pump by a corresponding amount. Energy is consumed by a circulation pump that works in series with the ERDs, however, because the circulation pump merely circulates and does not pressurize water, its energy consumption is minimal. Therefore, more than half of the membrane feed flow is pressurized with almost no energy input. This means that seawater RO processes with isobaric ERDs can operate affordably at lower permeate recovery rates compared to processes operating with no energy recovery devices or with turbine-based devices. As a result, in most seawater RO processes being built today, such as the SWRO plant built and operated by Inima in Alicante, Spain (“the Alicante plant”), isobaric ERDs and a recovery rate of between 40% and 45% are applied to save energy.

Isobaric ERDs allow the flow rates of the high- and low-pressure streams through the devices to be unequal or unbalanced. As a result, the membrane recovery rate and the overall process recovery rate can be adjusted independently. This feature adds a degree of freedom that can result in further reductions in energy consumption and/or process yield improvement. This paper considers recovery rate optimization for the Alicante plant.

II. ALICANTE PLANT OVERVIEW

Alicante is a city of approximately 350,000 people located in southeastern Spain south of Valencia. The desalination plant is located on the coast just south of the city. Alicante II was commissioned in April 2008. It is the second membrane desalination facility built on the site, the first having been put in operation in 2003. Alicante II was designed and built by Spanish original equipment manufacturer Inima of Grupo OHL, Construcciones Alpi and Sampol..

The plant is fed from beach wells. The high-pressure portion of the plant consists of seven independent SWRO trains with a combined permeate production capacity of 65,000 m^3/day. Each train has 128 vessels of Dow Filmtec membranes, with six SW30HRLE-400i elements plus one SW30XLE-400i element per vessel. The trains are fed with Flowserve 8 x 10 x 13 DMX axially-split double-volute pumps driven by a Siemens 1100 kW, 2,980 rpm, 6000 volt motors. Each train is also equipped with a Flowserve 8HHPX15C horizontal circulation/booster pump with a 90 kW, maximum maximum 1,475 rpm, 400 volt motor equipped with a variable speed drive (VSD). A photograph of one of the SWRO trains is given in Figure 1.

Figure 1 – High Pressure Pump, Circulation Pump and Membrane Array

Energy recovery is achieved with arrays of twelve ERI PX-220 devices dedicated to each SWRO train. In Alicante, the PX devices are installed in the piping run below the membrane arrays, as shown in Figure 2.

Figure 2 – PX Energy Recovery Device Array

PX energy recovery devices (ERDs) are positive displacement isobaric devices commonly used in SWRO processes built since 2003 (2). Pressure transfer occurs through direct contact between the high-pressure concentrate and pressurized seawater inside the devices. Because there are no pistons or barriers in the flow paths, high- and low-pressure flow rates through the devices can be manipulated freely.

The Alicante plant started production in April 2008. The plant was designed to operate at a 45% recovery rate with sufficient capacity in the energy recovery device arrays and circulation pumps to operate at a recovery rate of as low as 39% if desired. At 45% recovery, each train is designed to produce 411 m^3/hr of permeate for a nominal plant production capacity of 65,000 m^3/day.

Shortly after startup, fouling struck the membranes. This increased the membrane feed pressure by about 4 bar and decreased permeate production. When it was realized that the fouling was persistent and unavoidable, the recovery rate of the SWRO process was lowered to approximately 40%. Lowering recovery lowered the membrane feed pressure resulting in an increase in permeate production to the design flow rate.

After their success with recovery adjustment, the plant operations team was open to consider further optimization of SWRO system flows. A recovery optimization model was developed and run over a range of process conditions. The model results were verified with tests run on the system. A detailed description of the analysis and results is given in the following sections.

III. RECOVERY OPTIMIZATION

To explain recovery and how it is adjusted, a simplified process flow diagram is shown in Figure 3. Concentrate rejected by the membranes (stream G) flows to the ERDs, driven by a circulation pump. The ERDs replace the concentrate with feedwater from the low-pressure supply system (streams A and B). The pressurized feedwater (stream D) merges with the discharge of the high-pressure pump (stream C) to feed the membranes (stream E). Water leaves the process as permeate from the membranes (stream F) or as spent low-pressure concentrate from the ERDs (stream H). In these systems, the high-pressure pump flow rate equals the permeate flow rate plus the leakage loss through the ERD. The leakage loss is very small such that the permeate flow rate and the high-pressure pump flow rate are always nearly equal (2).

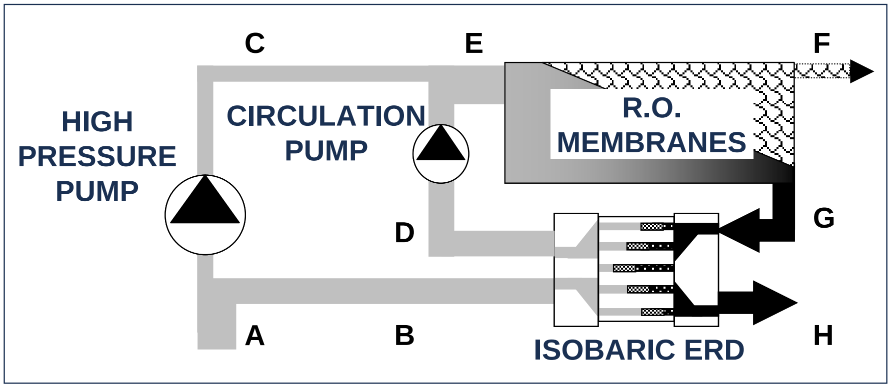

Figure 3: Simplified Diagram of an RO Process with Isobaric ERDs

With reference to Figure 3, the following terms are defined:

Membrane Recovery Rate – Permeate flow rate divided by the membrane feed flow rate or F / E.

Overall Recovery Rate – Permeate flow rate divided by the system feed flow rate or F / A.

Balanced ERD Flows – Flow rate of low pressure water fed to the ERD equals flow rate of high pressure water taken from the ERD or B = D and G = H. At balanced flow, membrane recovery and overall recovery are equal.

Lead Flow – Ratio of low-pressure flow rate to ERD divided by high-pressure flow rate from ERD, set by adjustment of low-pressure flow rate. A positive lead flow occurs when B > D.

Lag Flow – Ratio of high-pressure flow from ERD divided by low-pressure rate to ERD, set by adjustment of high-pressure flow rate. A positive lag flow occurs when D > B.

The membrane recovery rate, also known as the conversion rate, quantifies the amount of permeate extracted from the membrane feed. This, in turn, determines the concentration of the dissolved solids in the membrane reject stream. At high membrane recovery rates, the osmotic pressure of the concentrate stream is high, resulting in a high membrane feed pressure. Membrane recovery rate can be manipulated by altering the circulation pump speed. This, in turn, alters the membrane feed flow rate and changes the denominator in equation that defines the membrane recovery rate.

Lead or lag flow can be imposed by adjusting the low-pressure flow rate through the ERDs or by adjusting the speed of the circulation pump, respectively. However, for the sake of clarity in this analysis, the term lead flow will be used to refer to adjustments made by changing just the low-pressure flow rate through the ERDs. Therefore, positive or negative lead flows will be considered. Lag flow will be used throughout this analysis to refer to flow adjustments made by changing just the circulation pump speed. Positive and negative lag flows will be considered.

Some mixing occurs in the ERDs as a result of the direct contact between seawater and concentrate inside the devices. The ratio of ERD flows has a distinct affect on mixing as illustrated in Figure 4. If operated at positive lead flow, the excess seawater fed to the ERDs flushes the devices and reduces the salinity of the high-pressure water flowing from the devices. Negative lead flow results in some breakthrough of the concentrate to the high-pressure water flowing from the devices, evident as an increase in mixing. Lag flow has a similar affect on ERD mixing with a negative lag flow resulting in reduced mixing. Reduced mixing, in turn, results in lower salinity in the membrane elements and a corresponding reduction in the osmotic and membrane feed pressures.

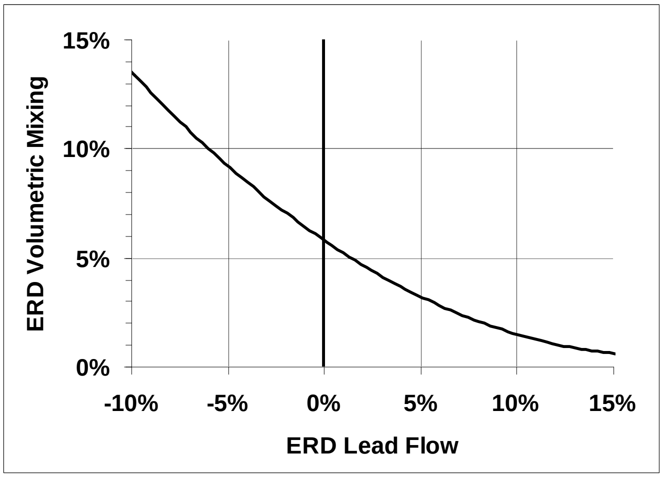

Figure 4 – ERD Mixing Versus Lead Flow

IV. PROCESS MODEL

The Alicante plant SWRO process was modeled using the characteristic curves of the high-pressure pump, the circulation pump, the membranes and the ERDs. Figure 5 shows the high-pressure pump curve, with head plotted as a function of flow. Adjustment of the high-pressure pump feed pressure, high-pressure throttling or permeate throttling can shift the pump curve up or down the chart. The duty point of the pump, however, always stays on the curve. For example, higher membrane feed pressure results in a lower flow rate as the duty point moves to the right and down the chart.

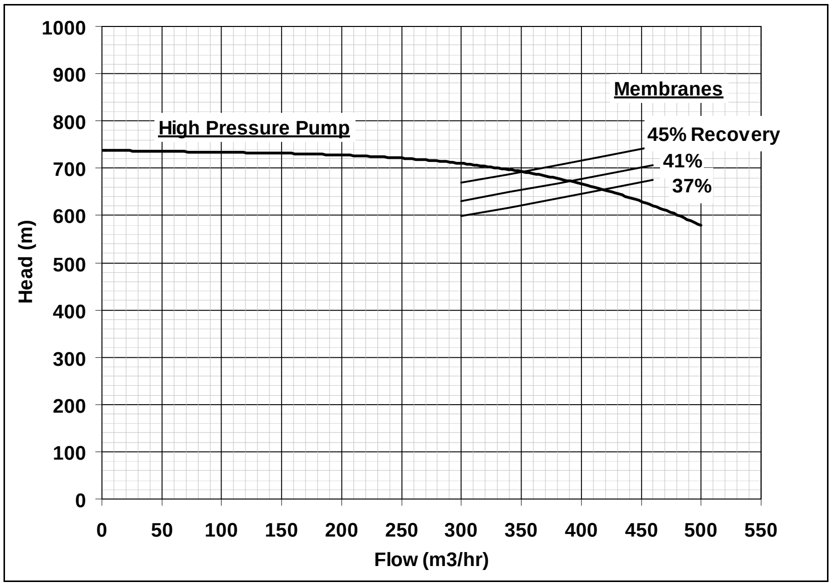

Figure 5 – High-Pressure Pump and Membrane Characteristic Curves

Membrane responses from the projection software for three different recovery rates were superimposed on the high-pressure pump curve in Figure 5. It is valid to consider these curves on the same chart because the high-pressure pump flow rate and the permeate rate are always nearly equal as described above. The membrane curves indicate that increased feed pressure results in higher permeate flow rates. These curves also indicate that higher pressures are required at higher recovery rates. Seawater temperature, seawater salinity and membrane fouling shift the membrane curves up or down the chart. The process operates at the pressure and flow rate where the membrane curve and the pump curve intersect.

Two characteristic curves for the circulation pump are given in Figure 6, corresponding to two different pump and motor rotation speeds. Although the duty point of the circulation pump always stays on a flow-head curve, adjustment of the VSD allows the operator to shift pump duty point from one curve to another. Therefore, the circulation pump can essentially be operated at any combination of flows and pressures within the operating envelope provided by the pump, motor and VSD. The circulation pump drives flow through the membrane concentrate channels and the ERDs such that the operation of these elements is coupled.

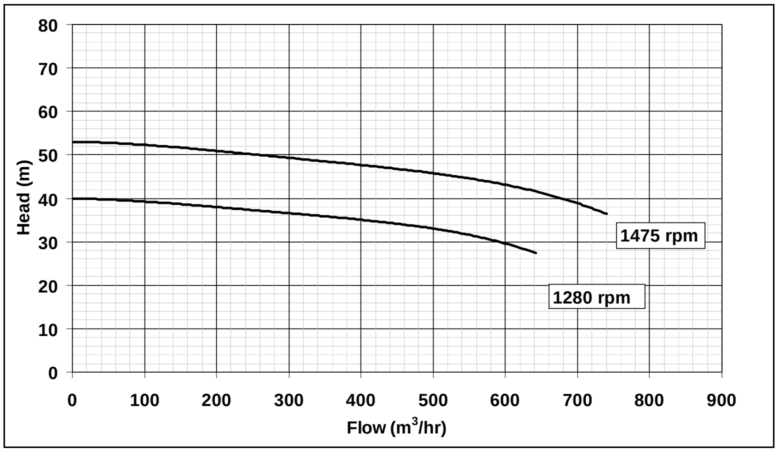

Figure 6 – Circulation Pump Characteristic Curves

The performance of the ERDs is also described by characteristic curves. These are shown in Figure 7 for a model PX-220 device. The flow rates through the ERD determine the pressure drops along the high-pressure and low-pressure flow paths. Conversely, with multiple ERDs operating in a device array, the flow rate through a particular device is determined by the pressure difference between the inlet and outlet manifolds at the manifold positions of the ERD (3). The ERD high-pressure flow is driven by the circulation pump and the low-pressure flow by the low-pressure supply pump.

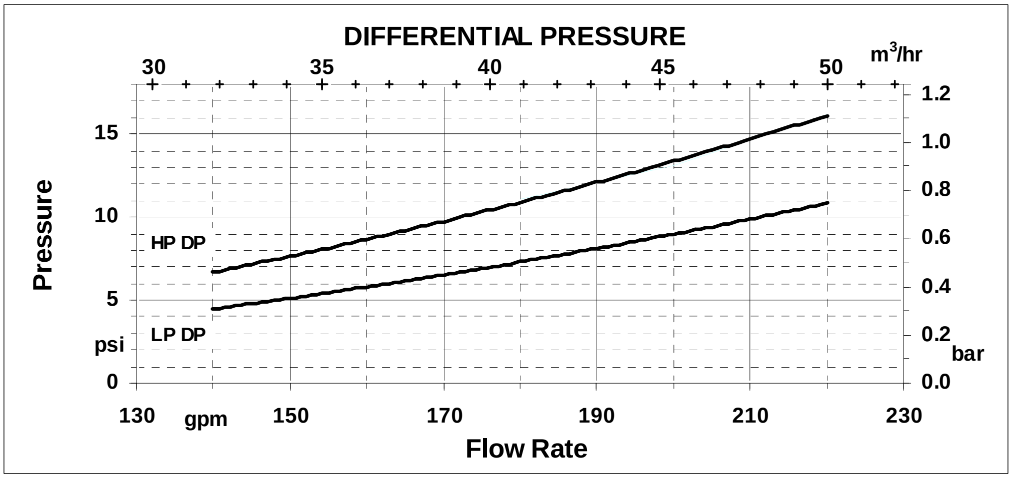

Figure 7 – PX-220 ERD Characteristic Curves

Resolution of the SWRO operating point for a given set of flow, pressure, salinity and temperature conditions involves the simultaneous consideration of the characteristic curves of the pumps, membranes and ERD. It is, therefore, an iterative computational process. After the system flows, pressures and corresponding pump hydraulic output requirements are determined, the energy consumption of the pump motors are computed using the pump and motor efficiencies (4, 5).

4.1 Lead Flow Modeling Results

Modeling results for a range of system recovery and membrane recovery combinations under lead flow conditions are shown in Figure 8. Specific energy in Figure 8 is the sum of the supply pump, the circulation pump and the high-pressure pump energy consumption divided by the SWRO permeate flow rate. Lead flow and overall recovery were adjusted by changing the low-pressure flow rate through the ERDs while holding constant the high-pressure flow rate of the circulation pump.

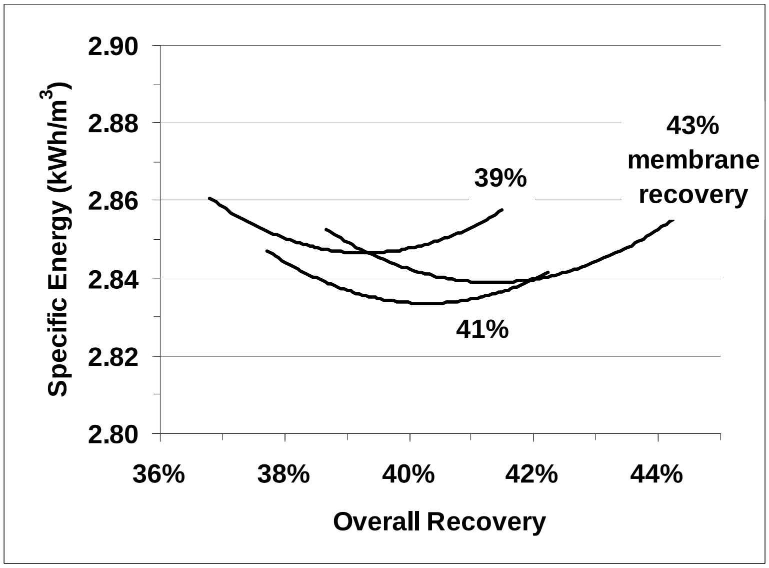

Figure 8 – Lead Flow Modeling Results

Considering any of the membrane recovery curves shown in Figure 8, as overall recovery is increased with reduced seawater fed to the ERDs, energy consumption by the high-pressure pump increases. This energy consumption increase corresponds with the increase in salinity in the membrane feed caused by extra mixing in the ERD in accordance with Figure 4. As overall recovery is reduced with extra seawater fed to the ERDs, excess energy is consumed by the system supply pump. The optimum overall recovery rate corresponding with the lowest SWRO specific energy consumption, therefore, is achieved by optimizing the low-pressure flow rate supplied to the ERDs by the supply pump.

At 41% membrane recovery, minimum energy consumption is predicted to occur at an overall recovery rate of nearly one percent less than the membrane recovery rate, corresponding to positive lead flow. At 43% membrane recovery, the optimal low-energy point is at an overall recovery rate that is about 1.5% lower than the membrane recovery, corresponding to more positive lead flow. At 39% membrane recovery, the optimal overall recovery is above 39%, corresponding with slight negative lead flow.

These data suggest that the system has a “sweet spot” close to 41.5% membrane recovery and 41% overall recovery. These recovery rates are close to balanced flow with 2% extra low-pressure seawater supply or 2% lower concentrate flow. If the membrane recovery is increased above 41.5% by reducing circulation pump speed, specific energy consumption can be reduced by reducing overall recovery by applying more low-pressure flow to the ERDs. Similarly, if the system is operating at a lower-than-optimal membrane recovery, overall recovery can be increased slightly by reducing low-pressure flow to the ERDs to reduce energy consumption.

It is important to note that this analysis does not take into account the full cost of pretreatment, the capacity of the pretreatment system or the energy or cost required for post-treatment. Recovery optimization requires consideration of equipment, contractual and cost constraints. For example, there is insufficient pretreatment capacity to allow the entire plant to operate at 41% recovery. However, the analysis does take into account changes in mixing through the ERDs and the associated impact upon membrane feed pressure. Volumetric mixing ranges from 2 to 13% in the data presented in Figure 8 in accordance with the lead flow dependency given in Figure 4.

4.2 Lag Flow Modeling Results

A similar iterative procedure was used to resolve the characteristic equations of the components to generate specific energy curves for a range of overall and membrane recovery rates for lag flow conditions. Lag flow and membrane recovery were adjusted by just changing circulation pump speed. For example, increased circulation pump speed resulted in positive lag flow and reduced membrane recovery. The results are shown in Figure 9.

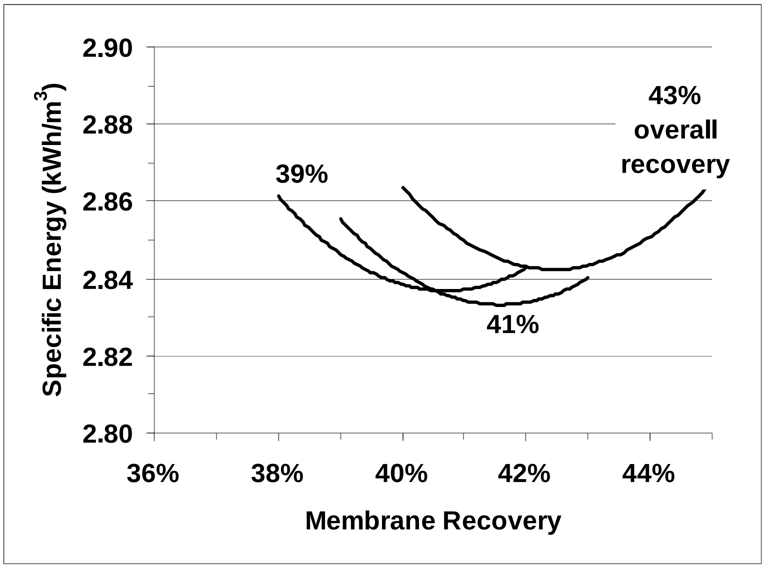

Figure 9 – Lag Flow Modeling Results

The overall trend of the data for the lag flow modeling was similar to the lead flow data. Considering any of the overall recovery curves, positive lag flow and reduced membrane recovery increased energy consumption by raising the salinity of the membrane feed and the corresponding duty of the high-pressure pump. Negative lag flow and increased membrane recovery increased energy consumption by raising the osmotic pressure within the membrane array. The optimum membrane recovery rate corresponding with the lowest overall specific energy consumption, therefore, is achieved by optimizing the high-pressure flow rate supplied to the ERDs by the circulation pump. As in the lead flow analysis, the “sweet spot” is at about 41.5% membrane recovery and 41% overall recovery.

Note that the overall recovery curves in the lag flow modeling results are more curved than the lead flow curves when the system is shifted away from its minimum energy points. Circulation pump speed changes alter both the mixing within the ERD and the salinity within the membrane elements. The compound affect of membrane recovery rate changes results in the steep curves in Figure 9. These results show that the process is more sensitive to the high-pressure flow rate through the ERDs than it is to the low-pressure flow rate through the ERDs.

It should also be noted that the overall range in specific energy indicated in Figures 8 and 9 is about 1.4% despite a variation in ERD flow of nearly 30%. This suggests that the system’s energy performance is robust and somewhat insensitive to flow imbalance through the ERD. The optimization exercise described above is "fine tuning." However, its importance is magnified when multiple years of operation and multiple SWRO trains are considered. In the Alicante plant, if the price of power is $0.09 per kilowatt hour, a 1.4% reduction in energy consumption would save nearly $90,000 per year in power costs.

Again, it is important to note that this analysis does not take into account equipment, contractual and cost constraints which may shift the optimal recovery rate of the process. However, the trend of the results can be useful for process optimization at any recovery rate. For example, if the process is operated at an overall recovery rate of 45%, the analysis above suggests that reducing the membrane recovery rate to below 45% will improve specific energy consumption. This can be achieved by increasing the speed of the circulation pump with no other changes to the process. Conversely, at overall recovery rates below 41%, increased membrane recovery rates and lower circulation pump speeds are energetically favored.

V. PROCESS PERFORMANCE

Between when the analysis above was conducted and process performance data was collected, several changes were made to the process. First, a partial open intake was added to the beach wells resulting in a decrease in the average salinity of the feedwater to the process from about 42,300 to about 39,300 ppm and reducing membrane feed pressure by about 1 bar. Second, the membranes of some SWRO trains were chemically treated to address the fouling problem resulting in a membrane feed pressure reduction of approximately 2 bar. Both of these changes reduced the specific energy consumption of the process compared to the energy consumption measured at the start of the analysis and predicted by the model.

Process data was collected in the Alicante plant from the SCADA screen in the plant control room at 41 and 43.5% overall recovery. The circulation pump speed or the low-pressure feed rate to the PX devices was varied and pump power consumption was measured. ERD efficiency ranged from 96.6 to 97.2% and volumetric mixing ranged from 3.6 to 10.6%. Specific energy data as a function of recoveries is shown in Figure 10. The curve identified as "43.5% overall recovery" was collected on a train that had received chemical treatment for fouling.

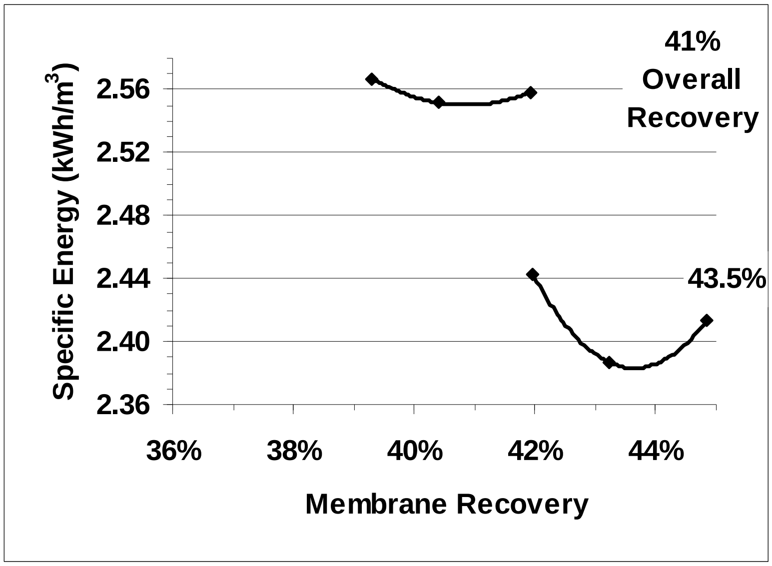

Figure 10 – Process Data

These data clearly demonstrate the energy reduction benefits of the feedwater and membrane changes. The data also suggest that the lowest specific energy was measured when the membrane recovery and overall recovery were set equal, at which point the ERDs were operating at balanced flow. However, the change in specific energy consumption and the ERD efficiency measured over the range of the membrane recovery rates examined was minimal despite the rather large range of mixing observed from the ERDs. This observation supports the conclusion that SWRO processes operating with isobaric ERDs are relatively insensitive to flow and flow ratio variations through the ERDs.

VI. SUMMARY AND CONCLUSIONS

The isobaric energy recovery devices in use in the Alicante plant gave the operators the flexibility to reduce recovery to achieve the plant's permeate production target despite persistent fouling that increased the membrane feed pressure. In addition, the PX devices used for energy recovery in the plant allow the operators to adjust the ratio of high- and low-pressure flows through the devices and thereby independently adjust the membrane recovery rate and overall recovery rate of the process. An analysis of the system over a range of recovery rates reveals the existence of a specific combination of overall and membrane recovery rates that results in minimum energy consumption. The analysis indicates how the membrane recovery rate could be adjusted to minimize energy consumption at whatever overall recovery rate that plant is operating. The results of the analysis were corroborated with process data.

VII. REFERENCES

1. MacHarg, J.P. and G.G. Pique, How to Design and Operate SWRO Systems Built Around a New Pressure Exchanger Device, International Desalination Association World Congress Manama, Bahrain 2002.

2. Stover, R.L., Development of a Fourth Generation Energy Recovery Device – A CTO's Notebook, Desalination, 165, pp. 313-321, August 2004.

3. Stover, R.L., J.G. Martin and M. Nelson, The 200,000 m^3/day Hamma Seawater Desalination Plant, Proceedings of the International Desalination Association World Congress, Maspalomas, Gran Canaria, Spain, October 2007.

4. Moch, I. and C. Harris, What Seawater Energy Recovery System Should I Use? – A Modern Comparative Study, Proceedings of the International Desalination Association World Congress, Manama, Bahrain, March 2002.

5. Stover, R.L., Energy Recovery Device Performance Analysis, Proceedings of the Water Middle East Conference, Bahrain, November 2005.