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Development of a fourth generation energy recovery device. A ‘CTO’s Notebook’

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Abstract

Energy Recovery, Inc.’s Big Rotor Pressure Exchanger is the result of over 100 years of technology development. Work exchanger devices developed for seawater RO plants are considered by many to be the most important breakthrough in desalination in the last 10 years. What has made this breakthrough possible and how have these devices affected the job of designing SWRO systems? This paper presents the challenges and solutions of the design and deployment of the PX. PX performance data and engineering design considerations from operating SWRO-PX process configurations and PX arrays will be provided. Recent technical advances and future products will be discussed.

Keywords: Energy recovery; Seawater reverse osmosis (SWRO); Pressure exchanger

1. Introduction

The pressure exchanger (PX) transfers pressure from a high-pressure fluid stream to a low-pressure fluid stream utilizing the principle of positive displacement. Unlike other devices which have been adapted from other less challenging applications, the PX has been specifically developed for use in SWRO systems. First introduced as a commercial product in 1997, the PX has undergone several design improvements that have increased the capacity of a single rotor to as high as 50 m^3/h. However, the basic technological platform upon which the PX is built has remained unchanged, namely, conducting SWRO-scale energy recovery with many small pressure transitions in a ceramic rotary device.

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2. Prior art

Engineers have been working on the problem of pressure or energy recovery from water streams since the Enlightenment. An early device was patented by Lester Pelton for gold mining operations in California (Fig. 1). The idea of using the momentum of water to turn a wheel was not new to Pelton. But his "peculiar-shaped" split buckets, which facilitated efficient transfer of the impinging flow from one bucket to the next during rotation, were novel and were what made the device work. Modern Pelton wheels utilize the split buckets and the flow-driven rotation of the original 1883 design. Their overall energy-recovery efficiency is the product of the efficiencies of the nozzle, the buckets and the directly-coupled pump. Efficiencies as high as 81% have been reported for 90% efficient devices coupled to 90% efficient pumps, but typical Pelton efficiencies range from 40 to 60%.

Another type of energy-recovery device, the turbocharger, was initially developed in the early 1910's to capture the energy of the gas exhaust of internal combustion engines. The patent for RO applications was issued in 1990 to Robert Oklejas. The turbocharger captures the energy of the reject stream with a turbine or wheel that is directly connected to a pump impeller spinning in the feed stream. Turbocharger efficiencies as high as 80% have been claimed, but the maximum possible efficiency, which is the product of the efficiencies of the two impellers, typically ranges from 50 to 65%.

To avoid the efficiency losses associated with multiple energy-conversion steps, engineers successfully developed positive displacement (PD) energy recovery devices for SWRO in the 1990s. The modern devices were preceded by displacement methods piloted decades ago. The first design that employed piston-type isobaric PD was a device invented by Chen-Yen Cheng in 1970. The first commercially viable piston device was the Dyprex built by Aqua Design which has been running since 1985. The technology to control flows in a multi-chamber pressurization device using conventional valves draws from work done by William Swaney in the early 1960s, and additional control features and flow designs for a piston device were patented by Bowie Keefer for Seagold Industries in 1984. An improved control device — the LinX spool valve — was patented by Scott Shumway for DesalCo in 1998. The theoretical efficiency of a piston PD device is limited only by energy losses for moving the pistons and valves, but there are considerable operational challenges such as dynamic control and prevention of water hammer, cavitation and pulsations.

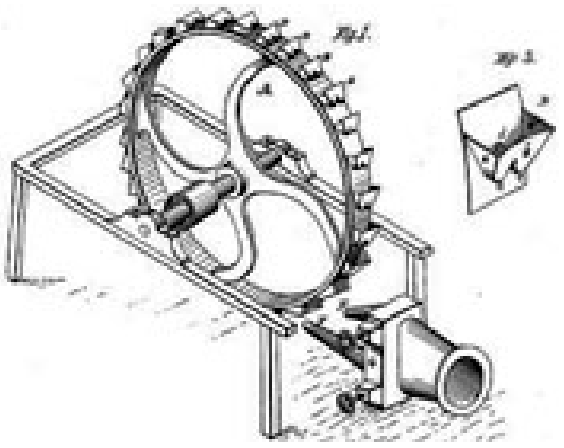

Fig. 1. 1883 Pelton wheel.

The Energy Recovery, Inc. pressure exchanger was designed and developed to combine the high efficiency of isobaric chamber PD with the operational simplicity of passive, flow-driven rotation. The PX drew from a much earlier externally-driven rotary-type displacement device — "An Apparatus Affecting Pressure Exchange" — patented by George Jendrassik of London in 1954 (Fig. 2). In adapting the concept of rotary PD to SWRO, ERI's founder Leif Hauge incorporated flow-driven rotation, a self-lubricating bearing and pressure transition control features. Pressure is transferred directly from the high-pressure reject stream to a feed stream with no

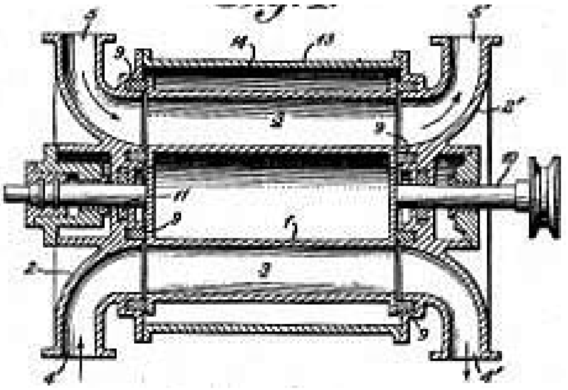

Fig. 2. 1954 rotary exchanger.

intervening walls and only one moving part. Five patents have been issued for the PX to date. The following section presents a chronology of the events leading to ERI's largest device: the PX-220.

3. Commercializing the PX

The initial PX design had flow channels in the end covers to direct the fluid streams into a rotor that was turned with a shaft. Flow-driven rotation was added in the next prototype. These devices employed stainless steel, titanium and other alloys, and the small clearances necessary to separate high and low pressure in the device led to galling and seizure. They were not capable of operating at the pressures required for SWRO application, but proved the concept of rotary isobaric-chamber energy-recovery device. These early prototypes can be considered first generation PXs (Fig. 3).

The employment of a ceramic rotor and sleeve gave birth to a second generation of devices. Ceramic is a hard material and very difficult to machine. Ceramic had been used in the past as a bearing surface, but only with much smaller parts than those necessary for the PX. For these reasons, critics doubted that the design was viable. But with persistence these obstacles were overcome and a functioning ceramic prototype with a hydrodynamic bearing similar to that employed by ERI today was achieved in the mid-1990s.

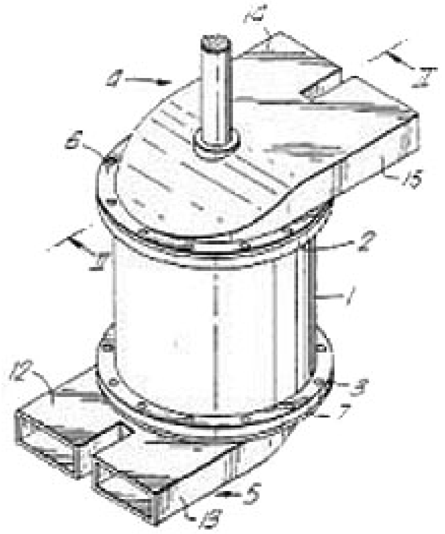

Fig. 3. 1989 metal PX.

The ceramic rotor became the platform upon which a commercially viable PX was built. The PX-60 (13 m^3/h/rotor) and other 4-inch diameter products including the PX-120 representing third generation rotary energy-recovery devices were introduced to the market in 1997. Packaged in durable vessels with standard piping connections, these devices were designed with features that prevent destructive phenomena such as water hammer and cavitation. Indeed some of the original 4-inch units are still operating today proving the long life and low maintenance inherent with the PX's ceramic rotor design.

ERI's technical philosophy for scaling the PX technology is to perform multiple operations in rapid sequence and/or in parallel rather than building larger parts and assemblies. The approach of building with small, manageable sub-processes mirrors natural structures such as cells. Membranes are similarly deployed as multiple modular units running in parallel.

The PX rotor, which rotates at between 500 and 2,000 revolutions per minute, is divided into 12 ducts and has two sides. It accommodates pressure transitions at a rate of 12,000 to 48,000 per min. Large PX arrays, built with as many as 40 rotors running in parallel, have demonstrated that the performance of PXs in arrays is identical to the performance of individual PXs. These designs incorporate redundancy, and this is a benefit for plant reliability. In applications where more than 6 rotors are arrayed in parallel, the loss of one rotor due to debris or damage has minimal impact on SWRO membrane performance and the plant can typically keep running until scheduled maintenance corrects the problem.

Nevertheless, as plant efficiencies increased and larger plants were built, the market demanded larger capacity PX units. ERI began working on the big rotor in late 2001. The author joined the company in early 2002 to lead this research and development effort. In early 2003, the big rotor PX-220 (50 m^3/hr/rotor) — a fourth generation rotary device — was born (Fig. 4).

As all research and development engineers know or eventually learn, increasing the size of a product involves much more than making larger components. The scale at which intermolecular forces and hydrodynamic phenomena occur is a determined by nature alone, not by the market or the board of directors. Water hammer and cavitation, which had been challenges for the development of the 4-inch PX, proved to be even greater challenges for the big rotor. Success was achieved by building upon the concepts and features that had proven themselves in previous PX designs, especially the division of the overall pressure transfer into small, smooth transitions. The housing was completely revised and built into a standard 8-inch Codeline vessel and heads. Other features that had been problematic in the 4-inch PX assembly were eliminated, resulting in a more elegant device with far fewer components.

Fig. 4. Author with PX-200.

4. PX operation and performance

4.1. How the PX works

To get the most from a PX, one must understand how it works. The PX facilitates pressure transfer from the high-pressure brine reject stream to the low-pressure seawater feed stream by putting the streams in direct, momentary contact. The transfer occurs in the rotor ducts. The rotor is fit into a ceramic sleeve between two ceramic endcovers with precise clearances that, when filled with high-pressure water, create an almost frictionless hydrodynamic bearing. At any given instant, half of the rotor ducts are exposed to the high-pressure stream and half the ducts are exposed to the low-pressure stream. As the rotor turns, ducts pass a sealing area that separates high and low pressure. Thus, the ducts that contain high-pressure are separated from the adjacent ducts containing low-pressure by the seal formed with the rotor’s ribs and the ceramic endcovers. A schematic representation of the ceramic components of the PX is provided in Fig. 5.

4.2. Rotor dynamics

Since there is no physical barrier between the brine and seawater streams in the rotor ducts, the degree of mixing between these streams is a function of the velocity of the streams and the duration of exposure. The duration of exposure is

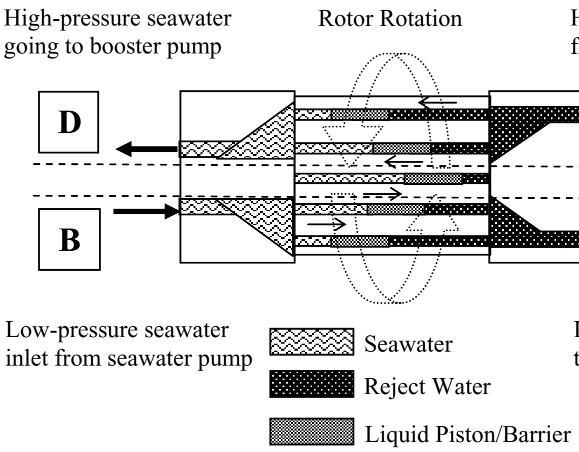

Fig. 5. PX flow schematic.

controlled by the rotation speed, which is in turn a direct function of the velocity of the streams. The PX is designed so that the interface between the brine and seawater streams never reaches the end of the rotor duct before the ends of the duct are sealed.

Therefore, a quantity of liquid — a "plug" — remains in the rotor duct at all times, traveling from one end of the rotor to the other and back again during a single rotation.

The relationship between rotation speed, the velocity of the brine-seawater interface in the duct ("plug velocity"), the distance the brine-seawater interface moves in the rotor duct ("plug travel distance") and the flow rate is illustrated in Fig. 6 in arbitrary units. As flow increases, the plug velocity increases, however, the rotor also speeds up which gives the plug less time to move in the duct. The slope of the blue curve in Fig. 6, which characterizes the responsiveness rotor to flow, is fixed by the design of the endcover. The variation of plug velocity and rotor speed with flow substantially cancel such that the distance the brine-seawater interface moves in the rotor duct varies little over the operating range of the PX. Accordingly, the degree of mixing between the streams varies little with flow.

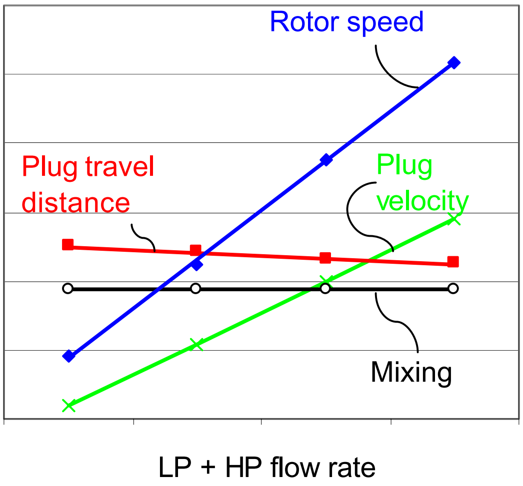

Fig. 6. Rotor performance dynamics.

4.3. Mixing

In SWRO-PX operations, increased salinity in the high-pressure circuit due to mixing in the PX increases osmotic pressure. If the high- and low-pressure flow rates are equal (balanced flow), mixing in the PX-220 calculated using the following equation is approximately 6%:

$$\text{Volumetric mixing} = \frac{\text{HP}_{\text{out}}\ \text{salinity} - \text{LP}_{\text{in}}\ \text{salinity}}{\text{HP}_{\text{in}}\ \text{salinity} - \text{LP}_{\text{in}}\ \text{salinity}} \times 100\%$$

The high-pressure flow from the PX/booster pump blends with the feed from the high pressure pump before going to the membranes. The typical salinity increase at the membranes for a plant operating at 40% recovery is approximately 2.5% calculated with the following equation:

$$\text{Salinity increase} = \frac{\text{Membrane feed salinity} - \text{Seawater salinity}}{\text{Seawater salinity}} \times 100\%$$

A 2.5% salinity increase at the membranes causes operating pressure to increase by approximately 1.3 bar. Expressed in terms of PX performance, the efficiency decrease caused by mixing in the PX-220 at balanced flow is approximately 1%. Most plant operators and engineers choose to accept the increase in membrane pressure without changing process settings or equipment. Indeed, the salinity increase caused by a 2°C temperature increase in the seawater feed — a daily occurrence in some plants — is the same as that caused by mixing in the PX.

However, if a plant operator or engineer chooses to compensate for the PX salinity increase to achieve the same permeate flow rate with no change in membrane pressure, the following three options are available:

1. Decrease recovery by 2% which will increase the seawater feed flow by about 5%
2. Add 6% more membrane surface
3. Increase the low-pressure supply to the PX by 5%

The advantage of going with the first option is illustrated in Fig. 7. The data presented in Fig. 7 is from a plant fed with 36,000 TDS water at 25°C. Decreasing recovery by 2% from 40% to 38% resulting in a net decrease in plant operating cost by 0.02 kWh/m^3.

4.4. Efficiency

The pressure-transfer efficiency of the PX can be calculated with the following equation:

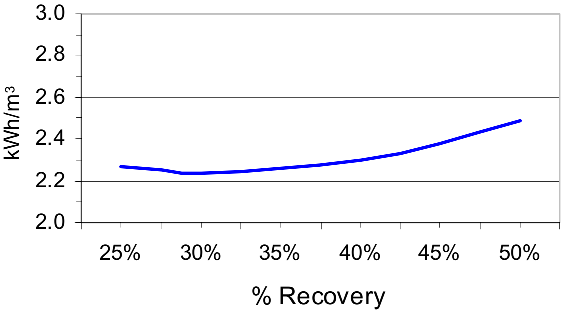

Fig. 7. Plant energy consumption as a function of recovery rate.

$$\text{PX efficiency} = \frac{\Sigma(\text{Pressure} \times \text{Flow})_{\text{out}}}{\Sigma(\text{Pressure} \times \text{Flow})_{\text{in}}} \times 100\%$$

The efficiency of the big rotor PX is approximately 95%. In other words, the efficiency loss in the PX is approximately 5%. About 1% efficiency is lost to the compression of the seawater. Another 2% is lost to viscous friction as the process streams are forced through the relatively small cross-sectional area of the rotor ducts. The remaining 2% goes to lubrication flow through the hydrodynamic bearing. Friction and lubrication flow increase with flow rate as illustrated in Fig. 8, however, the increase in lubrication flow is very small compared to the increase in overall

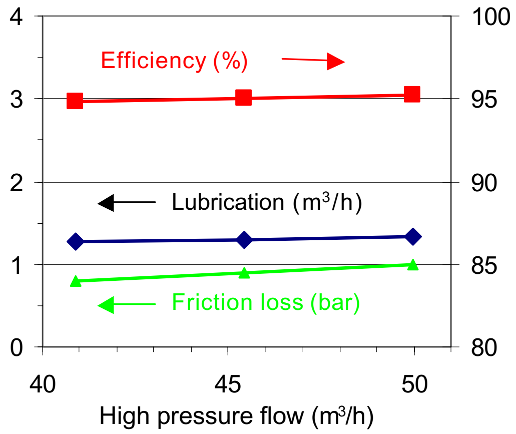

Fig. 8. PX efficiency.

flow. As a result, the overall efficiency of the PX is slightly higher at higher flow rates.

4.5. Multi-PX arrays

The largest PX available today, the PX-220, has a capacity of 220 gpm or 50 m^3/h. However, PXs can be manifolded to run in parallel such that unlimited capacity is possible. For example, a 10,000 m^3/d SWRO plant operating at 45% recovery requires approximately 10 PX-220s. As has been demonstrated in many long-running multi-PX arrays, PXs perform as well on manifolds as they do individually with no balancing or vibration problems. Figs. 9 and 10 illustrate two possible configurations for multiple PX arrays.

In multiple PX arrays, the pressure drop through the PXs (about 1 bar) is generally much greater than the pressure drop along the length of the manifold. The result is a natural balance with approximately equal flow through each PX. Even if one of PX rotor in an array stopped as a result of debris, the flow through the stuck rotor will be approximately equal to the flow through the other rotors. As described in a previous section, multiple PX-arrays are similar to membranes arrays providing the operator with beneficial redundancy. In applications where more than 6 rotors are arrayed in parallel, the loss of one rotor due to debris or damage has minimal impact on SWRO membrane performance and the plant can typically keep running until scheduled maintenance corrects the problem.

5. Designing with the PX

5.1. Incorporating the PX into SWRO systems

How does the PX fit into SWRO systems? Fig. 11 shows the flow path of a typical SWRO-PX system. The reject brine from the SWRO membranes (G) passes through the PX, where its pressure is transferred to a portion of the incoming raw seawater (B). The pressurized seawater stream (D) passes through a booster pump to add the small amount of pressure lost in the PX, the membranes and the associated piping. Fully pressurized seawater then merges with the seawater feed to the SWRO system (E). Depressurized brine goes to the drain (H).

Operation and control of the PX in an SWRO system can be understood by considering two

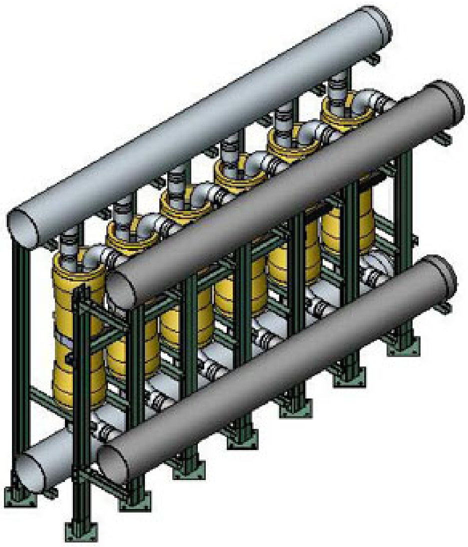

Fig. 9. 12 PX-120 array.

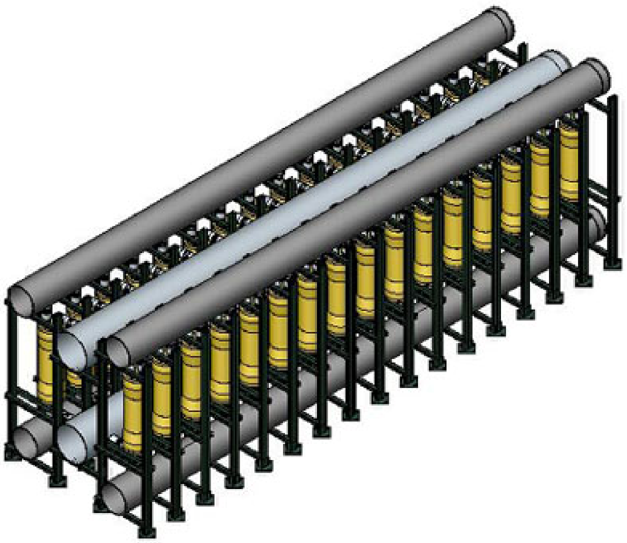

Fig. 10. 10 PX-220 array.

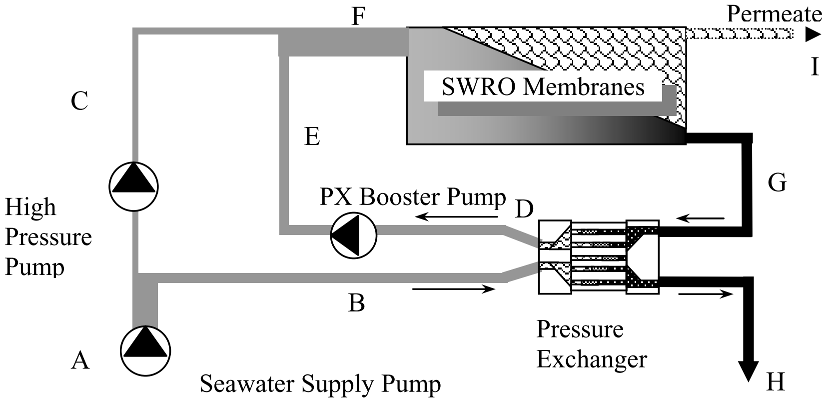

Fig. 11. Typical SWRO-PX flow path.

parallel pipes, one of high-pressure water and one of low-pressure water flowing in opposite directions. The high-pressure water flows in a circuit through the membranes, the PX, the booster pump and back to the membranes at a rate controlled by the booster pump. The low-pressure water flows from the seawater supply pump through the PX to the system discharge at a rate controlled by the supply pump and a throttle valve in the brine discharge line from the PX. Since the high- and low-pressure flows are independent, the SWRO-PX plant must be designed to monitor and control both streams. The simplest and most practical way to determine flow rates is by incorporating flow meters into the PX high- and low-pressure loops (D or G and B or H). The function of the rotor is to insert parcels of seawater into the high-pressure stream and parcels of brine into the low-pressure stream.

In the SWRO-PX system illustrated in Fig. 11, the main pump is sized to equal the SWRO permeate flow plus a small amount of bearing lubrication flow, not the full SWRO feed flow. Therefore, the PX significantly reduces the cost of the main high-pressure pump because a smaller pump is less expensive to purchase and operate than a full-size pump. In a typical system, the main pump provides 41% of the energy, the booster provides 2% and the PX provides the remaining 57%. Since the PX uses no external power, the total power savings is 57% compared to a system with no energy recovery.

5.2. SWRO-PX capacity design

The PX influences the operation of all components of an SWRO system. The following sequence illustrates how the capacity of the main components of an SWRO-PX system can be specified:

1. Permeate rate — Establish the required permeate rate.
2. Operating pressure — Determine the membrane operating pressure based on the salinity of the feed, the desired percent recovery, and the projected performance of the membranes to be used.
3. HP pump — Size the main high-pressure pump to equal the permeate rate plus 4% for PX bearing lubrication.
4. Number of membranes — Specify the number of membranes necessary based on the permeate rate and the recovery rate.
5. PX capacity — The required PX capacity equals the membrane reject rate plus optional additional capacity of 5–10% for safety and flexibility.
6. Booster pump — The capacity of the booster pump should equal the membrane reject rate

Table 1
The PX sizes available

PX model number	Capacity, m^3/h	Capacity, gpm
PX-220	41–50	181–220
PX-180	32–41	141–180
PX-140 (NEW!)	20–32	91–140
PX-90 (NEW!)	16–20	71–90
PX-70 (NEW!)	10–16	46–70
PX-45 (NEW!)	6–10	26–45
PX-25	3–6	16–25
PX-15	2–3	10–15

minus 3.5% that went to lubricate the PX bearing.

The PX is available in the sizes listed in Table 1.

6. Conclusion

The PX is built upon the work of many generations of innovation in the field of pressure transfer. Its elegant design with only one moving part provides both high efficiency and dynamic stability. The PX technology can be extended to unlimited capacity by installing multiple units in parallel. The design and performance considerations presented in this paper provide responses to some of the most significant challenges posed to ERI by critics and competitors. Many important aspects of SWRO design and PX specification have not been addressed herein. Interested readers are encouraged to contact ERI sales personnel at sales@energy-recovery.com or visit our website at www.energy-recovery.com for more detailed and project specific information.

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