Selection, operation and control of a work exchanger energy recovery system based on the Singapore project

Beat Schneider
Calder AG, Industrie Nord, CH 5704 Egliswil, Switzerland
Tel. +41 62 769 60 71; Fax +41 62 769 60 70; email: beat.schneider@calder.ch

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Abstract
A question often asked in the SWRO industry is: ‘How do I select the best energy recovery device for a reverse osmosis plant?’ This paper explains the most important points to be considered when installing a work exchanger energy recovery system. The basic plant design has to be different to fully benefit from the advantages a work exchanger system offers. A train or centre design for plant layout has to be selected at an early stage, and if a train design is planned the optimum size of the trains can result in significant savings of both initial investment and energy consumption. This paper explains how to optimise the overall power consumption of a plant, to reduce the capital costs and to evaluate the most economical energy recovery device.

Besides the main advantage of the inherently higher efficiency of a work exchanger energy recovery device there are other operational advantages compared to other energy recovery devices such as the Pelton turbine, pressure exchangers and so-called turbochargers. In order to illustrate such differences the paper explains how to operate and control a plant with a work exchanger based on the example of the Singapore project.

Keywords: Energy recovery; Work exchanger; Pressure exchanger; Reverse osmosis

1. Introduction
Direct transfer energy recovery devices such as the work exchanger are the most efficient way to recover the energy from brine in a reverse osmosis system. However, having selected the most efficient energy recovery equipment there are still a number of aspects to be considered in order to optimise the overall power consumption in a plant. This paper aims to explain the main aspects to be considered when selecting a work exchanger. Some advantages are in connection with the operation and controlling of a work exchanger. Therefore this paper will also deal with operation and control philosophies of a RO plant with work exchanger.
2. Principle of a work exchanger

2.1. Direct transfer

Energy recovery devices such as reverse running pumps, Pelton turbines and turbochargers first transmit the hydraulic energy of the brine stream into a mechanical energy at the shaft and back again to hydraulic energy through the pump. This will always be less efficient in principle then direct transfer where the energy is transferred directly from fluid to fluid or in this application from brine to seawater feed. The two fluids are separated by a piston to ensure minimum mixing (Fig. 1) of brine and seawater feed. This separation ensures that salinity increase and resulting increased membrane feed pressure are kept to a minimum.

2.2. DWEERTM work exchanger

In order not to interrupt the brine flow the DWEERTM work exchanger has a minimum of two pressure vessels in parallel. One vessel is in the working stroke while the other is filled with fresh seawater. As soon as the piston of the working pressure vessel finishes its working stroke and the filling vessel is fully filled with fresh feed water, the brine and feed line are switched (Fig. 2).

The DWEERTM work exchange consists of three main subassemblies that are the LinXTM valve, the pressure vessels and the check valve nest (Fig. 3).

Fig. 4 shows how a work exchanger is integrated into an RO desalination system. The main difference compared to a typical arrangement with a Pelton turbine is that the feed flow is split into the LP feed to the high pressure pump and to the energy recovery device. Only slightly more a flow slightly greater than the product flow will be handled by the HP pump. Therefore the size of the HP pump is reduced. For example, it is reduced to 40% for a membrane conversion of 40%.

A booster pump needs to be installed in the system to compensate for the differential pressure over the membranes and pressure losses in the piping and over the energy recovery device. Typically such a pump is designed for a differential head of about 30 to 40 m. Thus, compared to the HP pump this is a low power consumer. The booster pump needs to be designed for high pressure.

2.3. Losses of a work exchanger (efficiency)

For a work exchanger or a pressure exchanger it is more meaningful to discuss losses rather than efficiency. Unlike in the analysis of devices such as the Pelton turbine or reverse running pumps an assessment of generated shaft power is not possible and an analysis of hydrodynamic efficiency alone is insufficient. Since additional losses have a direct impact on other components of the system. Therefore the following losses should be considered when selecting a work exchanger device: Mixing, leakage, overflush, high pressure differential, low pressure differential, noise.

Mixing: Mixing results in increased TDS of the membrane feed water, and consequently a higher feed water pressure is needed. Therefore the HP pump will absorb more power. For the overall power consumption a low mixing value is most important.

![Diagram of piston to ensure minimum mixing of brine and seawater feed.](image-url)
since any increase in membrane feed pressure needs to be compensated by the relatively inefficient high pressure pump. The DWEER™ has a separating piston between...
feed flow and brine. Other pressure exchanger technologies on the market use fluid-to-fluid exchange with high and undefined mixing varying mainly with flow but also salinity.

Leakage: Leakage also sometimes called lubrication flow occurs when high pressure brine leaks to the lower pressure feed flow. As a result the HP pump has to supply more flow and will absorb more power.

Overflush: Overflush is feed water directly pumped through the equipment to drain. This is required to flush out remaining brine prior to filling with feed water. As a result the feed pump has to supply additional feed water and absorbs more power. Additionally one should not forget the cost of the pre-treated water that is wasted through overflush. The overflush is connected with the Mixing. If brine is not flushed out properly, feed water TDS will increase as a result. In case of a direct transfer device without a separating piston between the feed water and brine water a high TDS fluid plug will be formed that needs to be flushed out.

High pressure differential: This is the pressure loss between the HP brine and the HP feed outlet. As a result the Booster pumps have to supply more pressure and will therefore absorb more power.

Low pressure differential: This is the pressure loss between the LP feed inlet and the LP brine outlet. As a result the Feed pumps have to supply more pressure and will therefore absorb more power.

2.4. Other system components

Compared to a typical system with Pelton turbines, several components in a plant with work exchanger need to be designed differently. Additionally, new components are needed. Listed below are some components and comments with regard to their selection.

High pressure pump: For a plant with work exchanger, the HP pump needs to deliver only the product flow and some additional leakage flow. The size of the pump compared to a typical plant with

Fig. 4. Integration of the work exchanger into an RO desalination system.
turbines is reduced to about 35–45% of flow depending on conversion. From a pressure point of view the HP pump needs to deliver the membrane feed pressure (taking into account mixing) plus piping and valve losses and HP differential over the work exchanger.

**Booster pump:** The booster pump is often an inline centrifugal pump, frequency controlled with high pressure suction and discharge connections. The pump is designed to handle the brine flow plus leakage flow. The differential head of the pump is designed to overcome the pressure losses over the membranes as well as piping losses and differential pressure over the work exchanger. The pump with its frequency converter controls the brine flow and is therefore used to adjust the plant to the optimal conversion.

**Feed pump:** In a plant layout as in Fig. 4 the feed pump delivers 100% of the feed flow. At the feed pump discharge the stream is split in two—one going to the HP pump and one feeding the work exchanger. Another option would be to use separate feed pumps for the HP pump and the Work Exchanger. If these pumps are frequency controlled they can be used to control the membrane feed pressure in the system to run the plant at the best efficiency point.

### 3. Design limits of the DWEER™ work exchanger

The DWEER™ can handle the full range of operating pressures typically used in the RO industry. Pressure vessel, check valve end and LinX™ valve are standard components manufactured to international codes.

The main limiting factor with regard to flow is the generated pressure drop over the work exchanger. In order to reduce such losses to a minimum several options are possible. One option is to stack the DWEER™ together in a rack and run several in parallel. Another is to have different sizes of work exchangers as described in section 3.2.

Another limiting factor is the cycling of the work exchanger. Cycling refers to the number of times each pressure vessel performs a working and filling stroke per minute. Currently the DWEER™ is cycling 4 times per minute. The reason for this limit is due to field experience. Higher cycles will have to be operated in a plant for more than 2 years before they can be accepted. Cycling faster would mean that the same model could handle more brine flow but at a higher differential pressure mainly in the LinX™ valve and the check valve nest. However, capital cost can be reduced.

#### 3.1. Product range

**DWEER™ 1100**—The DWEER™ 1100 was developed to be operated most economically at a flow of 1100 USGPM or 250 m³/h up to typically 80 barg.

**DWEER™ 2200**—The DWEER™ 2200 was developed to be operated most economically at a flow of 2200 USGPM or 500 m³/h up to typically 80 barg.

Rack design—At brine flows above the standard product range flow several DWEER™s can be grouped in a DWEER™ Rack by connecting them with a LP feed, HP feed, HP brine and LP brine header as in Fig. 5.

Normally such a rack is controlled by one Hydraulic power pack driving the actuators of the individual DWEER™s off synchronisation. A PLC finally can be installed for each rack or in case there are several racks in the plant the power packs can be centralised in the control room.
3.2. Possible arrangements

Train design: The normal design of RO plants was so far based on the train design approach. Each train was equipped with a HP pump, a membrane rack and an energy recovery device such as a turbine as per Fig. 4. Especially with reverse running pumps but also with Pelton turbines, which are directly connected to the HP, pump this was obvious solution. Some of the plants had common feed and high pressure headers to allow more flexibility but still they were based on this standard train design approach.

With the work exchanger this approach can be changed since the energy recovery device is not any longer directly connected with the HP pump. Therefore the work exchanger offers an alternative which is the centre design.

Centre design: The basic idea of a centre design is that the different main centres such as the HP pumping centre, the membrane centre and the energy recovery centre are selected to achieve the best possible economical approach for each centre. Fig. 6 shows a schematic of the centre design.

A paper was presented by IDE at the IDA conference in the Bahamas [3] which explains in more detail the idea of a centre design. For example the size of the HP pumps can be increased to a maximum size. This allows the designer to optimise the efficiency of these pumps but at the same time reduces the capital costs. Clearly aspects such as redundancy and the option to operate a plant at a reduced capacity need to be evaluated in such a centre approach. However, in order to achieve the most economical approach in a seawater RO plant, each contractor should consider the advantages and disadvantages of a centre design as it applies to their needs.

4. Selection of a DWEER™ work exchanger
4.1. Train design

The Tuas plant in Singapore a private BOO contract awarded to Hyflux Ltd with a total production of 136,000 m³/day. It is a good example of an optimal train design plant. The plant is connected to the common...
water distribution network of Singapore and the requirement was that the plant is able to supply water very flexibly and with fast response, from 20% to 100% of plant capacity in relatively small increments. After considering several aspects, the decision was clear to move towards train design. Since it is a two-pass plant design with 90% recovery in the second pass, the actual production of the first pass relevant for the Work Exchanger is 150,000 m$^3$/day at a membrane conversion of 45%. The total plant brine flow therefore is 183,333 m$^3$/day or 7640 m$^3$/h.

Based on a DWEER$^\text{TM}$ 1100 with an optimal brine flow at 250 m$^3$/h a total of 30 DWEER$^\text{TM}$ 1100 are therefore needed to handle the total brine flow. Due to the requirements of the plant with regard to flexibility Hyflux decided to move forward with a 10 train design resulting in a train capacity of 15,000 m$^3$/day and a Triple DWEER$^\text{TM}$ per train. Fig. 7 shows the actual train layout of the Singapore project. Fig. 8 shows a different train design.

4.2. Centre design

With a centre design one should look at the plant as if it was a single train. As can be seen from the projection below, the quantity of DWEER$^\text{TM}$ 2200 is reduced to 16. The projection now shows a total flow for the HP pumps and for the recirculation pumps. The next step is to discuss with the pump manufacturer the most economical pump size based on operational aspects.

For the HP pump a possible approach could be to use 3 HP pumps. This would allow running the plant at 33%, 66% and 100% capacity. We would propose to have all 16 DWEER$^\text{TM}$ in one rack but split in 4 Quad DWEER$^\text{TM}$'s. In case of operation at 66% one quad could be switched off and at 33% two Quad DWEER$^\text{TM}$'s would be switched off.

4.3. Comparison between the different designs

Comparing the two projections the energy consumption of the centre design was reduced from 2.1 to 2.01 kWh/m$^3$ relative to the train.
design. This can mainly be explained by the following reasons:

- Increased efficiency of the HP pump and motor.
- Increased efficiency of the recirculation pump and motor.
- Reduced losses in the DWEER™.

Additionally, there is also potential to save capital costs for the following reasons:
- Reduction from 10 to 3 HP pumps and booster pumps. Even though they are bigger, the capital costs will be reduced, since the optimal pump can be selected.
- Less instrumentation and controlling.
- Reduced number of DWEER™s.

5. Operation and control

5.1. Commissioning

Commissioning of a work exchanger plant is not much different from a plant with any energy recovery device. With regard to the work exchanger the following should be ensured:

- All piping to the energy recovery device should be flushed out with clean water by the use of strainers or by disconnecting the pipe work immediately before the DWEER™ to ensure no particles are flushed in the DWEER™.
- Piping should be properly installed and supported to have minimum flange forces to the equipment.
- Hydraulic power pack oil tank to be filled with oil as per manufacturer’s requirement.
- Wiring of the hydraulic power pack, PLC and the connections to the sensors to be checked.
- A dry run test should be carried out before per DWEER™ rack to ensure proper timing of cycling Fig. 9.
5.2. Start up

Venting: Before every start up the system should be properly vented if there is any risk of air in the system to protect the membranes. In order to vent the system the pre-treatment system should run. The feed water pumps can be started and the relevant valves should be open to provide LP feed water to the HP pump and energy recovery system. Also the low pressure brine valve should be open to allow the brine to leave the train.

Open the vent valves in the plant.

Start stroking the LinX™ valve and afterwards the booster pump set to a brine flow rate of about 80% of design flowrate.

Ensure that all air is vented through the vent valves and close them.

Start up: In the following start up sequence it is assumed that the venting process was just completed and the feed pumps, the booster pump and the LinX™ are still running. Close or set the HP pump discharge valve to minimum flow and start the HP pump. Slowly open the pump discharge valve in accordance to the membrane requirements to increase the system pressure to the set pressure. Adjust the train for the desired operating conditions as per adjustment procedure.

5.3. Adjustment procedure

Generally there are 3 main control loops for a work exchanger as in Fig. 10.

- Adjustment of the VFD on the booster pump to control HP brine flow and therefore the conversion.
- Adjustment of the VFD of the HP feed pump to adjust the membrane feed pressure and therefore product flow rate. Alternatively the product flowmeter cold
also control a HP pump discharge control valve or a permeate throttling valve.

- Adjustment of the VFD of the ERS feed pump to adjust the fill flowrate to the work exchanger. Alternatively the signal of the DWEER\textsuperscript{TM} PLC could also control a brine back pressure valve.

5.4. Shut down

The shut down procedure is inverse to the start up procedure with the advantage that at the end when all equipment is shut down some pressure will be captured in the DWEER\textsuperscript{TM} loop at about the osmotic pressure. This osmotic pressure can be dumped through the flush out valve if required. The captured pressure has several interesting advantages. First in case of a short term shut down this captured pressure will insure no air entering into the system and the units are immediately without venting ready for restart. Further this effect will protect the membranes from any sudden pressure drops such as might occur with power failure, miss manipulation, emergency stops.

5.5. DWEER\textsuperscript{TM} plc

The DWEER\textsuperscript{TM} is supplied generally with a PLC. The DWEER\textsuperscript{TM} PLC has the following main functions.

Ensure cycling of a single DWEER\textsuperscript{TM} or a DWEER\textsuperscript{TM} Rack. This is ensured by a simple timer providing the hydraulic unit with a signal when to start cycling the LinX\textsuperscript{TM} valve. During normal operation and within normal operating conditions the cycling time does not change. The DWEER\textsuperscript{TM} is designed for a 90\% vessel utilisation that will allow absorbing additional 10\% of brine flow without any changes.

The DWEER\textsuperscript{TM} PLC which is connected to sensors can detect over-or underflush and provide the Plant PLC with the information how to adjust the overflush to a minimum.
Without the PLC it becomes difficult to control overflush especially in a rack design where several devices are connected.

The PLC also provides the plant PLC with several signals essential in large plants for diagnosis and controlling of the equipment.

Further to that it is possible with the DWEER™ PLC to carry out locally operating tests which can be advantageous during commissioning or maintenance.

Maintenance: The DWEER™ is designed for a lifetime in excess of 25 years. Materials used as a standard are Super Duplex or non-metallic. Therefore the main components do not need replacement throughout their lifetime. All wearing parts are easy to access and can be replaced in a short time. Typical wearing parts which are to be changed in the range of 2–5 years are shown in Fig. 11.

5.6. Flexibility of flow and pressure

One of the main advantages of the DWEER™ besides the basic high efficiency is the wide operating range with relatively constant energy consumption.

Constant flow: In case of constant flows but a changing system pressure the DWEER™ will only be little affected. The only change is the slightly increased leakage over the LinX™ valve at a higher operating pressure increasing the leakage from 1.5% to 1.9% based on the Singapore example Fig. 7.

As a result the HP pump will need to deliver at higher operating pressure more flow while the booster pump will deliver less. Based on the Singapore projection this would mean that the leakage would increase from 13.1 m³/h at design to 14.6 m³/h at

Fig. 10. Three main control loops for the work exchanger.
69 barg which means an additional leakage flow of 1.5 m$^3$/h.

Based on this data the increased power consumption of the HP pump is

\[
P_{\text{hp pump delta}} = 1.5 \text{m}^3/\text{h} \times (69 - 2.6) \text{barg}/36/0.846 = 3.2 \text{kW}
\]

The decrease in power consumption of the Booster pumps is

\[
P_{\text{booster pump delta}} = 1.5 \text{m}^3/\text{h} \times 3.2 \text{barg}/36/0.816 = 0.16 \text{kW}
\]

Total increased power consumption is therefore

\[
P = P_{\text{hp pump delta}} - P_{\text{booster pump delta}} = 3.04 \text{kW}
\]

If this additional power consumption is set into relation with the power absorbed of the high pressure and booster pump, together 1264 kW, this is equivalent to a negligible increase of 0.2%. This calculation demonstrates that changing pressure at a constant flow will not affect the DWEERTM efficiency.

The overall power consumption as shown in Fig. 12 increases therefore mainly due to the increased membrane feed pressure and therefore higher differential pressure on the HP pump.

**Constant membrane feed pressure:** Fig. 13 shows the calculated differential pressures over the LinX™ valve, pressure vessel and check valve nest at constant brine pressure but changing brine flows. The DWEERTM leakage will not change in this case. The booster pump will need to overcome the increased high pressure differential head while the feed pumps have to supply the increased low pressure differential head.

In the Singapore example (Fig. 7) where the high pressure differential pressure would
increase from 1.2 barg at design to 1.4 barg at 10% higher production this is equivalent to a increased power absorbed of the booster pump of:

\[ P_{\text{booster delta}} = 763.9 \text{m}^3/\text{h} \times 1.1^* (1.4 - 1.2)/36/0.816 = 5.76 \text{kW} \]

Additionally the low pressure differential pressure would increase from 2.1 to 2.3 barg. Therefore the additional power absorbed by the feed pump is

\[ P_{\text{feed delta}} = 750.8 \text{m}^3/\text{h} \times 1.1^* (2.3 - 2.1)/36/0.8 = 5.74 \text{kW} \]
In total the additional absorbed power of the booster pump and the feed pump is therefore 11.5 kW. If this is put into relation with the total absorbed power of the HP pump and the Booster pump of 1264 kW the increase would only be in the range of 1% while we increased the production by 10%.

5.7. Flexibility in number of operating work exchangers

With several DWEER™ installed in either a train or centre design, it is possible to have all of them operating or to divide the flow in a lesser number. It is therefore possible to carry out maintenance on a DWEER™ and operate the remaining DWEER™s at a higher flow by either increasing the cycles or vessel utilisation.

6. Conclusions

Work exchangers are the most efficient energy recovery devices commercially available today. Efficiency of a work exchanger depends on the efficiency of other components in the R.O. plant. It is therefore more expedient to consider all losses of a work exchanger when making system comparisons. All losses should be clearly stated by the work exchanger manufacturer and guaranteed to the user.

Work exchangers allow designing plants differently since the energy recovery device is fully independent of the HP pumps. This has the following advantages:

- Capital and maintenance costs can be reduced by selecting most economical equipment sizes.
- Operating costs can be reduced by designing pumps, work exchangers and other components at their best efficiency points.

Work exchangers allow operation at almost a constant efficiency over a wide range of changing conditions especially with regard to changing pressure conditions.

References