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The research and application progress of the isobaric ERD technique for SWRO desalination plant

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ABSTRACT

Due to the research and development of the energy recovery device (ERD), the cost and energy consumption of seawater reverse osmosis (SWRO) is dramatically dropped, rendering SWRO to be one of the principal and promising solutions for freshwater supply especially for the coastal region. The ERDs can be classified as two broad types, namely, centrifugal turbine and isobaric ERD, the latter of which can achieve the energy recovery efficiency above 90% and thus become the primary choice for the designers, managers and operators of the desalination plant. Aiming at supplying reference for ERD selection in reverse osmosis (RO) plant design and retrofit, some investigations were carried out about the representative products of isobaric ERDs including their working principles, performance testing and comparisons, as well as some retrofit practices. The efforts of the performance improvement and novel design which are always the research focus of isobaric ERDs were also studied and reviewed. Furthermore, general information and design data of the RO desalination plant awarded as the yearly winner and other regionally typical commercial SWRO plants with isobaric ERDs for energy recovery built around last 15 y were presented in chronological order, in order to reveal the application status of the isotropic ERD product and understand its irreplaceable roles.

Keywords: Seawater desalination; Reverse osmosis; Energy recovery device; Isobaric type

1. Introduction

Water scarcity has become a bottleneck for social advancement and economic development and this global issue is increasingly threatened by human activity and climate warming [1]. It is estimated that the global demand for water will outstrip viable freshwater sources by 40% by 2030 [2]. Consequently, seawater desalination technologies, ways to desalinate freshwater from the vast ocean, have been immensely explored and studied.

As reported by the International Desalination Association (IDA), the desalination market continued to grow with the total global installed desalination capacity standing at 97.4 million m^3/d, while the global installed contracted capacity reached at 104.7 million m^3/d [3] in 2018. Currently, reverse osmosis (RO) produces about 65% of total desalinated water because of its inherent advantages such as low cost and energy consumption [4]. In the RO desalination process, electrical energy occupies about half of the total cost [5], most of which is consumed to obtain

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high-pressure feed water. For more than half of the feed water is discharged as brine with high-pressure after the RO process, several types of energy recovery device (ERD) are continually invented to recycle the high-pressure energy stored in the brine. The adoption of ERD is one of the fundamental reasons for the reduction of energy consumption to its current level which breeds its domination of seawater reverse osmosis (SWRO) in the desalination market [6]. After decades of development, nowadays, all medium- to large-scale SWRO facilities have employed different kinds of ERDs into their process design [7]. The development of ERD starts from turbine-type ERDs such as Pelton wheel (energy recovery efficiency of 60%–80%) to the isobaric ERDs with the energy recovery efficiency over 95%.

In the 1970s, the energy consumption of RO seawater desalination was around 12 kWh/m^3 which was approximate to that of the thermal plants [8]. From the 1980s, technology breakthroughs, especially the ERD technology, enabled the cost of RO to decrease to a more acceptable level, thus creating the possibility for RO to be an economical and reliable desalination method [9].

The development of ERDs undergoes three stages and can be classified as two broad types, namely, centrifugal turbine and isobaric ERD. The working principle of the formal is to use the brine discharged from the membrane modules in the RO system to strike against the turbine and generate mechanical energy, decreasing the energy consumption. Therefore, for centrifugal devices, energy recovery efficiency increases with the flow capacity.

In the early 1980s, the first generation of ERD was applied in the RO system based on contemporary technology such as the Francis turbine, reverse running pump and Pelton wheel [10,11]. Francis turbine was first developed by British–American Civil Engineer James B. Francis in 1848. It was widely used for energy recovery due to its simplicity and ease of operation until more specialized ERDs were developed, such as the Pelton wheel [12]. The Pelton wheel was first invented and patented by Lester Allan Pelton in the 1870s, and its energy recovery efficiency can be around 50%–70%. From the first stage of the Pelton wheel, ERD dramatically decreased the cost of the RO system and substantially increased its popularity. However, the device is useless when the working condition is less than 40% of the designed demand [13]. Later, other types of the turbine based on the Pelton wheel were invented such as Turgo turbine, which had a more compact and simpler construction and was able to handle a greater flow rate.

In the late 1980s, a modified type of ERD with better performance was adopted indicating that the development of ERD went into the second stage, with the representatives like hydraulic pressure booster and TONKAFLO produced by Feedback Energy Distribution Co. Ltd. (FEDCO, Monroe, Michigan, U.S.A.) and Osmonics, Inc. (Minnetonka, MN, USA), respectively [14]. Compared with the first generation of ERDs, they have not only compacter structure and higher reliability but also the capacity to work in larger brine flow. Since the early 1990s, the hydraulic turbochargers manufactured by Pump Engineering, Inc., (Monroe, Michigan U.S.A.) were applied for SWRO energy recovery [15], with two impellers being mounted separately in the turbine section and pump section. Similar to the Pelton wheel, the brine flow is directed by the nozzles and then drives the turbine impeller converting hydraulic energy into mechanical form. Then, the mechanical energy is converted back to pressure energy by the impeller in the pump section. Hydraulic turbochargers can supplement about 40%–55% of the membrane pressure requirement given the operating conditions and capacity of the RO system [16] with recovery efficiency up to 70%, and they are still in favor for their least expensive and easiest implementation among all ERDs.

The recovery efficiency of the ERDs in the first two stages is generally below 80%. In the 1990s, the invention of isobaric ERDs offers a more efficient solution rendering the recovery efficiency to 90%, indicating the third stage of ERDs arriving. In isobaric ERDs, the energy is transmitted from saline water to feed seawater without undergoing any conversion thus being able to reduce the energy loss efficiently. The waste pressure energy recovered from RO systems accounts for 25%–30% of the energy required to overcome the osmotic pressure of seawater [17]. Up to now, the isobaric ERDs become the mainstream technology applied in the SWRO plant. Due to the obvious advantage of the high efficiency of isobaric ERDs, over 80% of newly established SWRO desalination plants were equipped with isobaric ERDs [18].

In this paper, some representative products of isobaric ERDs will be introduced in section 2 (Representative products and performance testing), including their working principles, performance testing and comparisons, as well as some retrofit practices. The performance improvement and novel design are always the research focus of isobaric ERDs, the efforts of which will be reviewed in section 3 (Performance improvements and novel designs). In section 4 (Typical applications), general information and design data of typical SWRO plants with isobaric ERDs for energy recovery will be offered, aiming at supplying reference for ERD selection in RO process or plant design and retrofit.

2. Representative products and performance testing

Isobaric ERD, also known as a pressure exchanger or work exchanger, is the most common ERD used in SWRO. It also refers to positive displacement type ERD due to the operational principle of positive displacement. Energy is transferred from the membrane rejected water directly to the membrane feed water without intermediate conversion to mechanical energy, and it has demonstrated an energy saving of 10%–30% greater than turbine-based ERDs or turbocharger [19]. Generally, there are two types of isobaric ERDs, that is, the rotary energy recovery device (RERD) and piston-type ERD.

2.1. Rotary energy recovery device

2.1.1. Commercial products and working principles

2.1.1.1. Pressure exchanger

First introduced commercially in 1997 as PX-40, pressure exchanger (PX), the flagship product of Energy Recovery Inc. (ERI), (San Leandro, California, USA), is the most typical and commonly used RERD. The first generation of PX made of titanium, stainless steel and other alloys often resulted in wearing and seizure. Therefore, ceramic material was applied in PX-60, PX-120 and products thereafter to generate a bearing surface. At present, PX devices are made of remarkably reliable alumina (ceramic) material to ensure the long-term and trouble-free operation of SWRO desalination [20]. In 2003, in order to meet the requirements for larger plants and higher efficiency, ERI invented the fourth generation named PX-220 with a water capacity of 50 m^3/h [21]. Currently, the series of PX-Q especially PX-Q 300 is the best ERD available for capital purchase and PX prime is the latest advanced product in ERI's award-winning pressure exchanger line for its better performance in fluid mixing, efficiency and operation.

The basic structure and operating principle of PX are illustrated in Fig. 1 [21,22]. In the PX, a rotor with several internal circumferential ducts was adopted to introduce both the low-pressure seawater and the high-pressure brine. When the rotor rotates at an appropriate position, the two water flows contact and achieve the pressure energy exchange, and then the brine with low pressure is expelled by the introduced raw seawater flow.

2.1.1.2. aXle positioned rotor

XPR [23] (aXle positioned rotor) technology was put forward by Isobaric Strategies Inc., (Riverside, CA, United States) a company dedicated to the development of isobaric energy recovery technology for incompressible fluids. All internal parts with relative motion are fitted inside a patented pressure vessel which can be split apart. For the product used for SWRO, the internal parts and the pressure vessel are composed of 99.8% alumina (ceramic) and titanium G2 respectively. The principle is based on a rotor revolving and located on a stationary axle, with higher flows than PX technology which is based on a rotor rotating inside a sleeve. In the PX device, for the duct size in and out of the pressure vessel for rotor sealing are dissimilar, extra hydraulic resistance is generated. In comparison, the XPR adopts a larger full-sized rotor with larger flow cross-section and fewer ducts, resulting in a remarkable decrease of flow resistance and an increase of overall device efficiency. Meanwhile, according to their own tests, the novel operation principle could decrease mixing by 50%, occupied area and fraction of the shipping weight, saving more than 20% of the inertial cost than PX.

2.1.1.3. SALINO pressure center

SALINO pressure center as shown in Fig. 2 was first launched by KSB in 2013 [24]. It integrates a single lubricant-free axial piston pump and a single axial piston motor together, with the function of both ERD and booster pump, to save the capital costs and connecting pipes [25]. The pump with an integrated energy recovery function is designed with radial fluid inlets and outlets. The hydraulic system and the motor controlled by a frequency inverter are connected by a coupling. The pump with the motor is fixed to a mounting frame and sealed by a mechanical sealing. In the operation, the axial piston pump transmits the mechanical energy of the electric motor to the feed seawater which is pressed through the RO membrane, separating the drinking water and leaving the concentrated brine. The high-pressure energy of brine is then transformed into mechanical energy again by the axial piston motor serving as an integrated ERD. Unlike most other systems based on the isobaric energy recovery principle, the mixing between brine and feed water can be avoided. The SALINO pressure center is an ideal choice of ERDs for small- and medium-scale desalination plants with a capacity below 10,000 m^3/d, with potential energy savings of up to 70% [26].

2.1.1.4. iSave

iSave is the product of Danfoss in Syddanmark, Denmark, with a similar appearance to SALINO and pressure exchange principle to PX, designed for automatic

Fig. 2. Appearance of SALINO Pressure Center (KSB) [24].

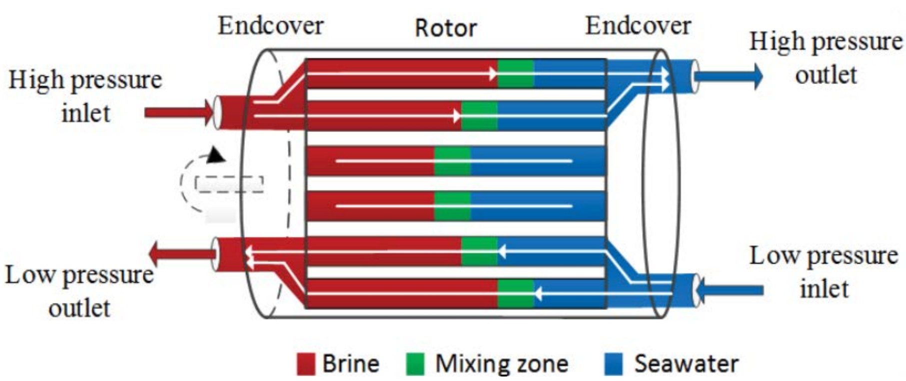

Fig. 1. Operating principle of PX [21,22].

operation and virtually fail-safe. It is composed of an electric motor, a pressure exchange module and a vane pump. The power output from the electric motor is used to drive the pressure exchanger and vane pump, most of which is consumed by the vane pump. The pressure exchanger module is in the rotary form with the function of recovering energy from concentrate brine. The vane pump is used to compensate pressure in concentrate stream and pressure exchanger.

As reported by Danfoss [27], iSave is much easier to install than other ERDs, requiring less space, lifting and pipework. The adoption of a positive displacement pump as a booster pump ensures constant flows all the time regardless of pressure fluctuations. Furthermore, several efforts have been made to prolong its service life. For example, all components are built from high-grade duplex/super duplex stainless steel or other materials with good corrosion resistance and the high-pressure shaft seal is replaced by a single low-pressure mechanical shaft seal, etc.

2.1.2. Performance tests

Most of the product test data mentioned in section 2.1.1 (Commercial products and working principles) are provided by their manufacturer which can be obtained in the product manual or brochure. Among the published literature, the testing efforts of RERD products mainly focused on the PX device. Stover and Martin [28] tested the Titan PX-1200 which was designed for the SWRO facility with a flow rate of 273 m^3/h in Inima Los Cabos, Mexico. The ERD can reach an efficiency of about 96.6% and increase the salinity at the membrane feed seawater of approximately 2.3%. The specific energy consumption (SEC) can be reduced by 15% to 30% compared to centrifugal ERDs. Cameron and Clemente [29] developed a formula to calculate the efficiency of PX and tested 65 series PX including PX-180 and PX-220 in three different desalination plants. After 3 y, the tested PX devices were still robustly operated with high efficiency and little performance degradation, proving PX was well suited for the long-term operation of the SWRO plant. Mambretti et al. [30] checked the behavior of a total of 288 units of ERI's PX in Hamma (Algeria, 20,000 m^3/d) desalination plant in the advanced design phase of energy recovery. The tests showed that the PX device could almost perfectly disconnect the high and low-pressure lines hydraulically, indicating that the hydraulic safe of the plant can be guaranteed under either steady or unsteady flows [30].

Mohamed and Papadakis [31] performed both the simulation and economic analysis of a stand-alone RO desalination unit equipped with the smallest available PX-15 as ERD. With the assistance of ERD, energy-saving achieved 48%, energy consumption dropped from 12 to 6.3 kWh/m^3, and water production cost dropped to 5.2 €/m^3. Geisler et al. [32,33] investigated the economical performance of a pressure exchanger system (PES). Compared with the traditional turbine type, SEC can be reduced by 35% and an efficiency of nearly 98% can be maintained for capacity larger than 2,000 m^3/d.

Pikalov et al. [34] tested the performance of Danfoss iSave 21 equipped in an SWRO system with a water production rate of 125 m^3/d. The results demonstrated that as the ERD, the iSave 21 can help the SEC of the system to decrease below 2.0 kWh/m^3. Besides, iSave 21 demonstrated a better performance comparing with its previous model, with a substantially lower lubrication flow of 2.3 l/min and a noise level of 86 dB(A). Wang et al. [35] experimentally tested a positive displacement energy recovery unit in the laboratory under a low-pressure range (within 0.6 MPa) to investigate the dynamic characteristics and the effects of HP pressure on the ERD. The results indicated the HP pressure was positive for the efficiency, and the downward variation of feed flow caused by switching of the valve had a negative effect on the stability of the system.

2.2. Piston-type ERD

2.2.1. Commercial products and working principles

2.2.1.1. Dual work exchanger energy recovery

Dual work exchanger energy recovery (DWEER) manufactured by Flowserve/Calder in Egliswil, Switzerland, is the most common piston-type isobaric ERD. Valves and pistons have to be well designed, arranged and controlled to press the high-pressure feed seawater through the membrane by the pressure energy stored in the discharged brine. Due to the complex structure and unacceptable cost of the initial models, DWEER was not commercialized until the appearance of the LinX valve which is able to direct the high- and low-pressure fluid efficiently [36]. In the DWEER, the high-pressure brine discharged from the RO module is led into the pressure exchange cylinder via the LinX valve to pressurize the low-pressure feed seawater entering into the membrane module. The exhausted brine then is expelled by raw seawater flow, and two pressure exchange cylinders operate in turn to ensure the continuous operation of the RO system. To raise its applicability and reliability, the DWEER has been ameliorated during recent years, for example, developing a type of DWEER with a smaller size and replacing electric devices by a hydraulic system to enhance the controllability of LinX valve.

2.2.1.2. SalTec®

SalTec® is another piston-type ERD manufactured by KSB. Similar to DWEER, it is equipped with necessary valves to transport high or low-pressure flow to the pressure vessels alternately by adjusting the position of the flow channels integrated into the valve [37]. Different from DWEER, the rotating valve driven by a servo motor and special check valve is adopted to control the flow rate and accommodate the operating conditions. Components in the critical position are made of corrosion-resistant super duplex stainless steel to prolong its service life. Since May 2004, this system was installed and tested under field test conditions in an SWRO plant in Sharm El-Sheikh (Egypt). The test results demonstrated its ability to handle higher flow rates (up to 7,000 m^3/d) with lower specific energy consumption [38].

2.2.1.3. RO Kinetic®

The RO Kinetic® was patented by Engineer Manuel Barreto from the Canary Islands. The core of this technique is a series of valves, that is, two servo-controlled valves (as shown in Fig. 3) separated by two inertia valves, to direct seawater input and brine output from the pressure exchangers in sequence, with no turbulence, cavitation and excessive pressure drop. The inertia valves are an extension of the pressure exchangers in the form of a closed-loop. They can provide a continuous flow of water whatever entering or leaving, avoiding extra loss of kinetic energy caused by pauses during the operation. To reduce the excessive pressure drops and mixing extent, the ratio of length to diameter is carefully designed. Furthermore, other measures are also proposed to maintain a continuous kinetic cycle. Valves are activated with a proper speed when the water flows from one chamber to another so that practically no interruption occurs. An expansion bladder is designed and equipped acting as a damper to alleviate the ineluctable water shocks caused by the instant stop of valve operation while the chambers are full [39].

2.2.1.4. Other piston-type ERDs

The recuperator manufactured by Aqualyng™ (Dubai, United Arab Emirates) is also a piston-type ERD product that allows up to 98.5% of waste energy recycled [40], dropping energy consumption of seawater desalination to 2–2.5 kWh/m^3. It consists of two vertical upward vessels made of duplex stainless steel, operating sequentially under the control of valves similar to DWEER [41]. The Clark pump energy recovery pressure-amplifier was developed by Spectra Watermakers Inc., California, USA, which can operate together with intermittent renewable energy sources, such as wind and solar-photovoltaic energy with no need for batteries [42]. PES developed by SIEMAG (Netphen, German) is composed of two or three pressure exchange chambers that operate discontinuously and respectively to deliver constant output as a whole. It often used in mining with volume flow up to 1,400 m^3/h and pressure up to 16 MPa [33].

2.2.2. Performance tests

Schneider [43] stated some operating issues about DWEER, emphasizing that DWEER can keep a constant efficiency approximate to 97% even in a fluctuating environment. There was scarcely any mixing between the raw seawater and the concentrated brine since they were isolated by a piston, resulting in a much lower salinity increase of feed seawater. Of course, DWEER has some limitations as well especially the unavoidable pressure drop in the device which could be ameliorated by stacking several devices together, and the effect of cycling speed on its cost.

Bross et al. [44] carried out field tests of a SWRO plant equipped with the SalTec® system in Sharm El-Sheikh (Egypt). SEC of the core hydraulic system was 3.24 kWh/m^3 and the mixing caused by pressure exchanger can be neglectable during a seven-month operation. Given steady conditions, it can be operated reliably with low noise, no pulsation and no vibration, and the control module was able to protect the components in critical situations by means of an emergency safety routine.

Peñate et al. [39] investigated the performance of a RO Kinetic® product based on the analysis of its structure and real experiences. The structure of Kinetic® enables it versatile in installation and operating with no over flush and mixing. The maintenance requirement was also minimal and simple due to its slow operation (about 5 cycles/min or less). Since it was operated under a continuous kinetic cycle, which allowed to sufficiently make use of the kinetic energy, it can achieve the maximum efficiency approximate to 98%.

Mohamed et al. [45] carried out an experimental study to figure out the effects of the Clark pump on the technical and economic performance of a small RO desalination plant with a capacity of 1.7 m^3/d. The results showed that the Clark pump could significantly reduce the SEC of desalination plant from 20 to 3.3 kWh/m^3, with the water production cost (excluding the energy production system cost) of 3.68 €/m^3 which was feasible compared with the transported water cost of 7 €/m^3 in Greek.

2.3. Performance comparisons

For large RO desalination plants built in the last 5 y, the energy consumption of permeate production was around 3.69–4.36 kWh/m^3, including raw water pumping, treatment as well as product water delivery [46]. Various factors must be considered to select the proper ERD economically such as the power cost, interest rate and loan period. Energetically effective but expensive isobaric ERDs would not be favored in places where the energy cost is low, the interest rate is high, and the loan period is short. Except for capital issues, the operating environment also critically influences the selection of ERD. The DWEER or PX systems can maintain substantial backpressure for brine discharge over long distances, while Pelton turbines create a foamy flow that has to be eliminated by gravity or pumps [47]. Hence, the efficiency is not the only goal for ERD to pursue, as environment and equipment differ, the most proper ERD may also be different [48]. Sufficient performance comparations according to the above factors among existing ERD products will be of benefit to the manager or operator for their final decision.

Eshoul et al. [49] carried out the energy analysis of an actual two-pass RO desalination system equipped with energy recovery turbine (ERT) and PX as ERD respectively

Fig. 3. RO Kinetic® body of valves [39].

by IPSEpro software and operating data. The power consumption can be reduced by 30% (ERT) and 50% (PX) respectively and the efficiency can be improved by 49% (ERT) and 77% (PX), resulting in a reduction of the SEC from 7.2 to 5.0 kW/m^3 (ERT) and 3.6 kW/m^3 (PX) and indicating a better performance of PX. Meanwhile, PX occupied a smaller area (4,766 m^2) compared with ERT (4,799 m^2) and was much suitable for the application with area limitation.

Choi [50] compared the performance of different ERDs in a pilot desalination plant with a capacity of 1,000 m^3/d including the turbocharger, PX and pressure exchanger for energy recovery (PEER). The results of SEC analysis showed that the isobaric ERDs achieved higher energy recovery efficiency than the centrifugal ERD which was expected higher in the theoretical estimation, and the isobaric PX and PEER system showed similarly high energy recovery efficiency of 95%.

Qureshi and Zubair [51] compared the effects of temperature, mass ratio, salinity and isentropic efficiencies on different ERDs or their combination such as throttling valve, turbocharger (TC), hydro-turbine (T), pressure exchanger (PX), pressure retarded osmosis unit coupled with hydro-turbines (PRO-T), pressure retarded osmosis unit coupled with a hydro-turbine and pressure exchanger (PRO-PX), and two-stage pressure retarded osmosis (2S-PRO-T). Compared with other ERDs, PX showed an absolute variation of salinity and SEC below 24% and 0.4 kWh/m^3, respectively.

Stover [52] compared the performance of DWEER 1100 and PX-220. The results showed that no overflush was required with the PX device whereas more than 3% over flush associated with DWEER. The salinity increase in feed water caused by PX was higher than that caused by DWEER. The necessary lubrication flow was almost identical while the high- and low-pressure differentials through the PX device were lower. Considering all the factors, the SEC of the two ERD was similar while the efficiency of PX was higher. With respect to the control, DWEER required an additional control module for the valve group while PX was able to operate automatically. With respect to maintenance, the pistons and valves of DWEER required periodic maintenance while multiple PX devices can operate indefinitely and safely with one or more stopped rotors to ensure continuous operation without periodic maintenance. For the service life, the ceramic material ensured the long service life of PX while the valve wear of DWEER had a negative effect on its life.

Dimitriou et al. [53] experimentally compared two small-scale SWRO desalination units which were equipped with Clark pump and Danfoss pumps respectively, aiming to figure out the ERD with the lower SEC. The experiments demonstrated that the Danfoss units were operated with a higher operating window and lower SEC than Clark pump in part-load condition, indicating that Danfoss was more suitable for the renewable energy-driven RO plant. Jeong et al. [54] compared the performance of PX and DWEER according to salinity increase, recovery rate and feed pressure. The results showed that both ERDs increased salt concentration slightly, and PX showed favorable recovery rate (17.0%) and feed pressure (67.0 bar) as compared to those of DWEER (16.7% and 65.8 bar) for the overflush of DWEER caused pressurized feed flow loss by 1.3% (or 0.4 L/min) and reduced the feed pressure by 1.8% (or 1.2 bar).

Urrea et al. [55] compared different kinds of ERDs to figure out which was the most suitable for medium- and large-capacity desalination plants including PX, DWEER, iSave, RO Kinetic® and Axial Piston Pump/Axial Piston Motor Danfoss device [56]. The investigation was based on interviews and surveys of experts, managers and operators from ten RO desalination plants and filed visits for eight desalination plants. The conclusion showed PX seemed to be the favorable ERD for the operators in the small, medium and large scale plant due to its robustness and modularity. Also, its low SEC of 2.2 kWh/m^3 and the ability to be independent of external factors and variation of the operating conditions seemed attractive to managers of the SWRO system.

2.4. Retrofit attempts of RO plant with advanced ERD

Due to the continuous development of ERD, replacing the existing noisy, inefficient ERD with more advanced type becomes popular to obtain more economical and efficient desalinated water production. The capital cost is often considered as the priority of ERD selection which is the exact reason for adopting turbine-based ERD generally the turbocharger. However, in the long-term run, the isobaric ERD would save costs significantly although its initial installation costs more. As estimated, retrofitting existing SWRO processes with turbine-based ERD by isobaric ERDs can reduce the power consumption by as much as 60%, with little or even no other power requirements and minimal additional equipment. The retrofit can be entire or partial depending on whether to change the high-pressure pump or the Pelton wheel [18].

Drak and Adato [57] presented the design considerations for the two phases of the Lahat brackish water desalination plant in the selection of turbocharger and isobaric ERDs. For the 1st phase, the turbocharger was selected due to its simplicity. For the second phase, the rotary type isobaric ERD was adopted due to its high constant efficiency of 92%–96% and the cost-saving which was more than 45,000 USD/y at 80% recovery. MacHarg [58] compared the power consumption and production rate between plants which were initially equipped with Pelton wheel, turbocharger or no ERD and plants after the retrofitting. The results demonstrated the remarkable increase of the capacity and reduction of the power consumption after the retrofitting, even compared with the advanced turbocharger. In specific, after retrofitting with PX, a plant in Caribbean Island which was previously equipped with Pelton wheel as ERD, can raise its capacity from 275 to 800 m^3/d and decrease the SEC (kWh/m^3) by approximately 36%.

Bozbura [59] compared the economical cost of two different ERDs (PX and turbine) caused by the electricity, chemical substance, maintenance and equipment replacement for two capacities of 1,000 and 10,000 m^3/d. Although PX costs much initially than the turbine device, it's lower energy consumption makes it much more economical than the turbine device. Shaligram [60] compared the energy and capital cost of ERD in brackish water reverse osmosis systems equipped with PX and turbocharger respectively. The application suggested the isobaric ERD such as PX was much more economical compared with a turbocharger, and PX was able to expend the reject ratio of an SWRO system with no need to replace the high-pressure pump and without substantial increase of energy consumption.

Marcos and Morgade [61] presented a retrofitting by replacing ERT with DWEER in the Las Palmas III desalination plant with an enlarged capacity of 86,000 m^3/d. Pelton wheel was adopted for energy recovery until 2010 and the plant was promoted in 2011 by replacing the Pelton wheel with DWEER 1550. After the retrofitting, the SEC for the HP pumps with ERD decreased to 2.30 kWh/m^3 for freshwater production, which implied a yearly energy saving of 3,657,500 kWh. Andrews et al. [62] described a retrofitting practice of replacing turbochargers with DWEER for the water production and distribution site of the Consolidated Water Company's Grand Cayman. The results showed a remarkable reduction in the specific electricity consumption by 26% from 3.00 to 2.22 kWh/m^3, an increase in the production rate by 59% from 1,071 to 1,699 m^3/d, and other minor improvements to the system and operation.

Lopez-Monllor et al. [63] presented the results of a retrofit in eight full-scale two-stage trains. The results showed that indicators such as SEC, water production variation and payback were important for the configuration selection to retrofit a train by isobaric chambers. Based on proposed three configurations and their comparison, it was shown that the configuration C patented by Emalsa was the most favored due to the lowest SEC, the configuration B which consisted of a single train to supply the required energy was the most productive and the configuration A, composed of two double-stage trains, had the shortest payback period of two and a half years.

Jamil et al. [64] performed the comparison of product cost between the ERT and four retrofit coupling with high-efficiency pressure exchangers. The results showed that the SEC can be effectively decreased by around 24% after the retrofit, and the combination of the booster pump and PXs was the best suitable for the expanded plant capacity due to the lowest price cost among the listed retrofit options. Peñate and García-Rodríguez [65] proposed five retrofitting schemes according to the technical criteria for the Pelton turbine retrofit. No.1 and No. 2 which used the same HP pump and installed the isobaric ERD in each of the two units were proposed to reduce the energy consumption. No. 3, 4 and 5 were proposed to expand the total capacity of the existing SWRO plant. In No. 3, each of the RO trains was installed with isobaric ERD. In No. 4, a new RO train was build as the second stage in each of the RO trains. No. 5 was similar to No. 4 with the modification that the brine of the second stage would pass through the existing Pelton turbine. The conclusion showed that No. 2 and 3 presented better performance comparing with No. 1 and 4 respectively. No. 3 can obtain less unitary cost in both types of equipment, and thus in the installations without space limitations, it was recommended to take place of No. 2.

3. Performance improvements and novel designs

The energy recovery efficiency of most isobaric ERDs is over 95% which seems to leave little if any space for efficiency improvement. However, as the formula used for calculation of energy recovery efficiency is not commonly agreed by different companies, the figures may be misleading without comparability. As mentioned in lit [50], the losses in an isobaric ERD system generally include HP differential pressure, low-pressure differential pressure, low-pressure brine backpressure, leakage and mixing. Although their relative importance differs from one system to another, they are major concerns for the performance improvement of isobaric ERDs. Thus, a lot of researches has been carried out to decrease the influences of these losses on rotary and piston-type isobaric ERD, either local modification or totally novel design.

3.1. Research progress of the rotary isobaric ERD

Goto et al. [66] proposed a set of unique flow distributors which was mounted at each end of the pressure exchange chamber to stabilize the contact surfaces and restrain the excessive mixing caused by contacting flows. The computational fluid dynamics (CFD) simulation results showed that the proposed flow distributors (distributors C or S) were able to maintain a uniform flow and minimum mixing, and the flow capacity can be increased by four times. Wu et al. [67] designed textured grooves on the contact surfaces of two end covers to reduce the energy loss caused by the leakage and thus improve the performance of RERD. The experiment demonstrated an efficiency of 96.3% when the operating pressure was 6.0 MPa and the clearance was 0.025 mm. Besides, the torque can be also reduced by 50% when the clearance was adjusted to 0.035 mm. Wang et al. [68] adopted pre-pressurization/depressurization grooves to reduce the flow fluctuation and its influences. The CFD simulation and the experimental results proved that the grooves had a positive effect on the ERD performance, for the flow fluctuation and pressure variation can be reduced by 75.3%–77.2% and 90.7%–92.5% respectively. Xu et al. [69] designed a rectangular grove in the endplate to control the flow fluctuation and pressure pulsation of RERD and investigated its performance by CFD simulation and theoretical analysis. The results showed that the flow fluctuation and pressure pulsation can be effectively reduced from 23.04% to 2.95% and from 2.05% to 0.85%, respectively.

Xu et al. [70] investigated the influences of operating conditions on the mixing degree of RERD in virtue of CFD simulation and experiment. Based on the mass conservation and simulating results, a theoretical formula was developed to reveal the relationship between the inflow length and operating condition, together with a polynomial relationship between the mixing and the dimensionless inflow length obtained from simulation and experiment, the mixing behavior of the RERD can be simply predicted. They also developed a predicting model to calculate the rotor speed for a self-driven RERD according to the key dimensions, to help the parameter determination in the design phase [71]. Bie et al. [72] investigated the mixing performances of an asymmetric rotary pressure exchanger (RPE) with the inlet modified by an extended angle based on CFD simulations of turbulence models. The simulation results indicated that a smaller mixing rate at an extended angle of ±30° can be achieved compared with no extended angle.

Liu et al. [73] studied the leakage performance of a fully-rotary valve–energy recovery device (FRV-ERD) in virtue of CFD simulations. The results indicated that for the designed sealing structure with the same clearance height, the forward and reverse leakage rates were almost the same and in good linear relation with pressure difference. The leakage rate was significantly influenced by and proportional to the third power of the clearance height of the sealing structure. Also, a dimensionless parameter which was a specific value of the axial length and the corresponding half circumference was defined and when the specific value was equal to the 1, the leakage rate can be decreased remarkably. They also designed another isobaric ERD based on the FRVs. Two FRVs were connected together by two pipelines for pressure exchange by switching the position of the semi-cylinders inside the stator to change the phases and ensure the continuity. The device had much better performance in the leakage and abrasion due to its special sealing form, providing an option to conquer some disadvantages such as leakage and abrasion between hard mating parts. The device was tested experimentally, and efficiency as high as 98.47% can be achieved due to the reduction of pressure loss caused by leakage [74]. Recently, they proposed another three seal structures for an FRV-ERD and studied their leakage reduction based on the CFD simulations. Results showed that the FRV achieved its best seal performance when employing the bilateral seal for both the efficiency and required clearance were improved, with the calculated efficiency improved from 89.48% to 92.05% at the clearance of 30 μm under operating pressure and the required clearance increased from 18.1 to 20.4 μm [75].

Al-Hawaj [76] proposed a novel type of RERD called as the sliding vane work exchanger. The brine side served as a turbine and the feed side acted as a pump so that the work transmitted mechanically via vanes and rotor from the brine side to the feed side. According to their theoretical analysis and parametric study, the hydraulic efficiency was above 90%, and the feed-brine mixing and the flow pulsation were both minimal. Yin et al. [77] put forward an innovative integrated energy recovery and pressure boost device (IERPBD), which consisted of a RPE and an axial piston-type booster pump. Three-dimensional CFD simulations were performed to optimize the structure parameters and working conditions, with the leakage through the lubricating gaps of valve port plate, fluid compressibility effect and cavitation damage being considered. Based on the study of the mixing process, pressure distribution, components distribution, leakage flow characteristics and related characteristic parameters of RPE, the optimal parameters were obtained, and it was suggested that the lubricating gap of the valve-port plate should be well-designed to improve both energy transfer and flow characteristics of IERPBD.

Liu et al. [22] put forward a visualization model of a RERD composed of a single stationary duct and two rotary end covers in virtue of a two-dimensional Particle Image Velocimetry (PIV) measurement, so that the flow behavior in the rotor duct can be revealed, according to which the design and improvement of RERD can be more reasonable. The vortex dynamics and the flow characteristics were investigated in virtue of the phase-locking and the time-averaged processing methods. Through the experiments which bred vortex in the duct, an "entrance effect" was observed, and it was found that the intensive mixing caused by the increasing turbulence intensity in the work cycle had a negative effect on RERD performance [78]. Based on the above PIV experiment, a numerical study was performed to investigate flow characteristics in a RERD. Standard k–ε, renormalization-group k–ε, and realizable k–ε were compared and validated by PIV experimental data, in which the realizable k–ε turbulence model presented a good agreement with the experimental data, being able to precisely reveal the swirling flow formed in the duct [79].

3.2. Research progress of the piston-type isobaric ERD

Song et al. [80] proposed a Programmable Logic Controller control scheme with the fault tolerance module to solve the control issue for piston-type ERD like the failure of the magnetic sensor. The experiment demonstrated a good stability and operational flexibility for variable pressures and capacities. With the assistance of the control system, the ERD can be operated reliably, stably and safely. In another experiment, a water hydraulic actuator driven by the high-pressure brine was adopted to generate the reciprocating switching movement of reciprocating-switcher energy recovery device (RS-ERD) taking place of the oil actuator, with the driving power consumption decreased significantly by up to 90.3% according to the testing results [81]. To decrease the switching load and fluid fluctuations, they performed modifications of RS-ERD by adopting pilot valve plates [82]. The experimental results illustrated that after modification, the starting-up pressure decreased by a half to be about 0.25 MPa, and 72.16% high-pressure brine consumption for water hydraulic actuator was reduced in stroke switching, leading to a significant reduction of the pressure fluctuation amplitude in HP fluids by 40% under the pressure of 6.00 MPa and the flow rate of 30 m^3/h, and meanwhile keeping a competitive energy recovery efficiency of up to 98.50%.

Ye et al. [83] matched the vane number and port location, in order to eliminate the short circuit flow, reversed flow, liquid decompression and compression, and their influences on the sliding vane pressure exchanger, with calculated maximum efficiency to be 96.4%. Besides, they performed a simulation to investigate the effects of the working condition of the contact surface between the cylinder and vane. It was revealed that an increase of rotational speed, vane thickness and vane length had positive effects on the contact performance.

Zhou et al. [84] set up a SWRO desalination platform to investigate the capacity flexibility of a piston-type ERD. The experimental results showed that the ERD can be operated under 66.7%–150.0% of the designed capacity (30 m^3/h) with a relative stable efficiency above 96.5% and leakage ratio within 2.62%–3.95%, proving its wide-range capacity flexibility to adapt to the varying conditions of the SWRO desalination system.

Bermudez-Contreras and Thomson [85] modified a Clark pump by switching the role of two chambers, that is, the low-pressure motorized pump that fed into the standard Clark pump was replaced by a high-pressure motorized pump paralleled with it. The comparison between the standard and modified pumps was experimentally carried out, indicating the modified version can operate in a wider range of input electrical power with a relatively constant velocity.

Wang et al. [86] proposed and tested a pilot-scale piston-type ERD with a fluid-switcher (FS-ERD) which acted similarly to the LinX valve. The rotor of the fluid-switcher intermittently rotated to alternate the working phases so that two strokes switched in cylinders. The device was tested with a capacity of 30 m^3/h and the operating pressure of 6.0 MPa. The efficiency can achieve 95.9% and minimum pressure pulsations occurred. The parallel operation of two sets of ERDs was also tested, be able to increase the capacity of the system as well as the stability and continuity of the working streams [87]. Qi et al. [88] proposed a pilot-scale fluid switcher-energy recovery device (FS-ERD) and investigated its internal leakage by CFD simulation and experiments. The results showed that the internal leakage rate was in a polynomial relationship with the dimension of the leakage gap and was proportional to the brine pressure. When the brine pressure was 6.0 MPa and the leakage gap of fluid switcher was smaller than 0.04 mm, the efficiency of FS-ERD was above 95% and the internal leakage ratio can be controlled within 2%, meeting the commercial product requirements.

Wang et al. [89] designed a single-cylinder energy recovery device (SC-ERD) which had a simpler structure than the conventional piston-type double-cylinder energy recovery device (DC-ERD). They evaluated the parallel performance of two SC-ERDs which proved to have the same basic function as the DC-ERD, with the pressure fluctuation of the SC-ERD being reduced by 80% compared with the DC-ERD and the energy recovery efficiency being remained as high as 98%.

4. Typical applications

In this section, general information and design data of the RO desalination plant awarded as the yearly winner (from 2006) and other regionally typical commercial SWRO plants with isobaric ERDs for energy recovery built around last decade will be presented in chronological order, aiming at revealing the application status and effects of the isotropic ERD product, meanwhile supplying reference for ERD selection in RO process or plant design.

Table 1 shows general information about some typical commercial desalination plant and equipped ERDs. Ashkelon SWRO Plant [90–93] located in Israel along the Mediterranean coast, was the winner of the 2006 desalination plant of the year. It supplied desalinated water of 330,000 m^3/d at one of the lowest prices, accounting for around 13% of the country's domestic water demand. Its energy recovery center consisted of forty DWEER devices (ten blocks, four DWEERs in each block) gathering pressurized brine from RO banks of each plant and recycling the energy in the first stage. The DWEER can maintain 96% efficiency of the system and thus no high-pressure pump needed to be equipped. Also, the ERDs can be operated flexibly and SEC was decreased to 3.9 kWh/m^3 ± 5%.

Perth seawater desalination plant [94,95] located in Kwinana Western Austria, was the winner of 2007 desalination plant of the year. It first delivered water in November 2006 in the face of declining natural supplies of water across the region with the capacity of 143,000 m^3/d. The average temperature of the treated seawater is 20.2°C and the salinity is 36.5 g/L. The equipped pressure exchangers can achieve an efficiency rate of 95% which provided energy savings of up to 20%. The first-pass SWRO component had a SEC of 2.4 kWh/m^3, which is the lowest record for a large-scale SWRO desalination plant.

Barcelona-Llobregat desalination plant [96], located in El Prat, near Barcelona, with the capacity of 20,000 m^3/d, was the winner of the 2010 desalination plant of the year. It was designed to address the water resource lack and improve the water quality in Barcelona's south area. It consisted of 10 RO trains and each was equipped with 23 PX-220, with the assistance of which the SEC can achieve 3.671 kWh/m^3 while the general PX efficiency was 96.5%.

Hadera desalination plant [97,98] located in Hadera, Israel, was one of the biggest seawater desalination plants in the coastal area around the Mediterranean Sea. It was started in January 2010 and its capacity was expanded to 146 Mm^3/y. Supported by PX-260 as ERD, the SEC of the plant was decreased to 4 kWh/m^3.

Kurnell desalination plant [99,100] located in south Sydney, Australia, was the winner of the 2011 desalination plant of the year, with a capacity of 250,000 m^3/d. It was the largest operating desalination plant in Australia and completely powered by renewable energy resources. The RO process consisted of two stages, in the first of which, DWEER devices manufactured by Flowserve were selected by the joint venture as the ERD, for DWEER devices can provide the highest efficiency with the lowest SEC of 3.35 kWh/m^3, and considerably reduce the time for maintenance and replacement.

Southern seawater desalination plant [101] located in Perth, Austria, with a total contracted capacity of 280,000 m^3/d, was the winner of the 2012 desalination plant of the year. The first phase with a capacity of 140,000 m^3/d was commissioned in August 2011. For the second phase, PX devices supplied by ERI was adopted as the ERD.

Victorian desalination plant (Wonthaggi desalination plant) [102] located in Wonthaggi, Austria, was the winner of the 2013 desalination of the year. It started water production in September 2012 with a maximum capacity of 444,000 m^3/d. It was estimated that more than 49 MW of energy would be saved by implementing PX provided by ERI.

Tuaspring seawater desalination plant [103,104] located in Singapore, was the largest SWRO plant in South East Asia with the capacity of 318,500 m^3/d and expected to meet up to 25% of Singapore's water demand. It was integrated with a combined-cycle power plant and began operating in September 2013, employing 68 DWEER-1000 units as the ERD.

Sorek seawater desalination plant [105,106] located in Tel Aviv, Israel, was the winner of the 2014 desalination plant of the year. It was the largest and most advanced SWRO desalination plant in the world at that time, with the seawater treatment capacity of 624,000 m^3/d which was more than the summation of the daily production of all desalination plants in South Africa. It began operating in October 2013 meeting about 20% of the municipal water demanding in Israel and serving to approximately 1.5 million people. Flowserve Corporation was responsible to provide Calder DWEER devices as the ERD with the SEC as low as 2.65 kWh/m^3.

Table 1
General information about typical commercial desalination plant and equipped ERDs

Project	Operational date	Location	Capacity (m^3/d)	SEC (kW/m^3)	Water cost ($\$/m^3$)	ERD type	Source
Ashkelon SWRO plant	8/2005	Ashkelon, Israel	330,000	3.85	0.7	DWEER	[90–93]
Perth seawater desalination plant	11/2006	Perth, Australia	140,000	3.60		PX	[94,95]
Barcelona-Llobregat desalination plant	7/2009	Barcelona, China	200,000	3.671		PX	[96]
Hadera desalination plant	1/2010	Hadera, Israel	400,000	4.00		PX	[97,98]
Kurnell desalination plant	1/2011	Sydney, Australia	250,000	3.35		DWEER	[99,100]
Southern seawater desalination plant	9/2011	Perth, Austria	280,000			PX	[101]
Victorian desalination plant	9/2012	Wonthaggi, Australia	444,000			PX	[102]
Tuaspring seawater desalination plant	9/2013	Singapore	318,500	4.10		DWEER	[103,104]
Sorek desalination plant	10/2013	Tel Aviv, Israel	624,000	<4.00	0.52	DWEER	[105,106]
Torrevieja desalination plant	2015	Águilas, Spain	240,000	3.00	0.90	PX	[107–109]
Carlsbad desalination project	2016	San Diego, US	204,390	<3.30	1.66	PX	[110,111]
Escondida SWRO plant	2017	Atacama, Chile	216,000			DWEER	[112]

Torrevieja desalination plant [107–109] located in Torrevieja Province of Águilas, south-east Spain, was the largest desalination plant in Europe with a capacity of 240,000 m^3/d, aiming at supplying water for about 400,000 people as well as irrigating 8,000 ha of agricultural land. The plant was started in 2015 and employed PX in its energy recovery system with SEC controlled to 3 kWh/m^3 for the total desalination process.

Carlsbad desalination project [110,111] located in San Diego County, California US, was the winner of the 2016 desalination plant of the year. It was the largest desalination plant in the western hemisphere with a capacity of 204,390 m^3/d. It can supply up to 10% of the total drinking water demand for San Diego. The energy-bearing brine flow incorporated with the PX-based energy recovery system designed by ERI provided 45%–50% of the feed seawater to the RO membranes for desalination.

Escondida SWRO plant [112] located in the Atacama Desert, Chile, was the winner of the 2017 industrial desalination plant of the year. It was finished in 2017 with a capacity of 216,000 m^3/d, becoming the largest desalination plant in Latin America. It was expected to serve the freshwater demand for Escondida copper mine in the desert, in which 27 DWEER were employed as ERDs.

5. Conclusions

Due to the research and development of the ERD, the cost and energy consumption of SWRO are dramatically dropped, rendering SWRO to be one of the principals and promising solutions for freshwater supply, especially for the coastal region. The ERDs can be classified as two broad types, namely, centrifugal turbine and isobaric ERD, the latter of which can achieve the energy recovery efficiency above 90% and thus become the primary choice for the designers, managers and operators of the desalination plant.

Isobaric ERDs transfer energy from the membrane rejected water directly to the membrane feed water without intermediate conversion to mechanical energy and can be classified into two types, that is, the RERD and piston-type energy recovery device. The typical commercialized rotary energy recovery device includes PX, XPR, SALINO pressure center and iSave, etc., among which PX is the application and research focus. The typical commercialized piston-type energy recovery device includes DWEER, SalTec®, RO Kinetic®, recuperator and Clark pump, etc., among which DWEER is the application and research focus and the Clark pump is suited to small scale desalination unit.

The performance comparisons of the above two types of isobaric ERD are carried out between the representatives of each type, which is PX and DWEER respectively. It was reported that over flush was not necessary for the PX device whereas more than 3% over flush associated with DWEER. The salinity increase in feed water caused by PX was higher than that caused by DWEER. The necessary lubrication flow was almost identical while the high- and low-pressure differentials through the PX device were lower. Considering all the factors, the SEC of the two ERD was similar while the efficiency of PX was a little higher. With respect to the control, DWEER required an additional control module for the valve group while PX was able to operate automatically. With respect to the operation, the DWEER was operated without rotary parts, with higher equipment stability and lower grade of noise. With respect to maintenance, the pistons and valves of DWEER required periodic maintenance while multiple PX devices can operate indefinitely and safely with one or more stopped rotors to ensure continuous operation without periodic maintenance. For the service life, the ceramic material ensured the long service life of PX while the valve wear of DWEER had a negative effect on its life.

In recent years, retrofitting the RO plant with the isobaric ERDs taking place of the turbine-based ERD to become popular, for in a long-term run, the isobaric ERD would save cost significantly although its initial installation costs more. As estimated, retrofitting existing SWRO processes with turbine-based ERD by isobaric ERDs can reduce the power consumption and expend the production capacity remarkably, with little or even no other power requirements and minimal additional equipment.

Although the energy recovery efficiency of most isobaric ERDs is over 95%, there is still some space for performance improvement to alleviate the losses in an isobaric ERD system generally including HP differential pressure, low-pressure differential pressure, low-pressure brine backpressure, leakage and mixing. Pointed at these losses and their effects, a lot of researches has been carried out on rotary and piston-type isobaric ERD, either local modification or totally novel design.

General information and design data of the RO desalination plant awarded as the yearly winner and other regionally typical commercial SWRO plants with isobaric ERDs for energy recovery built around recent 15 y are presented in chronological order in the final section, indicating the critical role of the isobaric ERD in the SWRO applications and the popularity of the representative products like PX and DWEER, and supplying reference for ERD selection in RO process or plant design.

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